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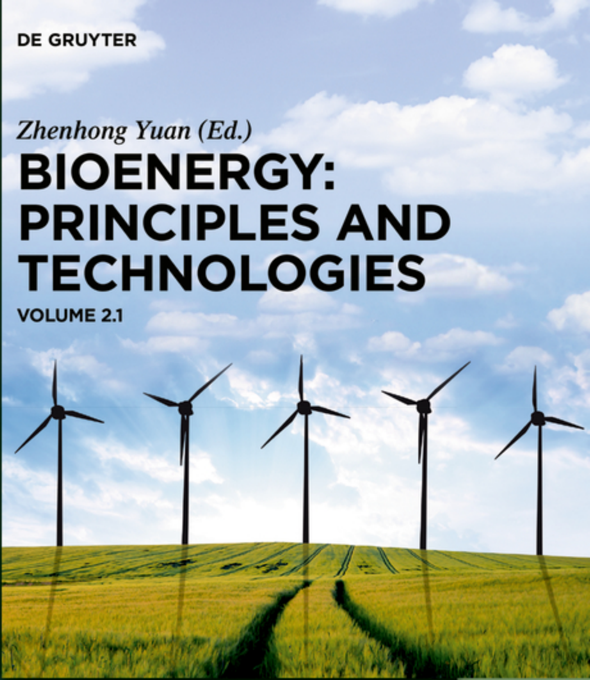

Zhenhong Yuan (Ed.)

BIOENERGY: PRINCIPLES AND TECHNOLOGIES

VOLUME 2.1

GREEN – ALTERNATIVE ENERGY RESOURCES

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Science Press
Beijing

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Bioenergy: Principles and Technologies

GREEN Alternative Energy Resources

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Volume 2.1

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Edited by
Zhenhong Yuan

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Science Press
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Editor
Zhenhong Yuan
Guangzhou Institute of Energy Conversion
Chinese Academy of Sciences
Guangzhou 510640
China
yuanzh@ms.giec.ac.cn

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Contents

Ying Guo, Jie Xu, and Zhenhong Yuan
1 Introduction —— 1
1.1 The status of biomass energy —— **1**
1.1.1 Global biomass energy consumption —— **2**
1.1.2 China's biomass energy consumption —— **5**
1.2 Biomass energy utilization technologies —— **7**
1.3 Introduction to biomass development and utilization outside China —— **8**
1.3.1 USA —— **9**
1.3.2 Brazil —— **12**
1.3.3 Europe —— **13**
1.4 Biomass energy development and utilization in China —— **14**
1.4.1 Biogas —— **15**
1.4.2 Liquid fuel —— **16**
1.4.3 Biomass molding fuel —— **18**
1.4.4 The biomass power plant —— **19**
1.5 The status of biomass energy in China's sustainable energy strategy —— **21**
1.6 Developmental direction and countermeasures of China's biomass energy —— **24**

Yishui Tian, Changzhu Li, Wen Wang, Changhua Shang, Liangbo Zhang, Zhongming Wang, and Peiwang Li
2 Biomass energy resources and energy plants —— 29
2.1 Material basis of biomass energy —— **29**
2.1.1 Photosynthesis —— **29**
2.1.2 Biomass feedstock —— **30**
2.1.3 Characteristics of biomass resources —— **30**
2.1.4 Chemical composition of biomass —— **31**
2.1.5 Calorific value of biomass fuel —— **33**
2.2 Existing biomass resources in China —— **35**
2.2.1 Crop straws —— **35**
2.2.1.1 Properties —— **35**
2.2.1.2 Resources and their regional distribution —— **36**
2.2.1.3 Main uses, amounts and proportions —— **36**
2.2.2 Livestock and poultry manure —— **37**
2.2.3 Forestry residue —— **39**
2.2.4 Starch resources —— **40**

2.2.5 Carbohydrate resources — **42**
2.2.5.1 Sugarcane — **42**
2.2.5.2 Beet — **43**
2.2.5.3 Molasses — **44**
2.2.6 Waste edible oils — **44**
2.2.7 Urban domestic garbage — **46**
2.2.8 Industrial organic wastewater — **46**
2.3 Energy plants — **47**
2.3.1 Concept of energy plants — **47**
2.3.2 Technology improvement for energy plants — **50**
2.3.2.1 Crossbreeding — **51**
2.3.2.2 Mutation breeding — **51**
2.3.2.3 Physical mutagenesis — **51**
2.3.2.4 Chemical mutagenesis — **54**
2.3.2.5 Plant cell engineering — **55**
2.3.2.6 Genetic engineering — **56**
2.3.3 Agricultural crops — **57**
2.3.3.1 Sweet sorghum — **57**
2.3.3.2 Sugarcane energy — **57**
2.3.3.3 Castor oil plant — **58**
2.3.3.4 Soybean with high oleic acid — **64**
2.3.3.5 High erucic acid rapeseed oil — **67**
2.3.3.6 Cassava — **70**
2.3.3.7 Sweet potato — **71**
2.3.3.8 Jerusalem artichoke — **73**
2.3.4 Woody oil plants — **74**
2.3.4.1 Jatropha curcas — **75**
2.3.4.2 Swida wilsoniana — **75**
2.3.4.3 Pistacia chinensis Bunge — **77**
2.3.4.4 Xanthoceras sorbifolia Bunge — **77**
2.3.4.5 Sapindus — **78**
2.3.4.6 Tung oil tree — **78**
2.3.4.7 Sapium sebiferum (L.) Roxb. — **79**
2.3.4.8 Elaeis guineensis Jacq. — **79**
2.3.4.9 Symplocos paniculata (Thunb.) Miq. — **79**
2.3.4.10 Idesia polycarpa. Maxim — **80**
2.3.5 Hydrocarbon energy plants — **80**
2.3.5.1 Eucalyptus robusta Smith — **81**
2.3.5.2 Euphorbia tirucalli L. — **82**
2.3.5.3 Sindora glabra — **82**
2.3.5.4 Simmondsia chinensis — **82**
2.3.5.5 Pinus massoniana — **82**

2.3.5.6 Copaifera reticulate — 83
2.3.5.7 Euphorbia lathyris — 83
2.3.5.8 Oil-producing herbs — 83
2.3.6 Wood energy forests — 84
2.4 Oleaginous microalgae — 85
2.4.1 Strains of oleaginous microalgae — 87
2.4.2 Isolation and selection of microalgae — 87
2.4.3 Culture of microalgae — 89
2.4.4 Harvesting and oil extraction — 90
2.4.5 Comprehensive utilization of microalgae — 92
2.5 Biomass resources forecast — 92
2.5.1 Crop straw — 92
2.5.1.1 Consumer demand growth — 93
2.5.1.2 Decrease in arable area — 93
2.5.1.3 Water shortages — 94
2.5.1.4 Low profit for grain — 94
2.5.1.5 Tight global food supply-demand situation — 94
2.5.2 Forestry residues — 96
2.5.2.1 Felling, logging residues bucking lave — 96
2.5.2.2 Forestry processing residues — 97
2.5.3 Wood energy — 97
2.5.4 Nonfood energy crops — 97
2.5.5 Oil-bearing energy forest — 99
2.5.6 Waste edible oils and fats — 100
2.5.7 Industrial organic wastewater — 100
2.5.8 Livestock and poultry manure — 100

Jinsong Zhou, Xinshu Zhuang, Hanping Chen, Chunjiang Yu, Jie Xu, and Xuesong Tan
3 Biomass direct combustion technology — 101
3.1 Principle of biomass combustion — 101
3.1.1 Biomass combustion process — 102
3.1.1.1 Characteristics of biomass fuels — 102
3.1.1.2 Typical combustion process — 103
3.1.1.3 Characteristics of pyrolysis — 105
3.1.1.4 Combustion characteristics of coke — 106
3.1.2 Characteristics of biomass combustion — 107
3.1.2.1 Effect of moisture — 107
3.1.2.2 Burnout of volatiles — 108
3.1.2.3 Ash-related issues — 110
3.1.2.4 Design calculation of the combustion process — 112
3.1.3 Pollutant emissions of biomass combustion — 114
3.1.3.1 Soot emissions — 114

3.1.3.2 Pollutants emissions in the gaseous phase — 115
3.1.3.3 Emissions of heavy metals — 117
3.2 Biomass ovens for domestic use — 117
3.2.1 Cooking stoves — 118
3.2.2 Cooking and heating oven — 123
3.2.3 Heating oven — 125
3.2.4 Energy-saving oven — 126
3.3 Industrial combustion technology and applications of biomass — 131
3.3.1 Combustion technology of biomass — 132
3.3.1.1 Biomass direct combustion technology — 132
3.3.1.2 Biomass briquette combustion technology — 133
3.3.1.3 Co-firing technology of biomass and coal — 133
3.3.1.4 Biomass gasification combustion technology — 133
3.3.2 Biomass hot air furnace — 134
3.3.2.1 Fluidized-bed combustion apparatus of biomass fuel — 135
3.3.2.2 Apparatus for diffusive combustion of biomass fuel — 135
3.3.3 Heating industrial boiler — 136
3.3.3.1 Fuel characteristics of the biomass industrial boiler — 136
3.3.3.2 Practical cases of biomass industrial boilers — 137
3.3.4 Biomass-fired power generation boiler — 139
3.3.4.1 Technical features of biomass-fired power generation — 139
3.3.4.2 Applications of biomass-fired power generation — 140
3.3.5 Co-firing boiler — 141
3.3.5.1 Classification of co-firing boilers — 142
3.3.5.2 State-of-the-art of co-firing boilers — 143

Lianhua Li, Changda Cai, and Yongming Sun
4 Anaerobic processes and biogas technology — 145
4.1 Concepts and principles — 145
4.1.1 Basic concept — 145
4.1.2 Fermentation principle — 146
4.1.3 Methanogenic pathway — 146
4.1.3.1 Methanogenic pathway from CO_2 and H_2 — 146
4.1.3.2 Methanogenic pathway from acetic acid — 148
4.1.4 Microbial fermentation — 149
4.1.4.1 Nonmethanogens — 149
4.1.4.2 Methanogens — 150
4.1.4.3 Microbial communities and their interactions during anaerobic digestion — 154
4.1.5 Microbial regulatory process — 156
4.1.5.1 Strict anaerobic environment — 156
4.1.5.2 Fermentation temperature — 156

4.1.5.3 Raw materials for CH_4 fermentation — 156
4.1.5.4 Suitable feed concentration — 157
4.1.5.5 Suitable pH — 157
4.1.5.6 C/N ratio of raw materials — 157
4.1.5.7 Inhibitors — 158
4.1.5.8 Stirring — 158
4.1.5.9 Inoculum — 158
4.2 Technology and equipment — 158
4.2.1 Pretreatment equipment and technology — 159
4.2.1.1 Equipment used in manure biogas plant — 159
4.2.1.2 Pretreatment methods for lignocellulose — 161
4.2.2 Anaerobic reactor and process — 166
4.2.2.1 High-concentration fermentation process and reactor — 167
4.2.2.2 Low concentration fermentation process and reactor — 172
4.2.2.3 Dry anaerobic digestion — 179
4.2.2.4 Two-phase anaerobic fermentation process — 185
4.2.2.5 Other anaerobic digestion processes and reactors — 187
4.2.3 Biogas storage — 190
4.2.3.1 Low-pressure wet-gas storage cabinet — 190
4.2.3.2 Low-pressure dry-type biogas storage cabinets — 191
4.2.3.3 High-pressure dry biogas storage cabinet — 192
4.2.3.4 Double-membrane dry-type biogas storage cabinets — 192
4.2.4 High-value utilization technology and equipment for biogas — 193
4.2.4.1 Desulfurization process and technology — 194
4.2.4.2 Dehydration process and technology — 201
4.2.4.3 Decarburization process and technology — 203
4.2.4.4 Deoxidation process and technology — 212
4.3 Projects and models — 213
4.3.1 Cogeneration project — 213
4.3.1.1 Introduction to engineering — 213
4.3.1.2 Technical Characteristics — 214
4.3.1.3 Financial evaluation — 216
4.3.1.4 Social and enviromental benefits — 216
4.3.1.5 The main experience — 217
4.3.2 Biogas project for vehicles — 217
4.3.2.1 Introduction to the project — 218
4.3.2.2 Engineering solutions — 219
4.3.2.3 Technical features — 219
4.3.2.4 Financial evaluation — 219
4.3.2.5 Social and environmental benefits — 219
4.3.2.6 The main experience — 220
4.3.3 Pipeline and central gas supply engineering cases — 220

4.3.3.1 Project introduction — **220**
4.3.3.2 Engineering scheme — **221**
4.3.3.3 Technical characteristics — **221**
4.3.3.4 Financial evaluation — **222**
4.3.3.5 The main experience — **222**

Tingzhou Lei, Yang Jiang, Xiaofeng He, Zhiwei Wang, Weizhen Li, and Shuna Liu
5 Biomass briquette fuel technology — 223
5.1 Concepts and principles of biomass briquette fuel — **223**
5.1.1 Concepts of biomass briquette fuel — **223**
5.1.2 History of biomass briquette fuel development — **225**
5.1.3 Properties of biomass briquette fuel — **227**
5.1.3.1 Relax density — **227**
5.1.3.2 Mechanical durability — **228**
5.1.3.3 Elemental analysis — **228**
5.1.3.4 Industrial analysis — **229**
5.1.3.5 Porosity — **229**
5.1.4 Principles of biomass compression briquetting — **230**
5.1.4.1 Effect of lignin bonding — **230**
5.1.4.2 Effect of particle bonding — **231**
5.1.4.3 Effect of water content — **231**
5.1.4.4 Effect of electric potential — **232**
5.1.4.5 Effect of “solid bridge” structure — **232**
5.2 Biomass briquette fuel technology and equipment — **233**
5.2.1 Biomass briquette fuel preconditioning technology and equipment — **233**
5.2.1.1 Biomass pulverization technology and equipment — **233**
5.2.1.2 Biomass drying technology and equipment — **235**
5.2.2 Biomass pellet fuel briquetting technology and equipment — **237**
5.2.2.1 Structure of the ring die — **240**
5.2.2.2 Material, hole shape, and thermal treatment of the ring die — **243**
5.2.2.3 Pressure roller — **244**
5.2.3 Biomass block-shaped fuel briquetting technology and equipment — **245**
5.2.3.1 Ring die briquetting equipment — **246**
5.2.3.2 Flat die briquetting equipment — **251**
5.2.4 Briquetting technologies and equipment for biomass rodlike fuel — **257**
5.2.4.1 Briquetting technologies for biomass rod-like fuel — **257**
5.2.4.2 Piston press — **257**
5.2.4.3 Screw extrusion press — **258**
5.2.5 Industrial production system for biomass briquette fuel — **259**

5.2.5.1 Processes —— 259
5.2.5.2 Industrial production system for biomass briquette fuel —— 261
5.2.5.3 Automatic control system —— 265
5.3 Application technologies and equipment for biomass briquette fuel —— 267
5.3.1 Burning technologies and equipment for biomass briquette fuel —— 267
5.3.1.1 Direct-fired boiler —— 267
5.3.1.2 Circulating fluidized-bed boiler —— 267
5.3.1.3 Segmented burning equipment for biomass briquette fuel —— 268
5.3.1.4 Biomass boiling, gasification, and burning devices —— 269
5.3.2 Gasification technologies and equipment for biomass briquette fuels —— 271
5.3.3 Household technology and equipment for biomass briquette fuel —— 272
5.3.3.1 Typical semi-gas cooking stove for biomass briquette fuel —— 272
5.3.3.2 Gas cooking stove for biomass briquette fuel —— 272
5.3.4 Carbon-based slow-release fertilizer technology and equipment —— 273
5.4 Example applications of biomass briquette fuel —— 275
5.4.1 Application example of scaled production of biomass briquette fuel —— 275
5.4.1.1 Ruzhou production base for stalk briquette fuel in Henan —— 275
5.4.1.2 Jiangtang Production Base of Jinhua Branch Company of Ningbo Aoke Lvying New Energy Development Co., Ltd. —— 277
5.4.1.3 Zhiziying Production Base of Hebei Aoke Ruifeng Biomass Technology Co., Ltd. —— 278
5.4.2 Example applications of burning heat supply with biomass briquette fuel —— 281
5.4.2.1 Heat energy service project of Excelic Food Technology (Nanjing) Company —— 281
5.4.2.2 Heat service project of Zhengzhou Songshan Hotel —— 282
5.5 Technological and industrial development trends for biomass briquette fuel —— 282
5.5.1 Technological development trends —— 283
5.5.1.1 Development trends in raw materials supply system —— 283
5.5.1.2 Technical development trends in briquetting equipment —— 284
5.5.1.3 Technological development trends in briquetting processes —— 284
5.5.1.4 Applications of briquette fuel equipment and technical development trends —— 284
5.5.2 Industrial development trends —— 285
5.5.2.1 Industrialization flow of briquette fuel —— 285
5.5.2.2 Briquette fuel industrialization mode —— 285
5.5.2.3 Briquette fuel industrialization guarantee —— 286

Xiaodong Zhang, Min Xu, Huacai Liu, Zhaoqiu Zhou, Xiuli Yin, Ying Guo, Lei Chen, Xiaoxu Fan, and Rongfeng Sun

6 Biomass gasification technology — 289
6.1 Fundamentals of biomass gasification — 290
6.1.1 Principle of gasification — 290
6.1.2 Thermochemical reactions involved in gasification — 291
6.2 Biomass gasification system and devices — 293
6.2.1 Biomass gasification system — 293
6.2.2 Types of gasification device — 295
6.2.3 Fixed-bed gasifier and applications — 297
6.2.3.1 Structural characteristics of the fixed-bed gasifier — 297
6.2.3.2 Updraft gasifier — 299
6.2.3.3 Downdraft gasifier — 300
6.2.3.4 Improved fixed-bed gasifiers — 301
6.2.4 Fluidized-bed gasifier and its applications — 302
6.2.4.1 Bubbling fluidized-bed gasifier — 303
6.2.4.2 Circulating fluidized-bed gasifier — 304
6.2.4.3 Factors influencing fluidized-bed gasification — 305
6.2.4.4 Dual fluidized bed — 307
6.2.5 Performance and important parameters of gasification devices — 310
6.2.5.1 Gasification intensity — 310
6.2.5.2 Gas quality — 310
6.2.5.3 Air requirement — 312
6.2.5.4 Output capacity of a gasification unit — 313
6.3 Biomass gas purification — 313
6.3.1 Impurities in biomass fuel gas — 313
6.3.2 Characteristics of biomass tar — 314
6.3.3 Gas cleaning: method and equipment — 315
6.3.3.1 Mechanical separation and purification — 315
6.3.3.2 Purification by electrostatic precipitator — 315
6.3.3.3 Purification by wet separation — 316
6.3.3.4 Purification by filter — 317
6.3.3.5 Tar removal by thermo-chemical conversion — 317
6.3.4 Guideline for selecting a gas purification system — 319
6.4 Applications of biomass gasification technology — 320
6.4.1 Biomass gasification and central gas supply — 320
6.4.2 Biomass gasification and power generation — 322
6.4.2.1 Four MW fixed-bed biomass gasification and power generation — 323
6.4.2.2 Rice husk power generation project — 324
6.4.2.3 3 MW cone fluidized-bed biomass gasification power generation project — 324

6.4.2.4 500 kW fixed-bed biomass gasification multi-energy cogeneration system — **326**
6.4.3 Biomass gasification gas as substitutive fuel — **327**
6.4.4 Applications of biomass gasification in chemical synthesis — **330**
6.4.4.1 Ammonia synthesis project in Finland — **330**
6.4.4.2 Hundred-ton pilot project for the synthesis of dimethyl ether — **331**
6.4.4.3 Thousand-ton cogeneration project of low-carbon mixed alcohol and DME — **331**

References — 335

Index — 341

Also of interest — 343

Ying Guo, Jie Xu, and Zhenhong Yuan*

1 Introduction

Biomass is one of the world's oldest sources of energy. Widely distributed, renewable and low cost, biomass energy presently accounts for 10 % of the global energy supply. Approximately two-thirds of biomass resources are concentrated in developing countries. China, for example, is an agriculturally-poor country with a large population. In China, biomass energy plays a very important role in the national energy structure. This is especially true in China's vast rural areas, where biomass energy has been the most important energy source. However, as biomass energy use is dominated by direct combustion, which has low thermal efficiency and emits large amounts of exhaust soot and ashes, the use of biomass fuels is one of the primary factors hindering the development of China's rural economic and social progress. With recent developments in science and technology, however, biomass energy can now be utilized more efficiently through various conversion processes. These processes produce various forms of cleaner fuel and electricity, making them an attractive alternative to fossil fuels such as coal, oil and natural gas (Fig. 1.1). Therefore, the development and utilization of biomass energy has great significance in terms of the sustainable development of energy supplies, guaranteeing the nation's energy security, improving the survival prospects of the environment and reducing carbon dioxide emissions.

1.1 The status of biomass energy

Biomass energy is renewable. Biomass is now included as a new energy in the energy classification system. The general categories of energy are illustrated in Tab. 1.1.

Ying Guo: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Jie Xu: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
***Corresponding Author: Zhenhong Yuan:** Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China;
E-mail: yuanzh@ms.giec.ac.cn (Z. Yuan), Tel. +86-20-870757735

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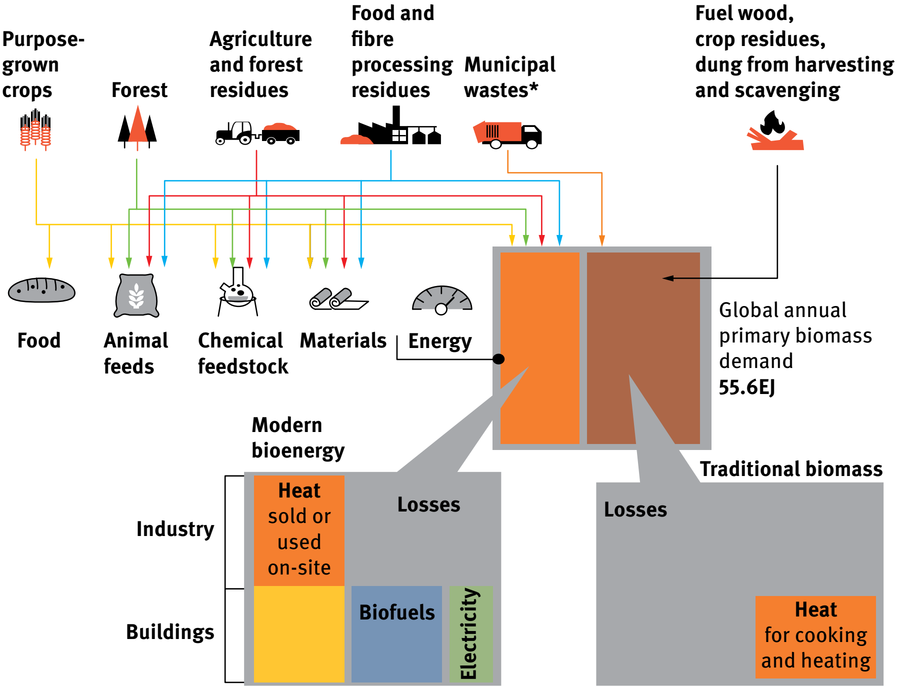


Fig. 1.1: Biomass energy pathways [1].

1.1.1 Global biomass energy consumption

Biomass energy already accounts for a significant share (approximately 10 %) of global energy consumption. Biomass is now the fourth largest contributor to total energy consumption, after oil, coal and natural gas (Fig. 1.2).

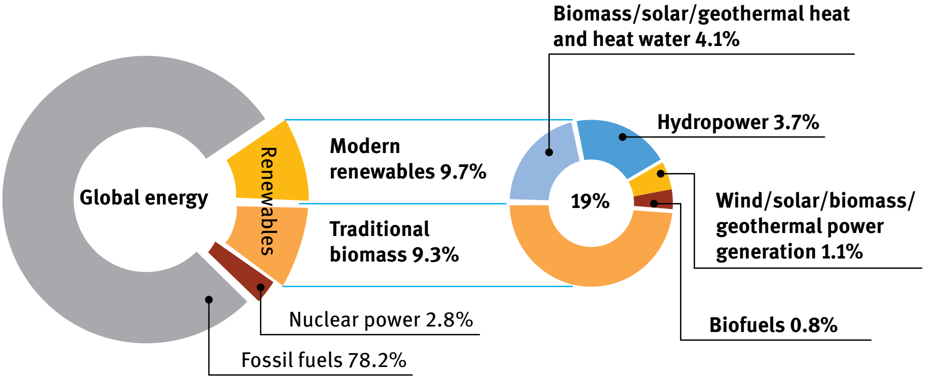


Fig. 1.2: Worldwide renewable energy and biomass energy [2].

Tab. 1.1: Status of biomass energy.

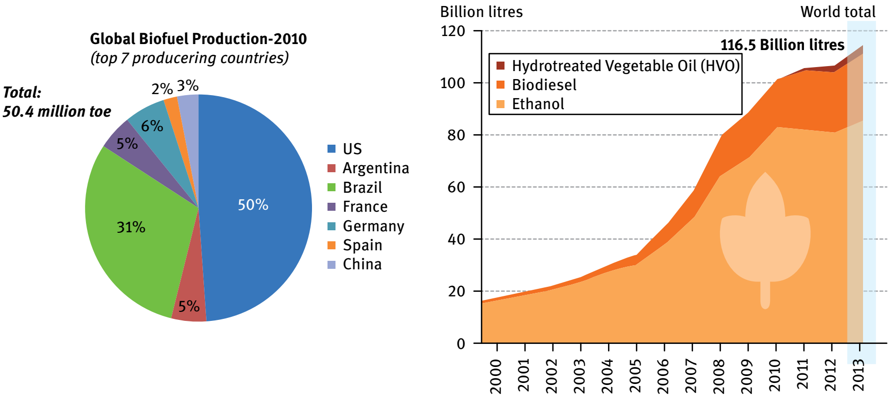
Category	Conventional Energy	New energy	
Primary energy	Renewable	Hydro-energy	**Biomass energy**, solar energy, wind, tidal energy, ocean energy
	Nonrenewable	Coal, crude oil, natural gas	rock-oil, nuclear fuel
Secondary energy	Coke, gas, steam, electricity, hydrogen, ethanol, steam gasoline, diesel, kerosene, fuel oil, liquefied petroleum gas, charcoal, biogas, syngas		

Note: (1) Primary energy refers to raw energy sourced directly from nature, i.e. the sun, including inherent material in the earth and energy caused by the motion of planets in the solar system; (2) secondary energy refers to the energy obtained from converting and processing; (3) new energy refers to the energy developed and utilized through innovative technology, where conventional or traditional energy has already been widely used.

The principal forms of biomass energy include liquid fuels, biogas, biomass molding fuel, and others. Biomass liquid fuel (including bioethanol and biodiesel) is currently the main component of biomass energy. Biomass molding fuel, sawdust and straw are mainly used for electricity generation and heat production. Biogas is mainly composed of methane and hydrogen, and is often obtained by way anaerobic fermentation of municipal and industrial waste [3].

Biomass liquid fuels account for approximately 3.4 % of transport fuels, on a global scale. First-generation biomass technologies are used to produce bioethanol (by fermentation of corn and sorghum which are rich in starch and sugars). In addition, oil-rich crops are converted to biodiesel. In 2013, global bioenergy production amounted to 116.6 billion liters, including 87.2 billion liters of ethanol, 26.3 billion liters of biodiesel, and an increasing amount of hydrogenated vegetable oil (HVO) which is being transformed into new biodiesel. North America is still the world's largest alcohol production and consumption area. Europe continued to lead in the production and consumption of biodiesel in 2013. Global alcohol production (mainly from the United States and Brazil) accounted for 87 % of global ethanol production. The US (mainly from corn) produced 50 billion liters in 2013, while Brazil (mainly from sugarcane) produced 25.5 billion liters. The efficiency of Brazil sugarcane alcohol is 1.4 times greater than the corn alcohol produced in the United States. Europe is still the biggest biodiesel production area, however, where 105 billion liters of fatty acid methyl esters (FAME) and 18 billion liters of HVO accounted for 42 % of global biodiesel production. Other regions which produce biodiesel include the United States (5.1 billion liters in 2013), Brazil (2.9 billion liters), and Argentina (2.3 billion liters [1, 3]). The feedstock used for ethanol fuel production are mainly corn (United States), sugarcane (Brazil), beet (Europe), sweet sorghum (China, the United States, Brazil), cereal (Canada and Europe) and cassava (Nigeria, Brazil, Thailand and Indonesia). Biodiesel is mainly produced from oil-rich crops, including rapeseed (Europe), soybean (United

States and Latin America) and palm and coconut oil (Malaysia and Indonesia). From 2000 to 2013, the total global biofuel output is shown in Fig. 1.3 [1]:



(a) (b)

Fig. 1.3: Total global biofuel output [1, 4].

Nowadays, producing biomass fuels using traditional livestock feed and food crops is placing huge pressure on global food security. Biomass energy draws on a rich pool of resources, the constant updating of applicable technologies, and the incentive policies which have been put in place by countries around the world attempting to support biomass energy development (in fields such as power, heating and refrigeration, and transportation). However, especially in terms of industrial power generation, the utilization of biomass technologies has developed unevenly. A number of technological and economic barriers continue to hinder the wide application of second-generation, nongrain biomass processes. Take the year 2012 as an example. In that year, only one-third of bioenergy came from agricultural and forestry residues [2], including 3 million liters from China, and 2 million liters from the United States, with a small number of demonstration plants built in Europe. At the same time, biomass molding fuel (sawdust and straw) began to be used to generate electricity and to produce heat. The global scale of biomass power generation capacity increased to 83 million kilowatts in 2012.

At present, bioenergy utilization technology predominantly falls into three categories, namely:

(1) the commercialization stage. This stage can be considered as one which employs mature technology and has characteristics of a certain amount of economic competitiveness. The technologies in this category have achieved commercialization and scale development. One such example would be biogas, which comprises only a small amount of current biomass energy technology.

(2) The policy subsidies stage refers to technologies that have entered into the early stages of commercialization. These technologies still need to enhance their competitiveness, and this is done through the use of subsidies acquired from incentive policies. Examples would include applications technology in biomass power generation, biomass molding fuel and nongrain biomass liquid fuels.
(3) The R&D stage refers to the period when new biomass energy utilization technologies (such as microalgae biodiesel and cellulosic ethanol) are only in the initial R&D or project demonstration phase. These technologies require progressive study to achieve future industrialization and commercialization.

Thus, the important and key points of current studies are those which concentrate on the second-generation biofuel technologies (those based on agricultural and forestry residues and municipal waste) and third-generation biofuel technologies (such as those based on microalgae). With ongoing developments in science and technology, biomass energy can, through various conversion techniques, be utilized efficiently for the production of cleaner fuel and electricity, and as an alternative to fossil fuels such as coal, oil and natural gas. Biomass energy will almost certainly become an important component of the world's future sustainable energy system.

1.1.2 China's biomass energy consumption

China is a country with a huge population and rapid economic growth. This nation will face the dual challenges of both high levels of economic growth and pressing environmental issues in the 21st century. Therefore, changing traditional energy production and consumption patterns (by developing biomass energy and other renewable energy sources) will be a meaningful step towards establishing a sustainable energy system, which in turn will benefit the country in terms of both economic development and environmental protection.

China's annual energy consumption is currently the equivalent of approximately 3.62 billion tons of standard coal, of which coal itself accounts for 67.1 %, crude oil 18.4 %, and natural gas 5 %. New energy sources such as hydro, nuclear, wind, solar and biomass provide a relatively low percentage of energy. In 2012, for example, these new forms of energy accounted for approximately 8 % of energy usage (Fig. 1.4). Due to the country's huge population and limited food production, China (unlike other developed countries, such as the USA) introduced the basic policy of "without sacrificing food, and without sacrificing the land for food". The main biomass resources in China are primarily in the form of residue resources. The current utilization of traditional biomass resources is at the equivalent of approximately 100 million tons of standard coal, which accounts for 15 % of the available total. This means biomass energy still has great potential for development. It is estimated that the biomass resources available in China are the equivalent of approximately 1.54 billion tons of

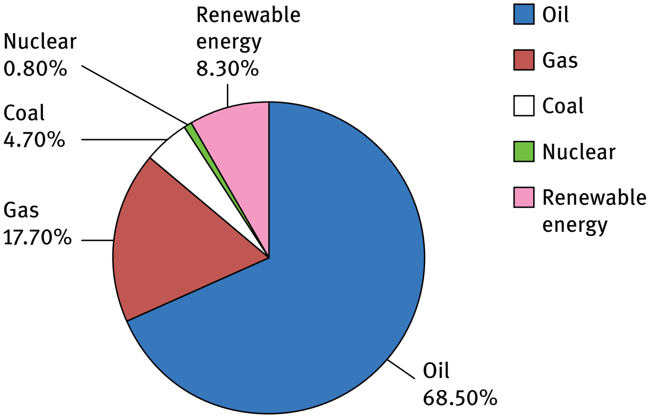


Fig. 1.4: China's energy structure [4].

standard coal. Of this total, 46.4 % can be collected and used as energy. The above figure includes 1.01 billion tons of forest residues, or approximately 577 million tons of standard coal. Of this figure, 314 million tons can be collected. In addition, 780 million tons of poultry and livestock manure equate to approximately 530 million tons of standard coal. Of this total, 500 million tons can be collected. Another source is the 740 million tons of crop straws, equivalent to approximately 317 million tons of standard coal and of which 308 million tons can be collected. Also, 142 million tons of agricultural residues are available, representing approximately 71 million tons of standard coal, and 128 million tons of these residues can be collected. Another biomass energy source is the 312 million tons of municipal garbage available, which is equal to approximately 45 million tons of standard coal and of which 154 million tons can be collected. Finally, 39.54 million tons of sludge are available, equivalent to approximately 39.5 billion tons of standard coal [5].

Approximately 50 % of China's population lives in rural areas. These people use straw, firewood, and other biomass energy as their main domestic fuels. With the rapid increase in the utilization of coal and other commercial energy forms in rural areas, biomass still has scope to play an important role. As such, the development and utilization of biomass energy has special significance in China's rural areas. The current situation (whereby biomass fuels are the main domestic energy source in vast rural areas) will not change for a long time. Thus far, biomass energy in rural areas has been utilized mainly in the form of direct combustion, which causes a waste of energy resources and pollutes the environment. Developing new technology for the utilization of biomass energy (in order to provide premium fuel for farmers in terms of energy use in everyday life and in production) is not only an important initiative for improving the environment. Such developments are also a vital task if farmers are to overcome poverty and become better off, thus achieving the goal of achieving a relatively comfortable life.

1.2 Biomass energy utilization technologies

For many years, people have utilized biomass energy, but throughout this energy form's long history, people have always utilized its heat through direct combustion, at least until the twentieth century. However, over the past one or two decades, people have improved their awareness of energy and environmental protection. They now sense the impending crisis that will occur as the earth's supply of fossil fuels rapidly runs out. Today, with the search for a sustainable energy supply from renewable energy becoming ever-more urgent, the research and applications of new technologies for biomass utilization have developed rapidly. The existing biomass utilization technologies in China and other countries are as shown in Fig. 1.5.

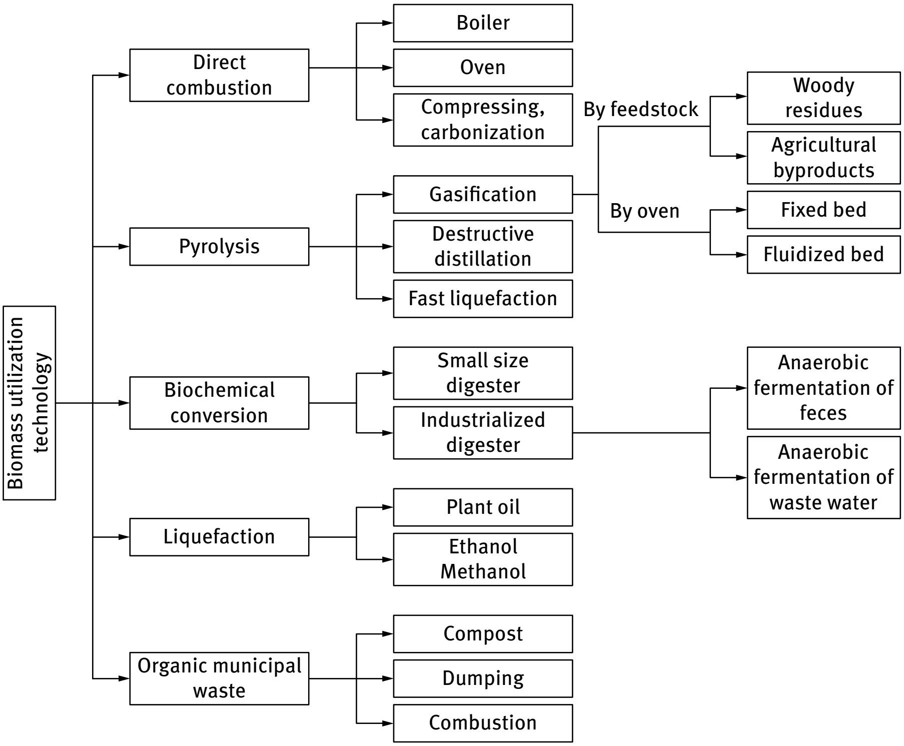


Fig. 1.5: Biomass utilization technologies.

The biomass energy utilization technologies illustrated in Fig. 1.5 have been gradually improving and developing. As research continues and technology improves, the level of application is gradually being advanced. For example, biomass gasification can produce combustible gas, which can then be used as fuel for heat and power (from engines to gas turbines), and even as a raw material for battery fuel and ammonia synthesis. The methanol and ethanol made from biomass can be used in transportation as replacement fuel for at least some of the fossil fuel petroleum currently used by internal combustion engines. Biomass can be dried for use as charcoal, which can then be employed as an adsorption agent for the metal smelting and environmental industries. Charcoal can also be directly used as an agent for the improvement of soil. Under the conditions of anaerobic fermentation, biomass can be dissimilated by marsh gas microorganisms. That biomass then becomes combustible, methane-containing gas, which is a type of fuel with a very high calorific value. This gas can then be employed for civil use, and can also be mix-fired with diesel as fuel for internal combustion engines. Biogas residue and biogas slurry are excellent organic fertilizers. Biogas slurry, in particular, can be used as a soaking medium for seeds. All-in-all, the above findings prove that biomass utilization technologies are now further developed than at any time in history, and the applications of biomass energy will become much broader in range in the future.

1.3 Introduction to biomass development and utilization outside China

Since The United Nations Conference on New and Renewable Sources of Energy, held in Nairobi in August, 1981, many countries have attached much greater importance to energy, environmental, and ecology issues. This is especially true of new energy sources, including biomass energy, which is increasingly being developed with new, modern energy technology and new materials. The technical research into and the development and utilization of biomass energy has become one of the hot topics around the world. Many countries have launched corresponding research and development plans, such as the Sunshine Project of Japan, Green Energy Engineering of India, the Alcohol Energy Project of Brazil, and others. Significantly, biomass has special carbon emission characteristics. A time delay exists between the carbon being emitted as a biological liquid fuel to when that fuel is reabsorbed by plants. In addition, the level of carbon emissions in carbon compensation time (carbon payback) differs with each full carbon cycle analysis (a full life cycle assessment), depending on the different sources of biomass materials. At this stage, each country has made their own detailed policies (each based on that country's own biomass material type and land source) to recommend or limit the use of certain specific biomass materials. Most policies, however, encourage the use of open spaces, wasteland, and other marginal land, as well as maintaining the sustainability of forest land. For example, the British government provided methods for the calculation of biomass energy in 2013, and the Danish government subsequently drew up its own relevant draft in 2014.

1.3.1 USA

Perspective planning for research into biomass energy in the USA is contained in *U.S. Biomass Energy Technology Roadmap*, and the *Prospect of U.S. Biomass Energy and Bio-Based Products* from 2002. In November, 2012, the USDA (United States Department of Agriculture) and DOE (Department of Energy) made detailed plans to source biomass materials. These plans looked at four main aspects: (1) forestry biomass resources, (2) agricultural biomass resources, (3) livestock manure, and (4) sewage and solid waste. At this stage, the available amount of biomass in the USA is 1.3 billion tons per year, and biomass energy utilization accounts for approximately 4.6 % of total primary energy consumption. The energy structure of the USA in 2012 is shown in Fig. 1.6.

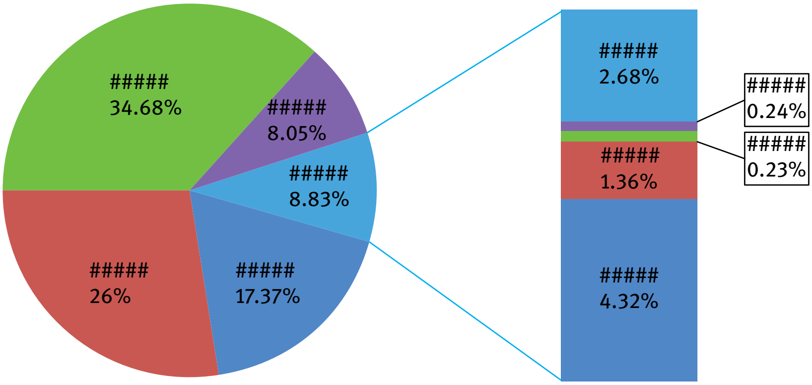


Fig. 1.6: Energy structure of the USA [6, 7].

Biomass molding fuel utilization

In the USA, biomass is mainly used for power generation by means of direct combustion. Approximately 85 % of biomass energy is comprised of wood processing waste and agricultural waste. By the end of 2012, in the USA, biomass power generated via direct combustion accounted for 75 % of the total generating capacity of renewable energy sources. More than 300 power plants have now adopted mixed biomass-coal combustion technology. The total installed capacity has reached 22,000 MW, which is equivalent to 1.3 % of the entire country's power generation capacity. Apart from biomass direct combustion power generation (and direct combustion power generation accounted for 66 % of total biomass power generation in 2013), other biomass power generation sources include 16 % from landfill biogas, 12 % from organic municipal waste, and 6 % from other forms of waste.

Liquid fuel utilization

The USA is the largest producer of fuel ethanol and diesel in the world. In recent years, the USA has faced two challenges in terms of biofuel production: (1) Vehicles have improved their efficiency, so there is less fuel demand. (2) Electric vehicles are now competing with gas-fueled vehicles. Apart from traditional corn-based alcohol plants, the USA is actively promoting the development of nongrain biomass energy. As of 2011, the companies utilizing biomass energy in the USA are as shown in Fig. 1.7. Table 1.2 shows the US ethanol plants that were utilizing nongrain biomass by 2013. Of these biomass energy plants, KiOR mainly produces biogasoline and biodiesel by utilizing pine debris. At the core of this technology is the catalyst patent system used in production. This system established the patented technology known as Biomass Fluid Catalytic Cracking (BFCC), which in turn is based on the more than 60-year-old Fluid Catalytic Cracking (FCC) technology. The technical concept of this company is to shorten the normal 10,000 years of the oil production process to an industrial catalytic time. Liberty Company's POET-DSM planned to build the first nongrain biomass ethanol commercial plant in Emmetsburg, Iowa, in 2014. In addition, OET-DSM's Project LIBERTY has plans to use raw materials such as corn cobs, leaves, husk, and straw. The company plans to produce 20 million gallons of cellulosic ethanol per year in the first few years, increasing to 25 million gallons per year in the future.

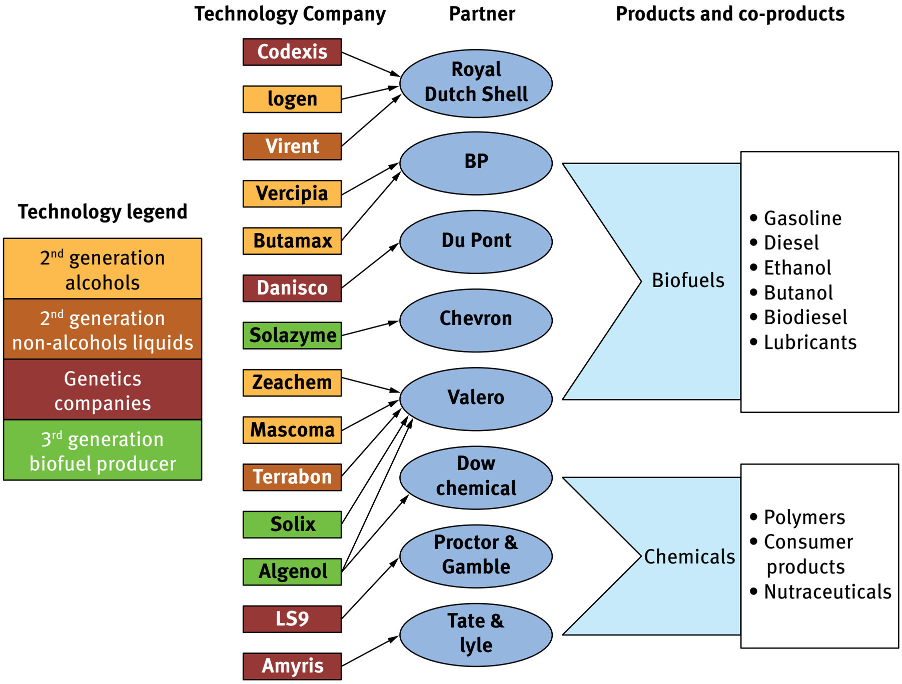


Fig. 1.7: Main biomass energy companies (2011) in the USA: [8].

Tab. 1.2: Top ten USA cellulosic ethanol plants (2013). Structure of ACR.

Company name	Mode of production	Place	Production capacity (MGY)	Raw material	Investment amount (US dollars)
KiOR	Catalytic pyrolysis & hydrothermal treatment	Natchez, MS	41	Yellow pine	350
ClearFuels	Gasification & FT synthesis	Collinwood, TN	20	Woody biomass	200
Sundrop Fuels	Gasification & MTG synthesis	Alexandria, LA	50	Mixture of biomass and natural gas	500
ZeaChem	Dilute-acid hydrolysis & synthesize alcohol by using acetic acid	Boardman, OR	25	Agricultural wastes	391
Abengoa	Prepare alcohol through enzyme hydrolysis	Hugoton, KS	25	Corn straw	350
BetaRenewable	Prepare alcohol through enzyme hydrolysis	Sampson County, NC	20	Arundoin, switchgrass	170
DuPont Biofuel Solutions	Prepare alcohol through enzyme hydrolysis	Nevada, IA	25	Corn straw	276
POET	Prepare alcohol through enzyme hydrolysis	Emmetsburg, IA	20	Corn straw and cob	250
Mascoma	Consoled	Kinross, MI	40	Wood	232

Biofuel is one of the most mature biomass energy technologies in the USA. By 2012, nearly 8,200 farm biogas projects were operating in the USA. Of that total, 192 are relatively large-scale biogas projects, with an installed capacity of 586 billion W. Another 1,238 are municipal sewage plant projects, with a daily average processing capacity of 4.5 million gallons and 100 kW of power generation. A further 594 are landfill biogas projects, with an installed capacity of 1813 MW (according to the American Biogas Council). Typical biogas projects such as the Staten Waste Disposal Station in New York dispose of waste by means of wet processing, then recycle biogas for power generation. Many of these projects also produce fertilizers. Another company, STM, is a specialized General Motors company, which helped develop Stirling engine technology. In fact, this company’s STM4-120 engine has been evaluated by the United States Department of Energy as the most advanced Stirling engine in the world. This engine can be combined with biogas technology or biomass gasification technology to deliver an approximately 50 kW village-level biomass power generation system.

In order to promote the development of biomass energy use, the United States federal and state governments continuously provide supportive policies and regulations.

These steps include regulations such as Biomass Research Methods (2000), American Agriculture Law (2002), Biomass Technology Roadmap (2002), U.S. Job Creation Bill (2004), National Energy Policy Act (2005), Advanced Energy Plan (2006), “20-in-10” New Strategy for Energy (2007), Energy Independence and Security Act (2007), National Biofuel Action Plan (2008), Development Measures for the Second Generation of Biomass Energy (2010), and the Federal Register (2013). Supported and guided by these very policies, the biomass energy industry has developed rapidly in the USA (Fig. 1.7 and Tab. 1.2).

1.3.2 Brazil

In Brazil, the main types of energy used are hydropower, alcohol, and biomass energy. Of these, hydropower accounts for the largest proportion of renewable energy in Brazil. At this stage, however, the proportion of hydropower in relation to other energy forms has been decreasing year-on-year, mostly because hydropower is limited in scale. With vast amounts of land and an advantageous climate, however, Brazil’s biomass energy status will be further improved. Brazil’s unique climate, geography, well-developed sugar industry and other advantages have all combined to promote the wide development of biomass energy in Brazil.

At this stage, biomass accounts for approximately 30 % of energy utilization in Brazil. Of that figure, bagasse and alcohol account for 13.6 %, wood and charcoal account for 13 %, and agricultural wastes and others account for 2.7 %. Brazil is the most distinctive country in terms of the development and application of ethanol fuel. The country grows massive amounts of sugarcane and has the largest sugar making process (for a breakdown of the sugar making process and energy by-products, see Fig. 1.8.) in the world. In line with its sugar making process, Brazil has been developing biomass ethanol fuel since 1975. Brazil is now the world’s second largest producer of ethanol and the world’s largest exporter of ethanol (with sugarcane, bagasse, etc. as the raw materials). Ethanol fuel now accounts for more than 50 % of vehicle fuel consumption in Brazil. The biodiesel industry started to grow in Brazil from 2005. By 2013, the country ranked third in the world (the main production places of biofuel are distributed as shown in Fig. 1.8). In Brazil, the biomass utilization rate of the sugar making process has improved remarkably since 2000. Except for ethanol production, bagasse has gradually become more widely used in power generation and heat production. In 2010, Brazil built a total of 314 power plants, which produce a total of 6022 MW of power. In these plants, bagasse is used as the raw material. By 2013, biomass power generation capacity reached 11.4 GW in Brazil. Of that figure, bagasse generating capacity accounts for 7 % of the total nationwide generating capacity. Black liquor generating capacity accounts for 1.1 % [1] of total capacity.

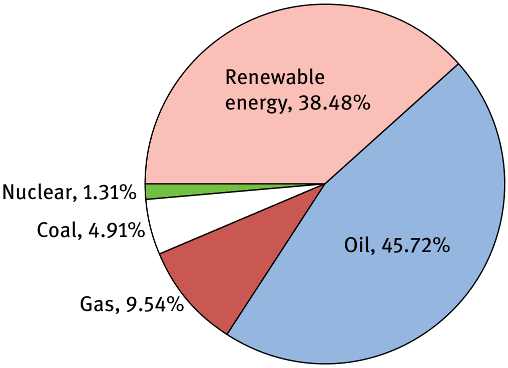


Fig. 1.8: Energy distributions in Brazil (2012) [9].

Brazil was the first country in the world to compulsively popularize ethanol gasoline through legislation. Over the last 30 years, the Brazilian government has taken the following measures to promote the development of biomass energy at home:

(1) formulated laws to compulsively popularize the addition of ethanol to gasoline and the use of ethanol pumps in multiple regions.
(2) Offered financial support to individuals and companies that plant sugarcane and produce ethanol.
(3) Fixed the sale price of gasoline and ethanol fuels.
(4) Developed and promoted flexible fuel vehicles on a large scale. At present, over 90 % of vehicles sold in Brazil are flexible fuel vehicles, which can use ethanol-gasoline mixed fuel.
(5) Invited investment to solve the problem of a funding shortage at home and expand exports.

1.3.3 Europe

In Europe, biomass energy is actively being developed and utilized with the continuous emergence of new technologies, which are applied in most countries. Generally speaking, at this stage in Europe, the mainstream biofuel process lies with biodiesel production. It is estimated that approximately 80 % of biomass resources are used for biodiesel production. Europe is the world’s largest market for diesel production and consumption. In 2013, approximately 42 % of global diesel was made in Europe, of which 10.5 billion liters came from FAME, and 1.8 billion liters came from HVO. Germany and France are the main diesel producing countries in Europe. Even so, Europe still needs to import 30 % of its biodiesel requirements. At this stage, European laws and regulations are promoting a flourishing biodiesel market. Biofuel in Europe is mainly composed of biodiesel, ethanol fuel, and part-vegetable oil and compressed natural gas (for vehicles).

In addition to the broad biofuel market, biomass is also employed in Europe for heat supply and power generation. Europe is the largest market currently utilizing modern biomass technologies to supply heat. In Europe, biomass generation accounted for 5 % of the total power source capacity in 2013. The European biomass power generation field not only includes the mature biogas power generation process (in Europe, most biogas power plants have adopted the CHP process; by the end of 2012, 13,800 biogas power plants were in operation, with a total installed capacity of 7.5 GW), but also biomass or biogas mixed-fuel power plants. This represents a significant improvement from the use of coal-fired power plants. Now, some power plants use 100 % biomass direct combustion. By 2013, Europe's biomass generating capacity had reached 34.5 GW [1].

European member states have put forward polices and measures (including expensive acquisition, subsidies for investment, biofuel tax relief, etc.) to promote the development of biomass energy use. For example, in 1975, Sweden began to provide financial support to advance the development of biomass combustion and conversion technologies, biomass energy CHP projects, subsidized biomass energy heating systems, and biomass power generation. Denmark started providing financial support to biomass production enterprises in 1981. From 1991 to 2001, the German Federal government supported the biomass energy field and provided low-interest loans. The German government formulated a *New Energy Law* to strengthen its support for renewable energy projects. From 1991 to 1995, Italy offered investment subsidies to biomass utilization projects. The Finnish government has also formulated climate and energy strategies. For example, by 2020, Finland hopes to increase the proportion of renewable energy used to 38 %. Currently, in terms of the utilization of various renewable energy sources in Finland, biomass energy represents the largest proportion, at nearly 90 % of renewable energy sources [1, 10].

1.4 Biomass energy development and utilization in China

Ancient farmers directly burned biomass products for cooking and heating. Even now, in the rural areas of developing countries, this traditional method continues. The thermal efficiency of a traditional stove, however, is very low, at only 10 to 15 %. After some reforms (e.g. firewood-saving stoves), the heat efficiency of stoves is still scarcely more than 25 %, which equates to a serious waste of energy. The direct burning of straw, firewood, dried dung, and grass is labor-intensive, it emits smoke which is harmful to the environment and human health, especially to those susceptible to respiratory diseases. In remote regions, farmers turned to nature, cutting down trees, grass, and forests, which in turn had serious consequences for the ecological environment, including vegetation deterioration in forests and grasslands, soil degradation and erosion, and even flooding hazards. In richly-resourced areas, including where people were busy with animal husbandry and cropping in summer, a lot of straw was simply burned in the fields. The resulting heavy smoke greatly affected everything from traffic to people's health, and was also a serious waste of resources.

With the development of China's economy and the corresponding improvement in living standards in rural areas (since the reform and opening-up of the economy), the need for premium fuel is becoming increasingly urgent. Traditional biomass utilization methods are not yet adapted to the developing trends of the gradual modernization of rural areas. Now, transferring to biomass energy optimization must be enforced. Towns are being expanded, township enterprises are rising, and the amount of organic solid waste and organic wastewater is increasing rapidly. If these situations can't be handled effectively, the result will be energy waste as well as further environmental pollution. Given this situation, the Chinese government needs to create research units and relevant organizations to speed up the research, development and application of new biomass energy technologies. The government also needs to formulate many relevant policies and plans and put them into effect. With the joint efforts of society as a whole, China has already made significant progress in the development and utilization of biomass energy.

1.4.1 Biogas

From the 1990s, the construction of China's biogas industry has developed at a stable rate. The biogas industry has made great progress, but the modes of use and production are still dominated by peasant households. Most of them are rural biogas engineering projects, small in size and widely dispersed across rural areas. The basic setup unit is a "one digester, three reforms" system. This system is comprised of the digester with a modified circle, modified toilet, and modified kitchen. Some systems combine biogas production with planting, which helps to develop ecological agriculture. By the end of 2011, the number of national families with household biogas (including centralized gas supply families) had reached 41.68 million in China. The national biogas project scale was 80,500 units, with annual output of 15 billion cubic meters, accounting for 11.4 % of total gas consumption. The reduction in annual CO_2 emissions was 6,100 million tons that year, combined with 410 million tons of organic fertilizer and 47 billion yuan of revenue for farmers. Currently, biogas transportation systems are being set by the Wuming Anning Starch Company, Zhenyuan Group and the CNPC departments in Wuming, Anyang, and Haikou, with gas capacity of 40,000, 10,000, and 10,000 cubic meters, respectively. Generally speaking, the Chinese biogas industry still has considerable room for improvement in terms of quantity and scale. An enterprising producing mode has not yet become the main component of existing biogas industries. The main biogas projects in China are shown in Tab. 1.3.

Tab. 1.3: Biogas projects in China Structure of HCF.

Plant	Location	Feedstocks	Capacity	Remarks
Shandong Minhe Animal Husbandry Co.	Shandong	Chicken manure	3	Built
Beijing DQY Agriculture Technology Co. Ltd.	Beijing	Chicken manure	2	Built
Jingdongtai Farm	Jiangsu	Pig manure	1.8	Built
Jiangsu Haifeng Farm	Jiangsu	Cow manure	1	Built
Mengniu Dairy Co. Ltd.	Inner Mongolia	Cow manure	1.26	Built
Anning Starch Co. Ltd. (The first stage	Guangxi	Cassavas residues after ethanol fermentation	15,000	Built
Anning Starch Co. Ltd. (The second stage)	Guangxi	Cassavas residues	60,000	In construction
Shandong Minhe Animal Husbandry Co.	Shandong	Chicken manure	60,000	In preparation

1.4.2 Liquid fuel

With its huge population and limited food production, China, unlike other developed countries such as the USA, has implemented the basic policy of “not sacrificing food and not sacrificing the land for food.” This policy was initially introduced during the process of biomass development. The main biomass resources in China are cassava, sweet potato, sweet sorghum, Jerusalem artichoke, duckweed and other nongrain crops and straw, along with forestry residues. By the end of 2010, the ethanol production capacity of nongrain crops was 318,000 tons, with the largest cellulosic ethanol production capacity of 27,100 to 200,000 tons capacity. According to China’s Renewable Energy Centre (2013) report, China’s ethanol production was approximately 2 million tons in 2012. A batch of new varieties of energy crops, with strong stress resistance and high output, have been cultivated. Cassava ethanol production technology has basically matured. Sweet sorghum ethanol technology has achieved initial breakthroughs, while research on cellulosic ethanol technology has made excellent progress, and several small-scale testing units have been built (Tabs. 1.4 and 1.5) [12].

Approximately 40 biodiesel manufacturers are operating in China. The main fuel of these plants is waste oil. The acidity component of waste oil makes diesel processing complex. Though the biodiesel production capacity in China is more than 3 million tons per year, the actual annual yield is less than 800,000 tons. Of that figure, the production capacity of biodiesel from waste oil is currently 500,000 tons per year. Many enterprises have introduced overseas technology. However, the biodiesel industry is in trouble in this regard, due to the fact that overseas industries have been unable

Tab. 1.4: Nongrain ethanol production plants in China. Structure of USB.

Plant	Location	Feedstock	Capacity K ton	Remarks
Tian Guan Group	Henan	Cassava and sweet potato	100	Built
China National Cereals, Oils and Foodstuffs Corporation	Guangxi	Cassava	200	Built
Zizhong Yinshan Hongzhan Industrial Co. Ltd.	Sichuan	Sweet potato	10	Built
Kinglong Beer	Hubei	Sweet potato	100	In construction
Jiangxi Yufan Alcohol Co. Ltd., Sinopec	Jiangxi	Cassava	100	In construction
Jilin Sanhua Group	Jilin	Sweet potato	30	In construction

Tab. 1.5: Cellulosic ethanol plants in China. Structure of UASB.

Plants	Location	Feedstock	Capacity K ton	Remarks
Songyuan Laihe Chemistry Co. Ltd.	Jilin	Straw	5	Built
Longli Bio Energy Technology Co. Ltd.	Shandong	Corn cob	10	Built
Tianguan Group	Henan	Straw	5	Built
Zesheng Bioengineering Technology Co. Ltd.	Shandong	Straw	3	Built
Fengyuan Group	Anhui	Corn cob	3	Built
Tianziguan Renewable Energy Co. Ltd.	Shanghai	Straw, rice husk	0.6	Built
COFCO Bio-Energy (Zhaodong) Co. Ltd.	Heilongjiang	Straw	0.5	Built
Fenghao Ethanol Co. Ltd.	Guangxi	Bagasse	2	In construction
Zhongke New Energy Technology Co. Ltd.	Liaoning	Straw	10	In construction
COFCO	Heilongjiang	Corn straw	100	In construction

to adapt to the use of domestic feedstock. The development of biomass pyrolysis oil is only at the initial stage. Currently, fluidized-bed pyrolysis processing capacity is approximately 5,000 t/a. A typical ceramic ball heat carrier heating recycled pyrolysis system with oriented pyrolysis can achieve 2,000 t/a, and the production of a moving bed pyrolysis device is in the pilot stage. Aqueous-phase catalysis and synthesis technology of relevant biomass (through a sugar platform, bio-oil upgrading, and direct application research) have been the main focus of recent research (Tab. 1.6) [5].

Tab. 1.6: Biodiesel production plants in China Structure of EGSB

Plant	**Location**	**Production for 2007**	**Market share %**	**Capacity K ton**	**Capacity in 2007 K ton**	**Capacity in 2008 (estimated) K ton**
Gushan Environmental Energy Co. Ltd.	Sichuan Hebei Fujian Beijing	165,000	44.4	240	190	240
Longyan Zhuoyue New Energy Sources Development Co. Ltd.	Fujian	26,116	7.0	100	26	150
Wuan Zhenhe Co. Ltd.	Hebei	25,000	6.7	30	30	30
Hefei Guofeng Co. Ltd.	Anhui	25,000	6.7	50		
Shandong Sunway Petrochemical Engineering Co. Ltd.	Shandong	25,000	4.8	50	50	
Yuanha Zhuoyue Energy Science & Technology Fujian Co. Ltd.	Fujian Zhejiang	18,000	4.6	50	23	80
Xinghuo Co. Ltd.	Henan	17,000	3.2	50		
Wuxi Huahong Biofuel Co. Ltd.	Jiangsu	12,000	4.6	60	14	100
Greennow	Shandong	9,500	2.6	25		
Tianyuan	Hunan	5,000	1.3	20	20	20
Dandong Refined Machinery Co. Ltd.	Liaoning			30	22	30
Hunan Rivers Bioengineering Co. Ltd.	Hunan			100	20	100
BIOLUX	Shandong					300
Lianmei Industry Co. Ltd.	Shanghai			50		
ELE (CHINA) LIMITED	Jiangsu					200
TOTAL (production in liters)		371,802				

1.4.3 Biomass molding fuel

The technological and industrial aspects of Chinese biomass molding fuel began in the 1970s. At present, the country has basically finished the independent R&D and innovation stages, and formed a development mode and industry chains that are suitable for China's national situation. Several types of biomass-compressed molding equipment (such as a screw extrusion model, piston ram-type and rolling type) have been developed. Of these, the screw-extrusion molding machine has been widely used, while the extrusion bolt has been improved to extend its lifespan. Biomass molding fuel can be used directly as a fuel and can also be carbonized to biochar, for use in roasting and metallurgy industries in carbonization furnaces. In China, most biomass molding fuels are produced from agricultural and forestry residues. Biomass molding fuel demonstration industries are mainly located in Henan, Shandong, Anhui, Hebei, Heilongjiang, Jilin, Liaoning, Guangdong and Beijing. China's briquette plants are located at more than 500 sites. Almost 100 plants can produce more than one million tons of briquettes per year. Up to 2012, briquette production was only 3.5 million tons per year. Agricultural straw plants are mainly located in north and central China, and plants making briquettes from forestry wood pellets are mainly in the northeast, Inner Mongolia, east, and south China (Tab. 1.7) [5].

Tab. 1.7: Biomass molding fuel plants in China. Structure of an IC reactor.

Plant	Location	Feedstock	Capacity K ton	Remarks
Guangzhou Devotion Thermal Technology Co. Ltd.	Guangdong	Wood sawdust, straw	130	Built
Beijing Aoke Ruifeng New Energy Co. Ltd.	Beijing, Henan	Straw	90	Built
Heilongjiang Sheng Yanxin Energy Co. Ltd.	Heilongjiang	Straw	80	Built
Sanli New Energy Co. Ltd.	Henan	Straw	50	Built
Shengchang Green Energy Co. Ltd.	Beijing	Wood sawdust, straw	50	Built
Liaoning Senon Renewable Energy Co. Ltd.	Liaoning	Wood sawdust, straw	40	Built
Dongguan Baifa New Energy Technology Co. Ltd.	Guangdong	Wood sawdust	40	Built
Ruixin New Energy Co. Ltd.	Heilongjiang	Straw	40	Built
Baichuang Tongchuang New Energy Co. Ltd.	Shandong	Straw	40	Built

1.4.4 The biomass power plant

In China, direct combustion power generation prevails in the biomass power generation industry. China occupies a leading position in global biomass power generation. The country's biomass generating capacity ranked third in the world in 2013, according to the *Global Renewable Energy Report, 2014* [3]. According to the report issued by the China National Renewable Energy Centre in 2012, China's biomass generating capacity was 36 TWh in 2012, an increase of 21 % from 2011. In addition, the installed capacity was 8 GW, an increase of approximately 14 % from 2011. Typical direct combustion power plants include the National Bio Energy Group, which adopted the approach of Denmark's BWE Company to make a timely investment in the building of China's first national biomass power generation demonstration project, the Shan

County Straw Direct Combustion Power Plant. The process of an autonomous circulating fluidized-bed firing boiler which burns biomass fuel was jointly developed by Zhejiang University and Beijing Zhonghuan United Environmental Engineering Co. Ltd. The latter is subordinated to the CECEP (China Energy Conservation and Environmental Protection Group) and is the demonstration project of straw direct combustion power generation of the CECEP in Suqian.

Tab. 1.8: Biomass power generation plants in China. Chemoautotroph biological desulfurization unit.

Plant	Location	Feedstock	Capacity kW	Remarks
Join to Energy Investment Co. Ltd.	Heibei	Corn straw, wheat straw, branches	25	Combustion/built
National Bio Energy Co. Ltd.	Shandong	Cotton stalk, branches	25	Combustion/built
National Bio Energy Co. Ltd.	Jiangsu	Cotton stalk	50	Combustion/built
Guoxin Bio Energy Co. Ltd.	Jiangsu	Rice straw, wheat straw	30	Combustion/built
Wuhan Kaidi Electric Power Co. Ltd.	Fujian	Chicken manure, rice husk	45	Combustion/built
Guodian Technology & Environment Group	Shandong	Corn straw, cotton stalk, branches	25	Combustion/built
Huadian Power International Co. Ltd.	Shandong	Coal straw	140 (18.5 %)	Co-firing/built
Teneng Bio Energy Technology Co. Ltd.	Jiangsu	Rice husk	0.4	Gasification/ built
Linyuan Industry Co. Ltd.	Jiangsu	Briquettes from straw	4	Gasification/ built
Hefei Tian Yan Green Energy Development Co. Ltd.	Anhui	Rice husk	0.4	Gasification/ built
Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences	Jiangsu	Rice husk, sawdust	5.5	Gasification/ built
Hejia Energy Development Co. Ltd.	Jilin	Rice husk	2	Gasification/built
Mengniu Biomass Co. Ltd.	Inner Mongolia	Methane from cow manure	1.36	Methane/built
VEOLIA Group	Beijing	Methane from MSW	2.7	Methane/built
Fuzhou Hongmiaoling Waste-to-Energy Co. Ltd.	Fujian	MSW	24	MSW/built
Chengdu Waste-to-Energy Co. Ltd.	Sichuan	MSW	24	MSW/built

In the biomass gasification field, after more than a decade of research, testing and demonstrations, biomass gasification technology has basically matured. Biomass gasification equipment has been applied to products with gas production at rates of 200–1,000 m^3/h and gasification efficiency of more than 70 %. By the end of the year 2000, 388 centralized straw gasification stations had been set up. A total of 79,443 households were using gasification products and equipment for fuel by the end of 2000. Some of the gasification products have been used as a drying heat source and for power generation. The technology formerly used for fixed-bed gasifiers from rice husks was only at a small scale. A few fluidized-bed gasifiers have been built recently, using rice husk and sawdust, or even crushed straw, as fuel. China’s power plant capacity reached approximately 40 MW by 2010, with the greatest capacity being 5.5 MW (Tab. 1.8). Due to the fact that biomass power plants have small construction scales, high unit costs, low efficiency of biomass power generation, and also because the key technologies in use still need to be improved, the majority of biomass power projects are still in the phase of measuring economic benefits. The majority of these projects are finding it difficult to reach the commercial stage.

1.5 The status of biomass energy in China’s sustainable energy strategy

With the continuing growth of both its population and its economy, China’s energy consumption is also constantly growing. China’s dependency on crude oil and gas were up to 58 % and 30 %, respectively, in 2012. It is estimated that, by 2020, China’s oil needs will reach 360 million tons, with net import rates exceeding 200 million tons. Such a development will hamper China’s economic and social development. Oil and gas dependency has become one of the most significant barriers in many years to sustaining China’s economic development and social progress. Unlike the USA and other developed countries, China has a large population. China’s grain output rates continue to require improvement. Therefore, the basic policy of “not sacrificing food and not sacrificing the land for food” has been implemented during the development of the biomass energy industry. Biomass resources are mainly from wastes. As such, new biomass technology should first aim to maximize the utilization of waste resources, then promote the comprehensive utilization of those resources, while also protecting the environment. Steps should also be taken to develop marginal land resources reasonably, without the over-use of ploughs, and without destroying forests, grasslands, and the natural environment. The development of the biomass energy industry has been clearly promoted by the *National Outline for Medium and Long Term S&T Development*, the *National 12th Five-Year Plan for S&T Development*, the *12th Five-Year Plan for National Energy S&T Development*, the *12th Five-Year Plan for Renewable Energy Development*, and the *12th Five-Year Plan for Biomass Energy Development* (Tab. 1.9) [16].

Tab. 1.9: China’s biomass energy plan [5].

Date	Policy	Main Contents
2007	Renewable energy medium- and long-term development plan	By 2020, the annual utilization of biomass briquette fuel should reach 50 million tons, and that of biodiesel should reach 2 million tons [5].
2007	Agricultural biomass energy development plan	By 2015, crop straw output in China is estimated to reach 0.9 billion tons, (equivalent to approximately 0.45 billion tons of standard coal), which can be converted to an equivalent biogas amount of approximately 300 billion cubic meters, with approximately 180 billion cubic meters of natural gas. Development of biogas will be likely to increase the proportion of gas energy consumption in China to approximately 8 %.
2012	Biomass energy development 12th Five-Year Plan	By 2015, the annual utilization of biomass briquette fuel had reached more than 10 million tons. We should strive to reach 50 million tons by 2020.

Biomass energy belongs to the clean energy category, which contributes to national environmental construction and CO_2 emission reductions. China’s SO_2 emissions from fossil fuels are the highest in the world, and the country’s CO_2 emissions are the second highest globally (after America). China’s total of 2.27 billion tons of CO_2 emissions equates to 0.62 billion tons of CO_2, which accounts for 11.8 % of global GHG (greenhouse gas) emissions. More than one third of the country experiences acid rain. We know that SO_2 and acid rain cause huge economic losses and environmental damage. The sulfur and ash content in biomass is only approximately one-tenth that of medium-quality bituminous coal. Meanwhile, the CO_2 produced and absorbed in the process of biomass production and energy utilization can be incorporated into the natural carbon cycle. This is the most important means by which to cut CO_2 emissions.

Big gaps also exist in electricity supply. To achieve the goal of quadrupling China’s GDP by 2020, ensuring a reliable power supply is one necessary condition. The establishment of decentralized and independent off-grid or grid-connected power plants has a prospective future in terms of the marketplace, especially for those plants which use local biomass resources such as wood chips, straw, firewood, and rice husk. Biomass products can be widely utilized for power, thus ensuring the security of the national grid power supply. If 40 % of current agricultural and forestry residues were utilized for power, 300 billion kWh of electricity would be produced, which would account for 20 % of China’s national electricity consumption.

Biomass fuel is always one of the main energy sources in rural regions, but these are largely dominated by direct combustion. This use of biomass has very low efficiency rates (less than 10 %) and emits huge amounts of soot and ash. In turn, these factors deteriorate people’s quality of life and living environment, and seriously impair children’s and women’s physical and psychological health. Biomass utilization combined with modern technology, however, can greatly improve the energy efficiency rates in rural areas. The rate of thermal efficiency increases up to 35 to 40 %, which in turn will save resources and improve farmers’ living conditions.

With the development of the rural economy and corresponding improvements in living standards, most farmers are inclined to use the more convenient energy sources, such as coal and gas. A large number of biomass resources have traditionally been abandoned in the fields, or even directly incinerated onsite. This practice has caused great waste, serious pollution, and even a great threat to highway and air traffic safety. While the Chinese government has prohibited straw burning, so far, no efficient methods have been found to solve this problem. The utilization of biomass fuels could radically solve the ubiquitous but not cured issue of “straw problems” in rural areas. In turn, this will fundamentally eliminate straw waste and convert agricultural and forest residues into high quality energy forms.

Finally, biomass energy will have a series of ecological, social and economic benefits. At present, fuel consumption based on wood exceeds the reasonable rate of 15 %. The corresponding results are forest destruction, soil erosion and ecological imbalance problems. Industrial, urban and rural organic wastes are accumulating at increasing rates; as much as 10 % every year. This accumulation of waste is becoming one of the most important obstacles to rural and urban modernization. Biomass energy can absorb all kinds of organic waste and eliminate those wastes’ negative impacts on the environment. In addition, biomass energy can push the development of rural and urban modernization and efficiently promote the greening of barren hills, reduce soil erosion, control deserts, and promote biodiversity, through the large-scale development of energy agriculture and forestry. Meanwhile, the integration of modern biomass energy systems will contribute to the development of modern farming, which will enhance new economic growth, increase employment opportunities in rural areas, and improve the living conditions and incomes of rural residents, thus revitalizing the rural economy.

In short, a national strategy for biomass energy functions will require many aspects and levels, including energy security, the environment, rural economy, social life, etc. Since biomass energy is so important, it is necessary for the relevant decision-making departments of the Chinese government to closely cooperate and coordinate research units, enterprises, local governments and other authorities. The government should also strengthen the support provided for biomass energy development and provide technical support to the formation and development of the biomass energy industry in the future.

1.6 Developmental direction and countermeasures of China's biomass energy

China has abundant biomass resources, which has led to good results in terms of biomass fuel development and utilization. A good foundation has also been laid for the further development of the biomass industry. However, the research, technology, and market structure of the biomass energy industry in China is different from many developed countries. Many problems exist, such as insufficient knowledge of the strategic significance of developing renewable energy. Biomass energy has not been brought into the national energy construction plan. In addition, there is no normal appropriation channel for a development fund, and there is little fund input. Another problem is the complete lack of incentive policies and relevant laws and regulations. Finally, small-scale production, high costs, a lack of product quality standards and quality supervision systems, a low degree of commercialization and weak industrialization, combined with disorderly management and divided policies from various sources are all issues to be addressed.

With the rapid development of China's economy, people's need for premium fuel is becoming increasingly urgent. In view of the limited amounts of normal energy resources and the growth in environmental stress, China needs to speed up the development of new energy and renewable energy sources. In particular, the pace of the modernized utilization of biomass energy must be accelerated. Steps must also be taken to improve conversion efficiency, reduce production costs, and bring about large-scale breakthroughs in the search for new energy forms and new processes. For the already mature technologies, China must realize large-scale and modernized production, and form perfect production and service systems. The country also needs to increase the proportion of new biomass energy in the country's overall energy structure. Over the next 20 years, basic development strategies for biomass energy include:

Rural energy: Further popularize practical technologies, give full play to the role of biomass energy as a supplementary energy source in rural areas, provide clean energy sources, and improve the living conditions of people living in rural areas.

Industrial applications: Promote the industrialization of mature technologies, increase the proportion of biomass energy utilization, elevate the status of biomass energy in the national energy field, and establish an industrial base for the large-scale application of biomass energy.

Technology and research: Enhance the utilization value of biomass energy, realize the multi-utilization of biomass energy, vigorously develop new technologies for high-grade biomass energy conversion, build demonstration projects for industrial testing purposes, and provide technical support and technical reserves for the large-sale utilization of biomass energy.

Basic research: Because significant scientific theoretical problems have already occurred in the technical research on biomass energy, and because these problems must be solved, China should be sure to attach sufficient importance to these issues and make greater research efforts to provide a theoretical basis for the development and research of new technologies and/or new processes for the production and use of biomass energy.

Resource development: Research, cultivate, and develop the fast-growing and high-yielding energy plant varieties, make use of mountains, wastelands, deserts, lakes, and offshore regions to develop energy farms, forest farms, or livestock farms, establish a biomass energy resource development base, and provide sugar, starch, wood, oils and other biomass energy resources, all of which can be utilized through industrialization.

Biomass energy is still in its initial stages, compared to the development of other forms of energy. As such, more support policies and incentives are needed from the government for the development and improvement of biomass technologies.

(1) Increase awareness and strengthen leadership
Governments and competent authorities at all levels, as well as the general population, should increase their respective awareness of the significance of the modernized utilization of biomass energy. Biomass fuel use should be made a basic energy policy, in order to push the development of biomass energy, strengthen leadership, specify focal points, and implement responsibility. The government should also bring new energy (including biomass energy) and renewable energy into the overall planning of national economic construction and the government's financial budget.

(2) Create preferential policies and increase fund input At present, the biomass energy technology development industry is scattered and on a small scale. Biomass energy offers remarkable economic benefits but has no market competitiveness. For this reason, the biomass industry should receive state macrocontrol policies and protection. The government should be sure to provide relevant finances, investment, credits, tax relief, price subsidies and incentives, and other policies, in order to develop the production and use of biomass energy. China should also strengthen its investment in scientific research, the trial and production of new products, as well as technical training related to biomass energy. Finally, the government should expand publicity, arouse investment enthusiasm in various sectors, expand the sources of biomass funding, and improve the usage results of funds.

(3) Apply high-quality and new technology, and accomplish experimental demonstrations
China should be sure to develop new projects based on high starting points, aiming to realize leap-up progress. Domestic and overseas advanced technology should also be introduced, based on local conditions. In-depth research, testing, improvement, and demonstrations should also be conducted. The general public should be educated and informed of achievements using high levels of technology and any remarkable benefits. Almost all Chinese accept that "seeing is believing."

After setting up a good mass base, regions should construct biomass facilities by stages and in batches, then popularize and gradually apply biomass technologies, based on the local natural conditions, economic base, energy demands, and other practical situations.

(4) Strengthen industry construction levels, and improve economic returns
China should pay attention to the conversion of scientific research achievements and try to finalize the design of products with mature technologies soon. We should encourage enterprises to break departmental and regional boundaries, carry out horizontal integration, and organize specialized production. We should also support the development of a batch of key enterprises in a planned and ordered way, thereby building an industrial system with scale production capacity, in order to continuously improve biomass product quality, reduce production costs, and broaden market sales. Currently, some projects are constructed with the color of a welfare model and for the appearance of public benefit. The biomass industry needs to gradually become industrialized, enterprising, and a commercially viable operation, functioning according to the rules of the market economy. The biomass industry must also ensure product quality, enhance company (or plant) credibility, develop domestic and overseas markets under fair competition conditions, boost product sales, achieve the integration of ecological, economic and social benefits, and develop and sustain a high degree of self-reliance.
With the development of biomass enterprises, China must be sure to establish a corresponding service system and continuously improve service quality. We should encourage capable individuals to jointly build an energy technology service company to manage the sales, installation, commissioning, maintenance and other technical services of new energy equipment. China should also be sure to establish a national quality supervision system and ensure product standardization, serialization, and generalization.

(5) Enhance professional quality, and expand the technical team
Biomass energy is mainly utilized in rural areas. Therefore, a large batch of relevant technicians (in terms of scientific research, management, production, promotion and other aspects) are needed, in order to develop the biomass industry with high-quality and new technology. The method we suggest would be to set up relevant majors and hold various types of courses in institutions of higher learning and specialized secondary schools. Technicians should be sent to study, and professionals should be invited to give guidance to and arrange interviews and visits for the technicians. China should also formulate some incentive policies, designed to keep the technicians working in this industry. Cultivating a large batch of technical experts in this industry in a planned way, enhancing research levels, realizing the goals of scientific management and production, and keeping the promotion and utilization of biomass fuels in order are all worthwhile objective.

(6) Develop international cooperation, and introduce advanced technology and funds

The development and utilization of new energy and renewable energy forms (including biomass energy) has become a hot topic around the world. Having joined the WTO, China must seize this excellent opportunity. The country must continue to follow a biomass technology roadmap, one which combines independent development with introduction, digestion, and absorption, and which actively seeks out foreign exchange and cooperation. We must overcome any thought of starting from scratch. Instead, we must introduce advanced technology and major equipment, intentionally and selectively, to develop China’s biomass energy application technologies at a high starting point. We must also strengthen this country’s contacts and cooperation with international organizations and institutions, promote bilateral and multilateral cooperative research and cooperative production, and enhance personnel, technology, and information exchanges. Finally, China must take practical measures to create the optimum conditions for channeling investment (from international institutions, social groups, entrepreneurs and individual investors, whether solely-invested or joint-venture entities) into new energy and renewable energy projects, including biomass energy.

Yishui Tian*, Changzhu Li, Wen Wang, Changhua Shang,
Liangbo Zhang, Zhongming Wang, and Peiwang Li

2 Biomass energy resources and energy plants

Biomass produced by plants through the process of photosynthesis is sustainable, and biofuels derived from biomass are not only renewable – which can alleviate dependence on crude oil – but are also beneficial in reducing CO_2 emissions. Biomass is the most plentiful substance in the world, while China is the largest grain producer in the world. In 2014, China produced more than 600 million tons of grains, generating at least the same amount of residues including corn stover and rice and wheat straw, which are suitable for the production of bioenergy.

2.1 Material basis of biomass energy

Generally, the term ‘biomass’ is used to denote organic matters produced by various living organisms or being part of the bodies of living organisms. The energy contained in biomass is called biomass energy. From the perspective of energy utilization, biomass that can be used as an energy source belongs to biomass energy.

2.1.1 Photosynthesis

Photosynthesis is a biochemical reaction that takes place in the presence of visible light. Depending on the photosynthetic pigments, cells, plants, algae, and some bacteria can convert water (H_2O) and carbon dioxide (CO_2), or hydrogen sulfide (H_2S) and CO_2 into organics, while releasing oxygen (O_2) or sulfur (S) as a by-product. In this process, photoenergy is converted to chemical energy.

***Corresponding Author: Yishui Tian:** Chinese Academy of Agriculture Engineering, Beijing 100125, China; E-mail: yishuit@yahoo.com
Changzhu Li: Hunan Academy of Forestry, Changsha 410004, China
Wen Wang: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Changhua Shang: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Liangbo Zhang: Hunan Academy of Forestry, Changsha 410004, China
Zhongming Wang: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Peiwang Li: Hunan Academy of Forestry, Changsha 410004, China

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There are two phases in the process of photosynthesis [1]: the light reaction and the dark reaction. In the light reaction, the hydrogen donors are cracked to produce reducing power (NADPH), while the high energy phosphate compound ATP is also formed. In the dark reaction, the reducing power and ATP are used to reduce CO_2 into organic matter, such as sugar.

2.1.2 Biomass feedstock

There are various types of biomass, which can be used for bioenergy production. According to different characteristics, it can be classified into different types [2].

Based on its chemical properties, biomass can be classified into the following types:

(1) sacchariferous biomass, such as sweet sorghum and sugarcane;
(2) starchy biomass, such as cassava and sweet potato;
(3) lipid biomass, such as rape, soybean and algae;
(4) cellulosic biomass, such as crops straws and forestry wastes.

Biomass is divided into different classifications according to its source. These include:

(1) agricultural waste, such as crops straws and husk;
(2) forestry waste, such as residues from wood cutting (branches, tree tops, leaves, bark, tree roots and rattan) and wood processing;
(3) excrement and living organic waste;
(4) industrial organic waste, such as organic wastewater and residue;
(5) energy plants, including crops, trees and aquatic plants which can be used as energy sources;
(6) algae, including macroalgae and microalgae, such as red algae and *Chlorella*.

2.1.3 Characteristics of biomass resources

Biomass is a clean low-carbon resource, and has low nitrogen and sulfur contents. The ash content is also low in biomass. After combustion, the release of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and dust from biomass is less than that from fossil fuels. For example, the sulfur content in coal is usually 0.5–1.5 %, while in biomass it is less than 0.2 %. Additionally, the quantity of CO_2 released in the combustion of biomass can be fixed by growing equivalent plants that through their photosynthesis lead to a balancing of CO_2 emissions and absorption. The utilization of biomass cannot change the CO_2 balance in the world. The exploitation and use of biomass energy will be beneficial for reducing environmental pollution and improving the ecological environment. There are also further characteristics of biomass energy resources [2], including:

(1) Renewability: Biomass energy can be regenerated through photosynthesis. As long as there is sunlight, photosynthesis will continue to take place in plants, thus making biomass energy inexhaustible. Especially nowadays, tree and grass planting, rational cutting and environmental protection are strongly encouraged, which can ensure a continuous supply of natural biomass energy resources.
(2) Huge reserves: Earth has an abundant supply of biomass. The total quantity of terrestrial biomass energy is estimated to be 3.3×10^{22} J energy, which is 80 times more than the annual global energy consumption. The energy that can be harvested through the annual net production of biomass is nearly 10 times higher than annual global energy consumption.
(3) Ubiquity and easy accessibility: Biomass resources are distributed everywhere. They are low cost and easy to access.
(4) Storage and substitution: Biomass is a kind of organic resource that can be stored. The liquid and gaseous fuels produced from biomass can also be stored, and can partially or totally substitute fossil fuels.
(5) Volatility, carbon activity and flammability: Most volatiles of biomass can be released at around 400 °C, while only 30 % volatiles of coal are released at 800 °C. Therefore, it is easy to convert biomass into gaseous fuels. After combustion of biomass, a little ash will be formed, which does not agglomerate, making the ash removal system simpler.
(6) Low grade energy with low energy density: Due to its low weight and large volume, the transportation of biomass is not very convenient. Different factors such as wind, rain, snow, and fire are harmful to its preservation.

2.1.4 Chemical composition of biomass

Biomass is diverse, and its main components include cellulose, hemicellulose, lignin, starch, protein, saccharides, lipids, and ash [3]. A proper energy conversion pathway should be chosen to handle biomass according to its composition and characteristics.
(1) Cellulose: The most abundant component of lignocellulosic biomass is naturally evolved to be recalcitrant to degradation, providing protection to plants. It is a linear glucan, which is linked by β-D-glucopyranose through β-1,4-glycosidic bonds. Several glucan chains are gathered into a molecular bundle with periodic lattices called crystallites or micelles. Several micelles exist in the same microfiber in parallel. Furthermore, polysaccharides are arranged loosely and disorderly among micelles.
(2) Hemicellulose: The second most abundant component of the lignocellulosic biomass. It is a heteropolysaccharide consisting of xylan, glucomannan, galactoglucomannan, xyloglucan, and β-1,3-glucan. Most of these polysaccharides containing 50–400 residues have side chains, and bind with microfibers via noncovalent means in the cell wall.

(3) Lignin: The third most abundant component of lignocellulosic biomass. It is a highly complex, three-dimensional polyphenolic compound, which is formed by three phenylpropanol monomers, namely *p*-coumaryl, coniferyl, and sinapyl alcohols. The molecular weight of lignin is around 10,000 Da. In the plant cell wall, lignin links with xylan via covalent bonds.

(4) Starch: The main component of starchy biomass. Natural starch has two components, namely amylose and amylopectin. Amylose is a linear molecule linked to D-glucose through α-1,4-glycosidic bonds. Amylopectin has branches, which have α-1,6-glycosidic links. In each branch, amylopectin has around 25–30 glucose units.

(5) Protein: The main component of organic wastes, such as vinasse, and sludge. It is a high-molecular weight compound, which is polymerized by amino acids.

(6) Saccharides: These exist in sacchariferous biomass, such as sugarcane, sweet sorghum, and beet. They mainly include sucrose, glucose, and fructose. Sucrose is a disaccharide polymerized by D-glucose and D-fructose. Glucose and fructose are monosaccharides having six carbons each. Glucose is aldohexose, while the fructose is ketohexose.

(7) Lipids: The main component of oleiferous biomass. They mainly consist of glyceride, which is polymerized by glycerol and fatty acid. According to the quantity of fatty acid groups, glyceride has three types, namely monoglyceride, diglyceride and triglyceride.

(8) Ash: It exists in all kinds of biomass and contains many chemical elements including potassium (K), calcium (Ca), sodium (Na), magnesium (Mg), aluminum (Al), iron (Fe), chlorine (Cl), and phosphorus (P). Different kinds of biomass have

Tab. 2.1: Composition of some typical oven-dry biomass (the contents of ash and other components are not included, %).

Biomass	Cellulose	Hemicellulose	Lignin
Hardwood	40~55	24~40	18~25
Softwood	40~50	25~35	25~35
Bamboo	43~46	22~30	27~28
Leaves	19~34	7~35	9~32
Rice straw	28~41	22~27	10~22
Corncob	27~37	25~40	13~18
Corn straw	33~42	22~35	18~20
Wheat straw	24~49	28~36	8~18
Rye straw	31~38	22~37	18~25
Sweet sorghum bagasse	36~40	21~30	19~24
Sugarcane bagasse	35~39	20~25	21~27
Switchgrass	30~40	21~28	10~23
Pennisetum	32~35	19~20	18~20
Newspaper	40~55	25~40	18~30

different ash contents, which contain different chemical elements. The ash contents in woods are lower, while those in herbaceous, aquatic, and waste biomass are higher.

The components of biomass are composed of chemical elements, such as carbon (C), oxygen (O), hydrogen (H), nitrogen (N), Ca, K, silicon (Si), Mg, Al, S, Fe, P, Cl, Na, manganese (Mn), and titanium (Ti). The compositions of some typical biomasses are shown in Tab. 2.1, while the chemical elements contained in some typical biomasses are presented in Tab. 2.2.

Tab. 2.2: Composition of chief chemical elements in some typical biomass (%).

Biomass	C	O	H	N	S
Hardwood	45~53	39~46	5~7	0.06~0.6	0~0.1
Softwood	48~53	37~45	6~8	0.1~0.7	0.01~0.4
Bamboo	47~48	43~44	5~6	0.3~0.6	0.05~0.1
Leaves	30~50	24~43	3~6	0.1~3	0.03~0.2
Rice hulls	38~47	33~40	4~6	0.2~1	0.02~0.4
Corncob	41~49	43~51	5~7	0.1~2	0.01~0.13
Corn straw	44~45	41~43	5~6	0.8~1	0.05~0.2
Wheat straw	45~48	38~44	5~6	0.3~2	0.03~0.1
Rye straw	47~48	41~44	5~7	0.2~0.6	0.04~0.1
Sweet sorghum bagasse	39~48	39~43	5~8	1~2	0.1~0.2
Sugarcane bagasse	44~50	37~45	5~6	0.2~0.5	0.01~0.1
Switchgrass	44~48	35~45	5~7	0.4~1	0.1~0.2
Newspaper	49~52	41~43	5~6	0.05~0.1	0.03~0.2

2.1.5 Calorific value of biomass fuel

The heating value of biomass is an important index to evaluate the utilization of biomass energy. It is the heat released by complete burning of a unit mass of biomass. The value is governed by the proportions of various components in the biomass, and the composition and proportion of chemical elements. Generally, the higher the carbon content is, the greater the heating value of the biomass. In the combustion process, water and hydrogen present in biomass can be converted to vapors, which can absorb a part of the heat. This portion of the absorbed heat is called the latent heat of vaporization. The heating value including latent heat of vaporization is called higher heating value. The higher heating values of monosaccharides, disaccharides, polysaccharides, crude carbohydrates, crude fibers, lignins, lipids and crude triglycerides are 15,600, 16,700, 17,500, 16,700–17,700, 18,800–19,800, 25,100, 39,800 and 36,500–40,000 kJ/kg, respectively [4]. The heating value excluding latent heat of vaporization is called the lower heating value, which is the *D*-value between higher heating value and latent heat of vaporization. In China, the lower heating value is often used as the criterion to calculate the heating value of biomass unless mentioned otherwise. The carbon contents and higher heating values of major components in biomass are shown in Tab. 2.3.

Since the process of heat absorption can occur during the conversion of water into vapors, the lower heating values of different kinds of biomass are different due to their varying water contents. Higher water content means that the biomass would have lower heating value, and vice versa. The lower heating values of some biomass fuels containing different contents of water are shown in Tab. 2.4 [2]. Furthermore, lower heating values of some air-dried biomass fuels are shown in Tab. 2.5 [2].

Tab. 2.3: Carbon contents and higher heating values of major components in biomass [4].

Component	Carbon (wt%)	Higher heating value (kJ/kg)
Monosaccharides	40	15,600
Disaccharides	42	16,700
Polysaccharides	44	17,500
Crude proteins	53	24,000
Lignins	63	25,100
Lipids	76~77	39,800
Terpenes	88	45,200
Crude carbohydrates	41~44	16,700~17,700
Crude fibers (containing 15~30 % lignins)	47~50	18,800~19,800
Crude triglycerides	74~78	36,500~40,000

Tab. 2.4: Lower heating values of various biomass fuels containing different water content (kJ/kg).

Water content %	5	7	9	11	12	14	16	18	20	22
Corn straw	15,422	15,042	14,661	14,280	14,092	13,710	13,330	12,950	12,569	12,192
Sorghum straw	15,744	15,360	14,970	14,585	14,393	14,008	13,623	13,238	12,853	12,464
Cotton straw	15,945	15,552	15,167	14,774	14,577	14,192	13,803	13,414	13,021	12,636
Bean straw	15,836	15,313	14,949	14,568	14,372	13,991	13,606	13,221	12,837	12,452
Wheat straw	15,439	15,058	14,682	14,301	14,155	13,732	13,355	12,975	12,598	12,222
Rice straw	14,184	13,832	13,481	13,129	12,954	12,602	12,251	11,899	11,348	11,194
Millet straw	14,795	14,426	14,062	13,694	13,514	13,146	12,782	12,460	12,054	11,690
Cattle manure	15,380	14,958	14,585	14,209	14,016	13,640	13,263	12,391	12,431	12,134
Willow stem	16,322	16,929	15,519	15,129	14,933	14,535	14,134	13,740	13,343	12,945
Poplar branch	13,996	13,606	13,259	12,912	12,736	12,389	12,042	11,694	11,347	10,996
Masson’s pine	18,372	17,933	17,489	17,050	16,828	16,385	15,937	15,493	15,054	14,611
Birch	16,970	16,422	16,125	15,715	15,506	15,096	14,686	14,276	13,870	13,460
Basswood	16,652	16,251	15,841	15,439	15,238	14,837	14,426	14,021	13,623	13,213

Tab. 2.5: Lower heating values of some air-dried biomass fuels (10 % water content) (kJ/kg).

Biomass	Lower heating value	Biomass	Lower heating value	Biomass	Lower heating value
Human manure	18,841	Firewood	16,747	Sugarcane leaves	13,816
Pig manure	12,560	Hemp stalk	15,491	Tree leaves	14,654
Cattle manure	13,861	Tubers straws	14,235	Sugarcane bagasse	15,491
Sheep manure	15,491	Cereal straw	14,235	Grass	13,816
Rabbit manure	15,491	Oil crops stalks	15,491	Aquatic plants	12,560
Chicken manure	18,841			Green manure	12,560

2.2 Existing biomass resources in China

2.2.1 Crop straws

Crop straws refer to inedible by-products (such as stalks and leaves), which are left after the harvest of rice, wheat, corn and other crops in the process of agricultural production [5].

2.2.1.1 Properties

Cellulose raw materials, such as crop straw, agricultural processing residue and forestry residues contain around 40 % cellulose, 30 % hemicellulose and 30 % lignin [6]. There are two ways to produce biofuel and bio-based chemicals (including fuel ethanol) from lignocellulose biomass feedstock. These are the biochemical and thermochemical pathways.

Biochemical conversion firstly converts cellulose and hemicellulose fractions of the lignocellulose into fermentable sugars. Then, they are turned into ethanol or other products using microbes. Cellulose is a straight-chain polysaccharide in which 100–1,000 β-D-glucopyranoses are connected by β-1,4-glycoside bonds. Thus, glucose originates from cellulose hydrolysis, and then is converted to ethanol through yeast fermentation. Hemicellulose consists of some inhomogeneous polysaccharides composed of pentose (xylose and arabinose), hexoses (mannose, glucose and galactose) and sugar acid. The structure of this heterogeneous polysaccharide is different from cellulose, where the mixture of sugars results from hydrolysis. According to different published reports, the mixture may include xylose, arabinose, glucose, mannose, and trehalose and rhamnose sugars. Lignin is a polymer originating from aromatic compounds that cannot be hydrolyzed into sugars, however its calorific value is equivalent to lignite and therefore it can be used as a fuel.

Thermochemical conversion gasifies biomass into synthesis gas, which is then chemically converted to ethanol or other chemicals. The fuel composition can be expressed according to the weight percentage of each constituent element, called the elemental analysis of the fuel.

2.2.1.2 Resources and their regional distribution

According to the 2009 crop straw resources survey and the evaluation report, it is estimated that the theoretical value for stalks as a resource was 820 million tons (air-dried, water content 15 %) in 2009.

Of these 820 million tons, 205 million tons came from rice and accounted for 25 % of the total, while 150 million tons originated from wheat straw and accounted for 18.3 % of the total. Additionally, 265 million tons came from corn stover and accounted for 32.3 %, while 25.84 million tons originated from cotton stalks and accounted for 3.2 % of the total. Furthermore, 37.37 million tons came from oil crops straw (mainly rape and peanut) and accounted for 4.6 %, while 27.26 million tons originated from bean stems and accounted for 3.3 % of the total. Approximately 22.43 million came from potato vine, which accounted for 2.7 % of the total amount.

From the perspective of regional distribution, Northern China and Lower Yangtze Valley have the biggest resources of stalk, with theoretical amounts of 233 million tons (28.45 %) and 193 million tons (23.58 %), respectively. These regions are followed by Northeast areas, Southwest areas and Inner Mongolia and Xinjiang, which contain 141 million tons (17.2 %), 8,994 tons (10.97 %) and 5,873 tons (7.16 %), respectively. The Southern China and Loess Plateau regions have considerably lower quantities, with 54.9 million tons (6.7 %) and 44.04 million tons (5.37 %), respectively. The Qinghai-Tibet area ranks last, with only 4.68 million tons of crop straw.

2.2.1.3 Main uses, amounts and proportions

Crop stalk is an important production resource for industry and agriculture. It can be used as a feedstock for fuel, fertilizer, animal feed, building material, papermaking, weaving and edible fungi culturing [7]. Therefore, when evaluating available straw resources for energy use, competing uses of the local straw resources should be deducted. Hence, the actual available source utilization of resources turns out to be less than the collected resources.

The survey results showed that the straw used as fertilizer is about 102 million tons (not including around 133 million tons of stubble remaining in the fields), accounts for 14.78 % of the collectable resource. Around 211 million tons of straw is used for animal feed, which accounts for 30.69 %, while 129 million tons is used as fuel, accounting for 18.72 %. Furthermore, around 15 million tons straw is used for culturing edible fungi, which accounts for 2.14 %, while approximately 16 million tons is used for manufacturing paper, which accounts for 2.37 % of the total. The survey results showed that around 215 million tons straw is used for incineration and disposal, and this accounts for around 31.31 % of the total (Fig. 2.1).

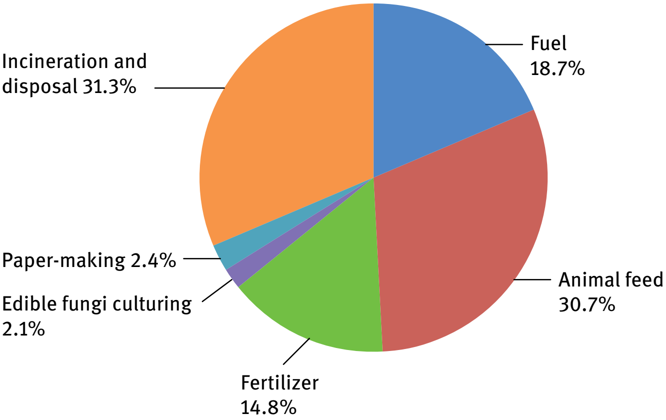

Fig. 2.1: Various uses of crop straw and their proportions [8].

2.2.2 Livestock and poultry manure

The animal husbandry industry is a pillar industry of the agricultural and rural economy in China, and has important practical significance in ensuring national food security, increasing the income of farmers and herdsmen, protecting and improving the ecological environment, promoting the modernization of agriculture, and promoting the steady development of the national economy.

The Central Committee of the Communist Party of China and the State Council of People's Republic of China had attached great importance to the development of animal husbandry. In this regard, the "eleven five" period promulgated a series of supportive policies, which not only increased the investment in infrastructure but also provided a powerful guarantee for the sustained and healthy development of animal husbandry. In 2012, national pork production was estimated to be 53,427,000 tons, while beef production was 6,623,000 tons. Furthermore, mutton production was estimated to be 4,010,000 tons (2012), while pork production was 475,922,000 tons (2012). Additionally, the egg and milk outputs were 28,612,000 tons and 37,436,000 tons, respectively. However, the aquaculture production process emits large quantities of waste, due to lack of centralized, efficient processing. As a result, serious pollution is caused in soil, air and water ecosystems.

Livestock manure is a general term used for the excrement of livestock and poultry, including poultry feces, urine and straw mixture.

According to livestock and poultry rearing, feeding and breeding periods, daily emission coefficients of manure were calculated according to the following equation:

$$\begin{aligned}&\text{Animal manure amount}\\&= \text{rearing volume} \times \text{daily emission coefficient} \times \text{feeding period.}\end{aligned}$$

According to the breeding cycle of dairy cows, cattle and laying hens of more than 1 year, and the amount left at the end of the year, 365 days were chosen as the feeding period. China's pig fattening period is around 105–110 days, while the weight is up to 90–110kg. With these characteristics, pigs are ready to be slaughtered. Additionally, the broiler feeding period is around 49 days. Feeding capacity determines when both pigs and broilers are ready to be slaughtered. Livestock manure excretions are based upon the variety, weight, physiological state, feed composition and feeding mode. However, there is no corresponding national standard in China for categorizing livestock manure. In the current work, data from various published articles was compared and the fresh feces excretion coefficients for various livestock were determined. The values determined are shown in Tab. 2.6.

Tab. 2.6: Daily emission coefficients for various livestock and poultry.

Category	Dung (kg/ head)	Urine (kg/ head)	Manure total (kg/ head)
Pig	1.38	2.12	3.5
Dairy cow	30	15	45
Beef cattle	15	8	23
Broiler			0.10
Laying hen			0.12

The goal of the biogas project is to convert waste to energy by anaerobic fermentation. The ultimate realization of biogas, biogas slurry, biogas residue and comprehensive utilization of ecological environmental protection engineering is an effective utilization way.

Many factors influence the efficiency of biogas production from poultry and animal feces, including anaerobic environment, organic matter, C/N ratio, suitable temperature, pH value, and stirring ratio. Different manures show different gas production rates. According to previous research, the gas production rates were found to be as follows: pig manure: 55–65m^3/t; cow manure: 40–50m^3/t; sheep manure: 62 m^3/t; chicken manure: 70–90 m^3/t.

The emissions of livestock and poultry manures were estimated to be 25 tons in China in 2012. These can be transformed into biogas resources amounting to 128,600,000,000 m^3 (Tab. 2.7).

According to the statistics, in 2009 the national large-scale farms had around 6,846,000 units of livestock. Out of these, 2,538,000 were pigs, 586,000 cows, 561,000 beef cattle, 733,000 laying hens and 522,000 were broilers [1]. By the end of 2009, China had built large-scale biogas farms, which number almost 56,500 [9]. Furthermore, plans for future, sustainable development and use of land are also looking great.

Tab. 2.7: Amount of feces discharged by livestock and poultry in China in 2009.

Species	Number (million head, only)	The total amount of livestock and poultry manure (10 000 t)	Biogas production potential (billion m^3)
Pig	46,766.93	59,744.8	35.8
Cow	10,360.46	170,170.6	76.6
Poultry	555,400	20,272.1	16.2
Total (million tons, m^3)		25.0	128.6

2.2.3 Forestry residue

Forestry residue can be divided into three categories. These are logging residues (including branch, tree top, bark, leaves, root, rattan, and bush), bucking residue (truncation waste), and processing residue (slab, plate, cutting end, sawdust, veneer, heart wood, wood bricks, and woody leftover).

Approximately 40 % of total logging volume is logging and bucking residue. Based on the data from the 12th Five-Year Plan, the forestry cutting quota was around 2.71×10^9 m^3/year (not including cutting quota of bamboo; approved by Chinese government), while the production of logging and bucking residue was approximately 1.08×10^9 m^3/year. Meanwhile, 10 % of woody log will be converted into processing residue, resulting into the production of 18 Mm^3/a processing residue.

The main forests in China are the northeast forest, southwest of the Himalayan forest, northwest and south slope forests. These four large forests account for around 54.5 % of the total national forest area, which consists of approximately 1,585,000 km^2. These regions are also the main producing areas for logging and bucking residues. Forest end processing industry is a major source of processing residues, resulting in dispersed and low unit production of processing residues.

Bioenergy (biomass power generation, biomass densification, biomass liquid fuels and biomass gasification) and palettes are the major consumer industries of the three forestry residues. In 2013, Hunan Provincial Academy of Forestry conducted a survey on the development of the forestry biomass energy industry in Central South of China, and found that the steady supply of the three forestry residues is the most important issue affecting the positive development of above-mentioned industries. Although the theoretical supply of the three forestry residues is large enough, most of them are produced in the inaccessible mountains. Therefore, a majority of the three forestry residues has not been utilized, as cheap transportation and storage methods are scarce due to difficult terrain. Additionally, most companies tend to choose smaller size wood and broken branches due to different geometrical sizes and high crushing costs for the three forestry residues, which results in severe competition and a high price for the raw material. Finally, due to less comprehensive consideration of the sources and issues of the raw materials, biomass companies are always too concentrated in certain areas, leading to supply-side shortages and higher prices for the three local forestry residues. Therefore, the rational long-term development plan for the forestry biomass energy industry, increasing government support, establishing a sound system for the biomass energy industry policy regime, strengthening the biomass research platform, and improving the biomass technology management system are effective ways to solve the issue of industrial utilization of the three forestry residues.

2.2.4 Starch resources

With growing awareness of global climate change, increasing environmental pollution and rising oil prices, all of the countries in the world are giving great importance to developing renewable energy. They are putting forward clear development goals, and actively developing strategies of energy development, and introducing new regulations and policies to help in developing renewable energy. China is a one of the largest oil consumers in the world. In 2012, the consumption of crude oil was 490,000,000 T, while China's crude oil imports were 271,000,000 T. The degree of dependence on foreign oil is up to 55 %. With the growth of the national economy, the oil supply and demand gap in China's will expand and the degree of dependence on oil imports will reach 70 %. Consequently, the issue of energy shortages is becoming more and more serious.

Bioliquid fuel refers to the fuel obtained from biomass used as a raw material for producing liquid fuels, including fuel ethanol, biodiesel, and ethers. Internal combustion engines, fuel systems, and different pieces of equipment either do not need to adjust or require slight adjustments to use biofuel. Therefore, it can be used to replace traditional fossil energy. Compared with conventional fossil fuels, the use of biofuels can reduce greenhouse gas emissions, and promote regional economic development, improve the energy self-sufficiency rate, reduce the economic burden of importing energy, and improve energy supply in the face of emergencies. These are the factors that can ensure national energy security.

At present, many governments are working to actively promote the development of biofuels. The European Union (EU) has put forward the "2020" action plan, which states that the EU will reduce its greenhouse gas emissions by 20 % relative to 1990 levels, and will increase the share of renewable energy in total energy consumption to 20 %, of which at least 10 % will come from biomass-based fuels. Since the beginning of 2000, the USA has passed the "Biomass Research Method", "Agricultural Law", "Energy Policy Act", "Energy Independence and Security Act", "Energy Act" and other laws and regulations, which are closely related to biomass-based energy resources.

At the end of the last century, due to the use of a relative surplus of food, China began to develop bioliquid fuels. According to the "Fifteen" period, the states of Henan, Anhui, Jilin, and Heilongjiang built plants for using aged grain (corn and wheat) as raw materials to produce ethanol. The annual production capacity of ethanol was 1,340,000 T, while nine Chinese provinces were to sell vehicle ethanol gasoline. Due to the limited land resources, shortage of cultivated land resources, grain supply and demand in a tight balance, the country put forward the use of saline alkali land, barren hills and wasteland, and other unused land to develop nonfood energy crops as raw materials for production of biofuels. In January 2008, the state of Guangxi built a cassava ethanol fuel project (200,000 t/a), whereas on the 15th of April, 2008, the whole state of Guangxi was using ethanol-based gasoline for motor vehicles.

Since 2008, fossil fuel prices have increased significantly. Some people think that the use of large amounts of food to produce biofuels leads to a global food crisis. Therefore, the first generation of biofuels produced from grains was quite controversial. Due to the factors of land, water resources, potential yield limits on the use of cassava, other crops such as sweet potato, sweet sorghum, and other nongrain crops are cultivated to produce ethanol fuel. At present, all the countries in the world are focusing on developing second generation biofuels.

Fuel ethanol refers to corn, wheat, and grain crops such as potato, sugarcane, beet, and sweet sorghum which are used as raw materials. After fermentation and denaturation, distilled ethanol dehydration is undertaken. Further processing can also be carried out according to the end-use of ethanol. Fuel ethanol is generally produced by the fermentation method, and uses microorganism to convert starch or sugar into ethanol. Furthermore, after the fermentation, monosaccharides can also undergo cellulose degradation to produce ethanol [2]. According to its different components, fuel ethanol feedstock can be categorized into sugars, starch, and cellulose.

Sweet potato starch (including cassava and potatoes (see Tab. 2.8 for chemical compositions)), and sorghum, corn, rice, millet, barley, wheat and oat grains (see Tab. 2.9 for chemical compositions) can be used as feedstock for ethanol production. Sweet potato cultivation is extremely extensive in China. Its adaptability and drought resistance are strong, whereas properties such as arid resistance, alkali resistance, low requirement for the soil make it a high yield crop. The main component of sweet potato is starch, which accounts for 66–70 % of the dry weight. The production of ethanol from sweet potato has the advantages of convenient processing and higher production rates, making it a kind of starch raw material which is widely used. The southern region of China is rich in cassava, while the northern regions are rich in potato. These are high-quality raw materials for the production of ethanol.

Under normal circumstances, cereals are the main food for humans. However, with the development of grain production in China, the use of corn to produce ethanol will gradually increase. The fruiting body of the corn is composed of two parts, namely the corn germ and endosperm. The corn germ accounts for the entire subentity (12–15 %). Additionally, the corn fat is also concentrated in the germ. Corn starch consists of amylose and amylopectin with compositions of around 10–15 % and 85–90 %, respectively. These are concentrated in the endosperm in irregular granular structure.

Tab. 2.8: Chemical composition of potato used as raw material for ethanol production.

The raw material name	Water/%	Starch/%	Crude protein/%	Crude fat/%	Crude fiber/%	Ash/%
Sweet potato	70~75	20~27	0.6~1.3	0.1~0.5	0.2~0.7	0.5~0.9
Sweet potato stem	12~14	66~70	2.3~6.1	0.5~3.2	1.4~3.3	2.0~3.0
Cassava	67~70	22~28	1.1	0.4	1.3	0.6
Dry Cassava	12~15	68~73	2.6	0.8	3.6	2.2
Potato	69~83	12~25	1.9	0.2	1.0	1.2
Dry Potatoes	12~13	65~68	7.4	0.5	2.3	3.4

Tab. 2.9: Chemical composition of several grains used as raw materials for ethanol production.

The raw material name	Water/%	Starch/%	Crude protein/%	Crude fat/%	Crude fiber/%	Ash/%
Corn	12.0 ~ 14.0	62.0 ~ 70.0	8.0 ~ 12.0	3.5 ~ 5.7	1.5 ~ 3.0	1.5 ~ 1.7
Sorghum	10.3 ~ 13.4	59.0 ~ 68.0	8.5 ~ 13.0	3.0 ~ 5.2	1.4 ~ 3.0	1.6 ~ 2.3
Barley	10.5 ~ 13.5	58.5 ~ 68.0	10.0 ~ 14.0	1.7 ~ 3.7	4.0 ~ 6.0	2.4 ~ 3.2
Wheat	12.0 ~ 13.5	65.0 ~ 70.0	8.0 ~ 13.8	1.8 ~ 3.2	1.2 ~ 2.7	1.3 ~ 1.7
Rice	12.0 ~ 13.7	70.0 ~ 75.0	7.3 ~ 9.4	0.4 ~ 2.0	0.4 ~ 1.3	0.3 ~ 1.3
Millet	10.5 ~ 13.0	58.0 ~ 65.0	9.0 ~ 11.0	3.0 ~ 3.5	4.0 ~ 6.0	1.2 ~ 1.9

2.2.5 Carbohydrate resources

Raw sugarcane (including sugar and molasses), beet, and sweet sorghum are included in carbohydrate resources. Sugarcane and beet sugar are used as raw materials in various industries, such as the sugar industry. The main raw material for the production of ethanol in China is sugarcane and beet sugar. Molasses is a by-product of the sugar industry, and has a considerable amount of fermentable sugar. After an appropriate dilution process and addition of nutrient salt, it can be used for ethanol fermentation. The process is simple and cheap to produce ethanol.

2.2.5.1 Sugarcane

Sugarcane (*Saccharum* L.) is a perennial plant of Gramineae. Sugarcane and its varieties belong to three or four modern interspecific hybrids, having C4, biological genetic diversity in photosynthesis and growth. High photosynthetic efficiency and high yield potential make it special. Generally, 4–6 tons of sugarcane result in a mu (where 1 mu = 666.67m^3). The energy yield per mu of cane can reach more than 8 tons. Additionally, sugarcane contains sucrose (12.5–14 %) and fiber (11.5–12.5 %). Asexual reproduction and a low propagation coefficient are other characteristics of sugarcane. The propagation coefficient is around 3–10. Sugarcane is a thermophilic crop and requires annual average temperature to be around 18–30 °C, which is the optimum temperature for sugarcane production. If the temperature is increased by 10 °C above the active accumulated temperature of 6,500–8,000 °C, the growth rate increases with the increase of accumulated temperature. In addition, a large temperature difference between day and night are also important to the growth of sugarcane. The most suitable temperature for sugarcane growth is between 25–32 °C. If the temperature is below 20 °C, the growth is slower, though sucrose accumulation is favored. At around 13 °C, sugarcane will either stop growing or grow at an extremely slow rate.

In 2012, China's sugarcane planting area was 1,795,000 hectares, while the total output was 12,114,000 tons. The high yield and high sugar content resulted in "popularization and application in large area ROC". This resulted in production of a series of varieties and independent innovation of sugarcane varieties. The average yield per mu increased from 4.4 tons to 4.57 tons.

2.2.5.2 Beet

Sugar beet (family: Chenopodiaceae) belongs to the genus beet, and is one of the most important sugar crops in China. These are biennial herbs whose first year is mainly for vegetative growth resulting in accumulation of nutrients in mast roots. During the second year, reproductive growth takes place, and the branches participating in the cross pollination of seeds are formed. Sugar beet root tubers are produced at 30–60 kg/m^3, while the sucrose content is around 14–21 %.

Beet is a thermophilic crop and has a strong resistance to cold. During the whole growth period at more than 10 °C, the temperature requirements are 2,800–3,200 °C. The suitable average temperature for the root growth period is above 19 °C. Beet has low temperature resistance, drought tolerance, salt tolerance and other characteristics. Beet seed germination takes place either at low temperature or at −1 °C. The seedlings can still survive such low temperatures. If the beet root is more developed, then the leaves are thicker (cuticles), while the drought resistance is also better. Beet's demand for sodium and chloride is higher than other crops, whereas due to its salt tolerance, it can be cultivated in saline lands.

The main production of beet is in North China, including the north, northeast and northwest of the district. The three regions belong to the spring beet area, having a short frost-free period, lower accumulated temperature, long sunshine, large temperature differences between day and night, high beet yield and high sugar content, and light disease. In 2012, China's beet sown area was 236,000 hectares, having a total output of 11,740,000 tons. The per unit area yield was 49,793 kg/ha. Production was mainly distributed in the provinces Heilongjiang, Xinjiang and Inner Mongolia.

2.2.5.3 Molasses

Molasses is a viscous by-product resulting from the conversion of sugarcane or sugar beets into sugar. To make molasses, sugarcane is harvested and stripped of leaves. Its juice is extracted usually by cutting, crushing or mashing. The juice is boiled to concentrate it, promoting sugar crystallization. The result of this first boiling is called “primary molasses” and has the highest sugar content. After refining the sugar crystals, the primary molasses turns into our everyday sugar.

Molasses is a thick, dark brown, semi-fluid substance. According to the degree of maturity of composition, it mainly contains a lot of fermentable sugars (mainly sucrose), hence making it a very good fermentation raw material, which can be used as a substrate or base material for yeast, monosodium glutamate, and organic acid fermentation products, as raw material for some food and animal feed crops, and as raw material for ethanol fermentation. Cane or beet sugar is extracted from it, and the composition depend on refining method. Sugarcane molasses is mainly distributed in the south of Guangxi, Fujian, Guangdong, and Sichuan provinces.

The yield is around 2.5–3 % of raw sugarcane. As a by-product of beet sugar, beet molasses production is mainly in the northeast, northwest, and North China regions of China, while the yield is about 3–4 % of the sugar beet.

2.2.6 Waste edible oils

Waste edible oils are produced either due to chemical degradation (oxidation, hydrogenation, etc.) and destruction of the original fatty acids and vitamins in edible oils, or due to the accumulation of contaminants (such as benzene, acrolein, hexyl aldehyde, and ketone). After degradation, these are no longer suitable for food processing. These originate mainly from waste vegetable oil, though a small quantity is obtained from animal fat. Waste edible oils mainly come from home cooking, catering services and food processing industries (such as frying processes).

Based on the source characteristics and collecting methods, waste edible oils can be divided into three categories. These are: (1) animal and vegetable oils originating from food production and consumption processes, which do not comply with food hygiene standards. Examples include vegetable acid oil and old frying oil; (2) the grease obtained from food remains from oil-water separation process, commonly known as “swill oil”; (3) when dishwashing waste goes into the sewer, animal and vegetable oils are separated by oil-water separator or grease trap, commonly known as “waste oil” or “junk oil”. Class 1 waste edible oils contain a single concentrated component, have less water and low impurities, and are easy to collect, separate and recycle. The production of waste edible oil is more decentralized, has complex composition, high water and impurities, and needs pretreatment before further recycling.

Class 1 waste edible oils are easily collected by fixed-point recycling, and are considered as the main recycling objects. Class 2 waste recycling edible oils are more difficult to recycle, though the number of recycling pathways and purposes cannot be estimated. Their illegal recycling was the main factor causing risk to human health and the environment. Since the waste edible oil is mixed with a lot of sewage, garbage, and detergents, and it also has a number of illegal processing pathways, it is therefore impossible to remove bacteria and harmful chemicals from it. Waste edible oils which have been repeatedly used to fry food contain large amounts of carcinogens, such as benzopyrene and aflatoxin. Waste edible oils enter the city sewage treatment plant or a natural water body via the sewer, and may clog the drains thus affecting the normal operation of sewage treatment plant and destruction of the ecology of natural water bodies.

Waste edible oils are rancid oils and are a kind of recycling resource. These can be used as raw materials to produce biodiesel.

According to the data of National Grain and Oil Information Centre, China's edible oil consumption reached 25.15 million tons in 2011, while the annual per capita consumption was around 20.5 kg. In comparison, the global per capita average is 20 kg. One kg edible oil produces 0.175 kg waste edible oil. Waste edible oil recovery rate is around 50 %. Furthermore, China recycled around 2.2 million tons of waste edible oil in 2010. The waste edible oil is used to produce biodiesel, for which the conversion efficiency is generally more than 85 %. If all waste edible oil would have been used to produce biodiesel, around 1.87 million tons of biodiesel could have been obtained in 2010. It is worth mentioning that the composition of fatty acids in waste vegetable oil is similar in different countries. Free fatty acids (14 %) and saturated fatty acids (26–50 %) in grease, swill oil and vegetable acid oil are very high. The free fatty acid content of waste edible oil is much higher than that of the standard edible oil. In addition, the fatty acid content was influenced by the grease storage time and storage temperature. Under the conditions of 20 °C, 45 °C and 60 °C, free fatty acid content of beef tallow increased with the increase in storage time, and the corresponding values were found to be around 0.002 %/d, 0.017 %/d and 0.083 %/d, respectively.

In addition, although the oil yield has generally increased in recent years, the animal fat yield basically remained unchanged. The growth in oil production is mainly from vegetable oils. At present, insufficient statistical data is available on animal fat oil. According to an expert investigation, the pork fat output is around 4 million tons, while that of cattle and sheep oil (tallow oil) is around 0.5 million tons in China. Pork fat is not permitted for international trade, and therefore tallow oil imports are about 0.5 million tons. Total waste oil imports are around 5 million tons, which account for about 20 % of the total amount of edible oil.

2.2.7 Urban domestic garbage

City solid waste (Municipal Solid Waste, MSW) is mainly composed of organic garbage from urban residences, commercial and service industry refuse, construction industry waste and other solid waste forms, and is also known as city garbage.

Solid waste is closely related to the population density and the standard of living of urban residents. With economic growth and improvements in living standards, city solid waste emissions will continue to increase. For example, private and commercial waste has an annual volume of 300 kg per person per year in EU, which is far more than the provisions of 100 kg per person per year, as set out in the Fifth EU Environmental Action Plan.

By the end of 2010, national city and town domestic garbage collection amounted to around 2.21 tons, whereas the proportion of the harmlessly treated garbage was 63.5 %. Additionally, the treatment rates for city and country were 77.9 % and 27.4 %, respectively. Rapid economic growth and high population density are key factors driving the increase of MSW in China.

2.2.8 Industrial organic wastewater

Industrial organic wastewater is discharged from the wastewater, wine, sugar alcohol, food, pharmaceutical, papermaking and slaughter industries during their production processes. Many types of industrial organic wastewater have a number of complex and diverse ingredients. According to the general content of organic matter in industrial organic wastewater, if the chemical oxygen demand (COD) in wastewater is greater than 5,000 mg/L, it is called high concentration organic wastewater. Examples include alcohol wastewater, brewery wastewater, monosodium glutamate wastewater, sugar wastewater, and bean products wastewater. In these industries, generally sweet potato, sugar and corn are used as the raw materials. If the organic wastewater has a COD of less than 5,000 mg/L, then it is called low concentration organic wastewater. Examples include meat processing wastewater, tanning wastewater, printing and dyeing wastewater, and papermaking wastewater. Industrial organic wastewater is rich in organic matter. Therefore, its anaerobic fermentation can be carried out to produce biogas for energy purposes.

According to the national environmental statistics bulletin (2012), national wastewater emissions were around 684.8 tons in 2012. Of these, industrial wastewater emissions were 221.6 tons, which accounted for approximately 32.3 % of the total wastewater discharged. Additionally, the COD emissions were 3,385,000 tons in 2012.

The amount of organic wastewater discharged by light industrial enterprises

According to the data obtained from a survey of the main light industries (including sugar, alcohol, liquor, beer, yellow wine starch, monosodium glutamate, beverage and paper), around 26.29 tons of organic wastes were discharged in 2012 in China, which can be transformed into 23,318,000,000 cubic meters of methane. Additionally, around 0.61 tons of waste can be transformed into 950,000,000 cubic meters of methane (Tab. 2.10).

The amount of organic wastewater discharged by non-light industrial enterprises

The main non-light industrial enterprise include pharmaceutical, slaughter, petrochemical, natural rubber and furfural industries. According to the statistics, around 32.54 tons of organic wastes were discharged in 2012, which can be transformed into 14,412,000,000 cubic meters of methane. Additionally, approximately 15.1 tons of wastes were also discharged, which can be transformed into 2,141,000,000 cubic meters of methane (Tab. 2.11).

2.3 Energy plants

Energy plants collectively refer to plants that are mainly used to provide energy or raw materials for the purpose of energy production. There are many kinds of energy plants. Such plants are found in almost all of the regions of China. Large-scale exploitation and utilization of biomass energy must have guaranteed sufficient raw material resources, and should rely on existing biomass resources. Since one type of renewable energy resource alone cannot meet the complete future energy needs, the development of energy plants is one of the ways to increase their share in the total energy mix. The development and utilization of energy plants can not only partly replace fossil fuels, but can also help to reduce the greenhouse effect, promote ecologically benign cycles, and become one of the important ways to solve the problem of energy and environment.

2.3.1 Concept of energy plants

Many energy plants are naturally grown and scattered resources. These plants are difficult to collect, and are not conducive to development and utilization. In order to solve this problem, people began to consciously cultivate some energy plants, using grafting, domestication and breeding, and constantly improved production to meet the growing demand for energy. Energy plants that are the result of artificial selection and domestication have higher yield and a stable nature, and are suitable for artificial planting on a large scale to provide raw materials and energy for industrial and

Tab. 2.10: Light industrial organic wastewater (slag) and its potential to produce energy.

No.	Industry	Unit	The main product's output	Organic wastewater		Organic waste	
				Wastewater production (million tons)	Biogas production (million cubic meters)	Waste production (million tons)	Biogas production (million cubic meters)
1	Alcohol	Kiloliter	9,115,498	9,966	291,696		
2	Refined sugar	Million tons	1,409	9,866	29,513	1,409	1,409
3	Beer	Million Liter	4,779	95,572	24,849		
4	Yellow wine	Million Liter	3,100	46,502	232,508		
5	Spirits	Million Liter	1,153			3,460	69,193
6	Starch	Million tons	2,253	45,060	901,200		
7	Starch sugar	Million tons	1,070			318	6,356
8	Monosodium glutamate	Million tons	300	7,500	187,500	900	18,000
9	Citric acid	Million tons	100	1,370	27,391		
10	Yeast	Million tons	20	2,485	29,824		
11	Enzyme preparation	Million tons	80	200	1,200		
11	Wood pulp	Million tons	810	12,150	243,000		
12	Non-wood pulp	Million tons	1,074	16,110	322,200		
13	Wine	Million Liter	138	719	17,966		
14	Sorbitol	Million tons	80	2,320	11,598		
15	Fruit and vegetable juice drinks	Million tons	1,180	1	0.6		
16	Liquid milk	Million tons	2,146.57	13,120	11,327		
	Total (million tons, million cubic meters)			26.29	233.18	0.61	9.50

Tab. 2.11: Non-light industrial organic wastewaters (slag) and their potential to produce energy.

	Industry	Output of products (10,000 tons/year)	Organic wastewater		Organic waste	
			Waste water (kt/a)	Amounts of methane (10,000 m^3/year)	Residue volume (million tons/year)	Amounts of methane (10,000 m^3/year)
1	Western medicine	289.87	120,085.30	1,002,588.33		
2	Chinese patent medicine	238.54				
	Honeyed pill, syrup	19.1475	7,566.25	453.80		
	Water pills, tablets etc.	40.95			683.25	170,812.50
3	Fiber board (million cubic meters)	5,554	37,322.81	244,091.73	149,956.49	11,696.53
4	Slaughter	8,221	134,824.44	122,690.20		
5	Flour	12,230	1,237.06	1,773.32		
6	Vegetable oil	5,176.2	517.62	3,882.03		
7	Soy sauce	700.36			181.01	19,186.80
8	Vinegar	300			138.00	12,420.00
9	Canned meat	12	12,600.00	5,670.00		
10	Canned fruit	240				
11	Petrifaction	350	5,250.00	5,2500.00		
	PTA	2,974	4,365.06			
12	Furfural	50	1,500.00	5,250.00		
13	Natural rubber	80	90.47	904.68		
14	Sisal + Agave americana	4.5	45.00	1,350.00		
	Total (million tons, million cubic meters)		32.54	144.12	15.10	21.41

domestic use. Due these reasons, these plants are also known as energy crops. The chemical energy of energy crops come from solar energy, which is inexhaustible. The sulfur content of energy crops is low, which means that they do not produce large amount of SO_2 when they are combusted, which can obviously reduce the possibility of acid rain. Additionally, energy plants can absorb CO_2, and hence help to realize zero emission of CO_2. There are several categories of energy crops, distinguished according to the plants' main biomass chemical: sugary or starchy energy crops, oil crops, hydrocarbon energy crops, fibrous energy crops, and firewood forests.

(1) Carbohydrate energy plants (including sugarcane, sweet sorghum, and beetroot) mainly produce sugar as the raw material that can be directly fermented into ethanol.
(2) Starch energy plants (including cassava, corn, and sweet potato) mainly produce starch as the raw material that can be fermented into ethanol after hydrolysis.
(3) Cellulose energy plants (such as silver grass) can be fermented into ethanol after hydrolysis. Cellulose energy plants can also be utilized to produce gas, liquid, and briquette fuels.
(4) Oil energy plants (including rape, sunflower, oil palm, and peanuts) can be converted into biodiesel. In the past decade, Chinese researchers have paid much attention to castor, Jatropha curcas L., Swida wilsoniana, Pistacia chinensis, and Xanthoceras sorbifolia [10] in this regard.
(5) The alkane liquid fraction can be obtained from alkane energy plants (including Euphorbia lathyris, Euphorbia tirucalli, Cuban Hong trees, Parthenium argentatum Gray, Metroxylon sagu, and Simmondsia chinensis), which have similar properties to those of fossil oil.
(6) Firewood forests are kinds of shrubs and trees that can be used as firewood or fuel, including willow firewood forest, oak firewood forest, pine firewood forest, and bush firewood forest.

The quantity of energy in an energy plant is related to its category, species, cultivation situation, growing method, harvesting method, and its resistance to pests. Therefore, the general conditions for artificial cultivation of energy plants are a large quantity of seeds, high production, easy breeding, high photosynthetic efficiency, short growth period, easy regional soil management, and good anti-adversity.

2.3.2 Technology improvement for energy plants

The Earth is rich in energy plants, however most of these grow in wild conditions and have lower yield per unit area. Currently, the problem is to harness energy plants that have a high solar energy conversion rate, high photosynthetic rate, and are fast growing. Within legal, ethical, and species protection regulations, technologies including genetic improvement, hybrid breeding, mutation breeding, cell engineering, and genetic engineering are being used to improve photosynthesis, respiration, stress resistance, and other aspects of physiological metabolism and energy plant yield per unit area.

2.3.2.1 Crossbreeding

Crossbreeding can produce homozygous varieties by hybridization between different populations or different genotypes. Hybridization can provide abundant variety according to the parents' gene recombination that can combine excellent genes to control parents' different characteristics or accumulate the control of the same traits in different minor genes. Crossbreeding is the primary means of creating and nurturing variation of new varieties, and so far, is considered the most effective breeding method. Crossbreeding can be divided into sexual hybridization breeding and asexual hybridization breeding. Based on the distance of genetic relationship, sexual hybridization breeding can be divided into interspecies hybridization and distant hybridization. Crossbreeding generally refers to crossbreeding between species. According to the requirements, a crossbreeding process can be simple hybrid breeding, hybridization backcross, and duplex mode breeding. Crossbreeding process generally consists of the following components: identification of the crossbreeding goals, determination of the matching parental and hybrid methods to carry out artificial hybridization, getting the hybrid offspring, cultivation of the hybrid offspring. Currently, crossbreeding is widely used in breeding *Jatropha curcas, Swida wilsoniana*, and Chinese silver grass and *Pistacia chinensis*.

2.3.2.2 Mutation breeding

Mutation breeding can contribute to generating genetic variation by the introduction of external factors, such as radiation, laser, ion beam, and chemical mutagens. Mutation breeding can yield a new phenotype, a new mutation, and a gene, which are very difficult to generate either naturally or by conventional methods. Compared with natural selection, mutation breeding is of high mutagenesis frequency, has wide variation extent, and has short breeding periods. Based on the mutation method, mutation breeding can be divided into physical mutagenesis and chemical mutagenesis.

2.3.2.3 Physical mutagenesis

Physical mutagenesis is a method of inducing mutations using external factors, such as X-rays, alpha rays, beta rays, gamma rays, ultraviolet rays, fast neutrons, microwave, ultrasonic, electromagnetic, laser processing (ammonium glass laser, carbon dioxide laser, ruby laser, molecular nitrogen laser and He-Ne laser), heavy ion implantation, and high hydrostatic pressure. At present, physical mutagenesis is commonly conducted using radiation, laser, heavy ion implantation, and high hydrostatic pressure.

2.3.2.3.1 Radiation mutation breeding

Ray mutagenesis refers to the use of high energy electromagnetic waves, such as X-ray electromagnetic wave, α-rays, β-rays, and γ-rays. The use of these waves makes some aquatic organisms more vulnerable to the impact of radiation. Such an impact can break through chemical bonds and cause a change in the structure of DNA to acquire new phenotypes, new mutations, and new genes to nurture new germ plasm or new varieties. X-ray was the first ray mutagenesis, and has an ionizing radiation wavelength of 100–1,000 Å. β-rays are a beam of electrons or positrons, and can be generated directly from radioisotopes of ^{32}P and ^{35}S. γ-rays are of a shorter wavelength, ionizing radiations having a wavelength of 0.1 Å. Currently, the most widely used γ-ray sources for a wide variety of energy plants are ^{60}Co and ^{137}Cs.

2.3.2.3.2 Laser mutation breeding

Laser effects on biological species can last for more than 40 years. With the development of science and technology, and deep understanding of the mechanism of laser mutation, it has been widely used in energy plants to improve the varieties and yields. The mechanism of energy accumulation in vivo may be interpreted as a resonance phenomenon, where the frequency of the laser is the same as the frequency of the molecular vibration. It is very easy to break the chemical bonds in molecules to generate new molecules due to the accumulation of large energy. It is understood from the perspective of molecular biology that the energy gathers within the DNA of a cell via absorption, whereas energy redistribution takes place during mutations, and subsequently, the cell will undergo some changes, such as polymerization, bond breaking, and crosslinking leading to mutation. In addition to energy laser mutagenesis, heat, pressure, and electromagnetic fields are also used, so that the biological effects of laser mutagenesis can directly be produced using the combined effects of light, electricity, heat, pressure and magnetic effects. Currently, ammonium glass laser, nitrogen molecule laser, ruby laser, carbon dioxide laser and helium-neon lasers are the ones commonly used in the field of breeding.

Compared with the traditional means of UV mutagenesis, mutagenesis laser has some advantages including high efficiency, stability, high selectivity, low back mutation, targeted mutation rate, radiation damage light, contemporary variation, and less pollution. The process also improves photosynthetic efficiency of plants, and frequency of the root tip mitosis occurrences.

2.3.2.3.3 Ion implantation mutation breeding

Ion implantation mutation breeding is a new technology, which was developed from radiation mutagenesis. The interaction of the ion beam is not only biological, physical and chemical, but also momentum, energy, and mass deposition also contribute to the overall biological effect. The energy deposition can cause ion sputtering on the surface of organisms. However, a part of the incident ionic energy is transferred to the rear surface of the organisms to produce particles which will sputter. With continuous injection, the biological surface layer is peeled off and hence the particles can travel long distances such that the ions fall within a predetermined position. The quality of the precipitation effect depends upon the injected ionic energy, which can ionize or oxidize the biological molecules. The process causes ionization damage, while with the increase in depth, the ionic energy is gradually reduced. With the reduction in further energy loss in the incident ions, the peak reaches the end position. When the reactive ion is in the process of injection, it will continue to interact with the biological molecules, such as bonding, replacement or filling vacancies to form new molecules. The charge exchange effect takes place when negative ions are injected and make organisms more electronegative. The injection of cations lowers the electronegativity and even causes a change in polarity. The electrical change will change the physical fields of the cells when crossing the membrane. This affects the cells inside and outside in terms of energy conversion, material transport, information transmission, metabolic regulation and other biological processes. Thus, ion implantation may constitute chromosomal breakage, rearrangements, deletions, and other changes caused by the molecular structure of the base, which then induce mutations but also cause strong biological effects. Hence, the process contributes to producing a variety of biological variations. Since the 1980s, China's science and technology industries have applied ion implantation to biological mutation breeding and have made a series of remarkable achievements. The main advantages of ion implantation mutation breeding are summed up in the following points:

(1) high mutation rate, which on average is more than 1,000 times the natural variation rate;
(2) spectral width variation, variation of the type, which can generate a new type that has never been seen in nature;
(3) variation is stable and fast and therefore can greatly shorten the breeding period;
(4) stable, reliable and easy.

2.3.2.3.4 Space breeding

Space breeding is based on radiation mutagenesis and combines high-tech aerospace research with agricultural genetics and breeding. Space breeding is a new technology combining space, breeding, genetics, radiation, and other interdisciplinary sciences. Space breeding takes a crop seed planted on Earth into space using a recoverable satellite or spacecraft. By means of ultra-high vacuum, microgravity, and cosmic rays the seeds mutate after several generations of breeding. The soil is kept with stable genetic traits to nurture new agricultural varieties. At present, only the United States, Russia, and China have successfully conducted space breeding research in satellites or spacecraft. Since 1987, China has used retrievable satellites. Shenzhou spacecraft carried 70 kinds of seed plants. China has adopted space breeding as a national project. Space breeding research in China has reached advanced level. Cosmic rays cause mutations, whereas the seed itself undergoes gene mutation that is safe and reliable.

2.3.2.3.5 Physical high breeding

In recent years, the Institute of Geochemistry and the Chinese Academy of Sciences have collaborated using high pressure water (750 atm) to treat some plants requiring breeding improvement. The collaboration has achieved initial results, and created a few high-quality varieties. As for the specific mechanisms of mutagenesis, high pressure is now considered to affect germinating seeds when the cell is just in the stage of DNA replication and RNA transcription. The increase in environmental pressure will change normal DNA replication, which will either lead directly to a base pairing error or will affect the repair enzyme systems, causing changes in the molecule's DNA sequence. Additionally, the spatial structure of DNA change may also lead to different RNA transcription changes. After high-pressure treatment, the seeds will have some physiological and biochemical changes. These factors can cause the molecule's DNA sequence to change.

2.3.2.4 Chemical mutagenesis

Chemical mutagenesis can contribute to generating genetic variations by the introduction of external factors such as EMS, NaN_3, and colchicine. Chemical mutagenesis can produce new phenotypes, new mutations, and genes that are difficult to evolve naturally or by conventional methods. As early as 1948, Gustafson used mustard gas to obtain mutant barley. In 1967, Nilan used diethyl sulfate to obtain dwarf and high-yielding varieties of Luther. Since then, the popularity and application of chemical mutagenesis is developing gradually. Compared with physical mutagenesis, the characteristics of chemical mutagenesis are more diverse and beneficial. These include: a high rate of induced mutations, less chromosomal aberrations and a wide range of mutagenesis. The process causes slight damage to material, while some chemical mutagens are limited to certain parts of the DNA to mutate. Most effective chemical mutagens show a larger damage than physical mutagen, and therefore result in easy viability and fertility decline.

Azide is recognized as the most effective and most widely applied alkylating agent. The main mutation mechanism is as follows:

Alkylating agents are compounds with an alkylating function with one or more active alkyl groups. The alkyl is transferred to a molecule having high electron density, and exchanges oxygen atoms in the bases. After the bases have been alkylated, copied DNA will cause a matching error, producing the mutant. Sodium azide is an inhibitor of plants' and animals' respiration, and causes DNA replication to occur. The process results in a high mutation rate. Furthermore, EMS (ethyl methyl yellow acid) has also been widely used for the purpose.

Sodium azide (NaN_3) is a potent point mutagen. Its mechanism is neutral in a solution of pH 3.0. Both NH and NH_3 molecules can freely pass through the cell membrane into the cell, and in the form of base substitution, affects normal DNA synthesis, resulting in mutagenesis. Seed treatment should be applied when DNA synthesis begins. NaN_3 is simple to use, efficient, low cost and has no residual strength and the mutations it produces are mainly at the level of gene mutation.

2.3.2.5 Plant cell engineering

Based on the theory of cell totipotency, and the technology of cell and tissue culture, plant cell engineering is applied in the genetic manipulation of plants at cellular and subcellular levels. The technical system consists of plant tissue, organ culture, cell culture, protoplast fusion, and culture techniques, while the genetic manipulation technology is applied on the subcellular level.

2.3.2.5.1 Protoplast culture and somatic hybridization

Protoplast culture and somatic hybridization are the core technologies of plant cell engineering, and can overcome the incompatibility of distant hybridization to create new germplasm resources. The technology provides an important technical support for plant genetic transformation and basic research in cytology. Root tip, leaf tissue, callus or cell suspension culture are treated by a liquid mixture of cellulase and pectinase under higher osmotic pressure conditions, the cell wall is digested, and spherical protoplasts without wall can be obtained in large numbers. This way, new plants can be generated by protoplast culture. Somatic cell hybridization studies can be conducted on protoplast fusion and gene engineering with the protoplast culture. Through specific vectors, such as plasmids, phage or virus, and liposome, foreign genetic material (DNA) is introduced into the protoplasts of receptors, and then through the culture of protoplasts and cells. The technology is applied to energy plants, including *Swida wilsoniana*, *Jatropha curcas*, and Chinese silver grass.

2.3.2.5.2 Doubled haploid technology

Doubled haploid technology can obtain haploids by tissue culture of anther, pollen, unfertilized ovary, and ovule. Afterwards, using natural or artificial doubling methods, diploid plants can be obtained. Nevertheless, anther and pollen culture is used most widely.

2.3.2.5.3 Somatic cell clone variation and selection

A new type of crop with useful agronomic traits is selected from the genetic variations that are cultured using a cell culture. Cell engineering techniques are used to study the genetic improvement in many ways.

2.3.2.6 Genetic engineering

Genetic engineering is a new technology of biological engineering. Based on purpose and design, it operates on the DNA molecule via in vitro processing, and then uses receptor biology to change the genetic traits and to culture new biological types. A complete genetic engineering technology program with production purposes consists of the following eight levels: (1) isolation, cloning, and structure/function study of exogeous targent gene; (2) construction of suitable vectot for gene transfer and expression or expression regulation and restruction of target gene; (3) Introduction of exogeous gene; (4) integration, expression and detection of exogenous gene in host genome and screening of genetically modified organisms; (5) physiological function verification of products from exogenous gene expression (6) breeding, establishment and benefit analysis of novel transgenic organisms (7) establishment of guarantee mechanism for ecology and evolution safety, (8) evaluation on consumption safety. At present, genetic engineering is being used to improve the characteristics of energy plants. A lot of research has been conducted to improve the total biomass of plants and to change the lignocellulose components. Additionally, a focus has also been laid on using plants to produce cellulase and change the oil plant's oil composition and content by using genetic engineering. Such efforts have resulted in a series of achievements. Currently, genetic engineering has been used to study and modify cloning of the functional genes related to the energy plant *Jatropha*'s oil content and quality, biological and other aspects of metabolism, and stress resistance. These plants mainly have stearic acid transporters to saturate the enzyme gene, which include: ethylene response element combination factor (ERF) that is an AP2/EREBP transcription factor, allene oxide cyclase, phospholipase D genes, cell membrane transport protein gene JcPlP water molecules, cloning to small seed of tung tree 3-inositol phosphate synthetase gene (JcMIPS), glycerin-3- phosphate acyltransferase, flowering control genes FT/TFL1, Jc-Tctp1, small seed of tung tree toxic protein 1, small seed of tung tree poison protein 2, ammonium aldehyde dehydrogenase, phenylalanine deaminase, acetyl CoA carboxylase hydroxyl transferase, acetyl CoA: diacylglycerol acyl transfer, glyceraldehyde 3-phosphoric acid dehydrogenase, small TongZiYou qualitative protein 1, small TongZiYou qualitative protein 2, superoxide dismutase [11], peroxidase, catalase, acetyl CoA carboxylase, acetyl CoA synthetase, malonyl CoA:ACP acyltransferase, such as sulfur esterase A acetyl CoA.

2.3.3 Agricultural crops

2.3.3.1 Sweet sorghum

Sweet sorghum (*Sorghum bicolor* L.) is an improved variety of grain sorghum Moench in Gramineae plant [12]. Sweet sorghum is efficient in photosynthesis, has high yield of biomass, strong resistance and good adaptability. The stem of sweet sorghum is rich in sugar and contains about 15–21 % of sap. Generally, the yield for stem is around 4 t/mu, while that for grain is around 150–400 kg/mu. Additionally, stalk fiber content is approximately 14–18 %, while the fiber yield is ca. 600–1,000 kg/mu.

Sweet sorghum is one of the Hatch–Slack crops, whose compensation point of CO_2 is nearly zero. Photosynthates are generated when CO_2 concentration reaches 1 ppm, and still increases when CO_2 level reaches 1,000 ppm.

Entitled the “camel” of crops, sweet sorghum is highly resistant to drought, saline, high temperature and sterility. The concentration of salts that sweet sorghum can tolerate is 0.5–0.9 %. The water logging resistance of sweet sorghum is such that, even after one week of immersing in flood water, it can recover to grow normally. It also has wide adaptability to soil conditions within the pH range of 5.028.5. Additionally, the regions suitable for the growth of sweet sorghum are extensive: it requires a temperature above 10 °C and accumulated temperature between 2,600 and 4,500 °C. Sweet sorghum can be grown from Heilongjiang in the far north of China to Hainan in the south of China.

Planted in every province of China, major production of sweet sorghum is scattered, though it is mostly in the north of China and still on small scale. Sugar shortage in the 1970s drew great attention to sweet sorghum, along with the introduction of new varieties from abroad, improvement in varieties, and research in overall utilization of sugar extraction, refining and brewing. After the sugar demand in China was met (mostly by imports, sugarcane and sugar beet), sweet sorghum’s primary uses have been for forage and energy.

2.3.3.2 Sugarcane energy

Utilization of sugarcane for energy production in the form of ethanol is the most economical and effective measure, and sugarcane has high efficiency and a high amount of biomass. Additionally, the energy cane varieties are the core technology of ethanol production. In the early 1970s, Brazil invested $ 39.6 billion on it “bioenergy plan”, and bred SP71-6163 and SP76-1143 energy sugarcane varieties. In 1979, the United States developed a “UPR” program, which involved the selection of high biomass as the goal of new energy sugarcane varieties US67-22-2. In the mid-1980s, India and the United States jointly implemented the IACRP plan, which used tropical species and wild sugarcane to produce hybrid-bred ethanol whose output reached 1.2 million L/HA of energy sugarcane varieties IA3132. A comparison of the production capacity and ethanol yield from sugarcane is given in Tab. 2.12.

Tab. 2.12: Production capacity and ethanol yield of sugarcane.

Project	Energy Sugarcane	Sugarcane
Raw material output (ton dry weight/year)	49.0	28.7
Ethanol consumption of raw material (ton dry weight)	2.63	2.40

China's energy sugarcane research started late, but developed rapidly. Fujian Agricultural University Sugarcane Research Institute became the center for national sugar crop improvement of sugarcane. Similarly, the Ministry of Agriculture, Genetics and Breeding Key and Open Laboratory and the Department of Agriculture's Sugarcane and Products Quality Inspection Center initiated Energy Sugarcane Research. During the "Ninth Five-Year Plan", it was decided to tackle sugarcane breeding as a key scientific and technological problem with the aim of developing "high efficiency, high biological quantity of breeding research". Varieties of sugarcane have been grown having genetic diversity using saccharum complex and high photosynthetic efficiency. Through saccharum interspecific hybridization, a high-separation breeding group was created. During the process, in vivo measurement techniques, molecular marker techniques, cell engineering technology and conventional breeding were used to improvethe advanced photosynthetic efficiency. By using total biomass and total amount of fermentation sugar as the breeding goal, a new type of energy sugarcane was created, while the evaluation of technical and economic indices was made through a series of experiments. Through self-fertilization, a number of new varieties (lines) of energy sugarcane have been created, which are either close to or exceed the level of second generation energy sugarcane varieties. The requisite project funding to explore sugarcane energy and R&D in more detail continues to be provided by Fifteen national 863 plan, 948 major projects, national key projects, the Ministry of Agriculture, Major technical research projects, the Ministry of Agriculture's "Southern Energy Agricultural Technology Pilot and Industrialization Demonstration", Fujian Province's major science and technology projects: "Novel Sugarcane Varieties Breeding for Special Energy Production", Fujian Province crossing project "Energy New Sugarcane Varieties (lines) Test and Industrialization".

2.3.3.3 Castor oil plant

Castor oil plant or *Euphorbiaceae Ricinus communis* L. is a dicotyledonous annual or perennial herb. It is one of the world's top ten oil crops and its seeds have a high oil content. The seeds have around 46 % castor oil, while the seed kernel oil content is as high as 70 % or above. Castor oil contains castor alcohol acid, oleic acid, linoleic acid, stearic acid, and glycerin. Of these, the content of castor alkyd is about 82 %. Castor oil has the characteristics of not deteriorating even at high temperatures like 500–600 °C, not burning and not solidifying at low temperature of minus 18 °C. Its application prospects are very extensive and it acts as an important industrial raw material. High-quality castor oil can be used for medical purposes, however it can also be used to produce biodiesel. Its economic value is very high, and therefore has attracted the attention of many chemists, biologists, medical scientists, and entrepreneurs.

Castor originated in East Africa, and spread through Asia to America. It then spread to Europe, to Mexico, Guatemala, Latin America and other regions. Castor was transferred from India to China and has been planted for the past 1,400 years. World castor production is more than 110 tons per year. Brazil, India, former Soviet Union and China are the most important producers. China's existing castor acreage is around 150,000 to 200,000 hm^2, with an annual output of castor bean ranging from 150,000 to 250,000 million tons. The average yield is around 1,200–1,300 kg/hm^2, which comes mainly from Inner Mongolia, Jilin, Shanxi, Xinjiang and other places.

The castor root system is particularly well-developed and large, has wide adaptability, drought and salinity resistance, and is widely grown in tropical, subtropical and temperate countries. It is one of the world's top ten important oil plants. Castor is a single species and has four subspecies: persicus, chinensis, africanus and zanzibarinus. The first subspecies's yield is the highest, and is without caruncle; chinensis has a small caruncle. The other two subspecies do not have large caruncles. All the castors are diploid with $2n = 2\times = 20$. According to Hilterbran, it belongs to the secondary balance polyploid, base $x = 5$. it has been thought that a tetraploid system emerged from diploid ancestors ($2n = 10$), but is no extinct. If so, this evolution must have occurred in ancient times, because this low base does not exist in the Euphorbiaceae. All the castor subspecies and types can freely cross with each other and are fully fertile. Some experts believe that the first cross took place between the two subspecies strains from China and Africa.

Castor is typically monoecious but outbred. Natural outcrossing rate is between 5–50 %, while the rate of outcrossing some dwarf varieties is up to 90–100 % for outbred characteristics. Castor female flowers generally account for 30–50 % of the upper raceme, whereas the male flowers are located at the bottom. Furthermore, there are some variants with raceme type (A) alternate male and female; (B) female account for 70–90 %; (C) female accounted for 100 %; (D) there are some bisexual flowers. These phenomena must be affected by environmental factors, however genetically stable and environmentally less sensitive strains was bred out. It has been found that N-female and S-female are the two female types. The former determines the female recessive gene switch f. Female stock (ff) can be mated by compatriots (ff * Ff). Within the sex change variants, S-female flowers can be obtained. At the beginning, these variants are female flowers, while they later translate into a monoecious. The sexual performance of genetics and female lines could be used in hybrid seed production.

2.3.3.3.1 Research on castor's genetics-based quantitative character

From the genetics of the quantitative traits of castor, we could find that the cumulative gene was dominant on plant height, spike length, spike number, he number of primary and secondary poly umbel per plant and yield of each control group Superior genes affect stem and node production, which directly affect the first branch and number of each main spike capsule. The barbed capsule is dominant, while the unarmed ones are recessive. Based on the correlation between 15 traits, Through principal component analysis, we could reveal the effect of the main component on high quality oil-related selection. it also has been thought that the incomplete dominant gene determined thorn fruit capsules, and proposed that five pairs of genes determine the seed yield, whereas genes for stems, leaves, flowers, as well as the color of stems and flowers were also involved.

2.3.3.3.2 Genetic research on castor single female

Research on castor single female inheritance is the foundation and key technology of castor heterosis utilization. Castor single female is a karyotype phenomenon, recessive monogenic and two female series N145-4 was bred out reported a single female single dominant gene controlled castor, and raised the possibility of utilization of heterosis. Based on the recessive nuclear sterility and temperature sensitivity embedded in the male sex, a temperature-sensitive recessive female series was breed out. The temperature-sensitive female series 240 was successfully bred out. The integrated sine IV species was found in a single female plant. By genetic analysis, it has been found that the single female-like cytoplasm is controlled and accessed to the recouvery system.

In the 1980s, single female-like castor inheritance was made progess. The single female performance boils down to two types: one is the female form without the mark, while the other is the female form with the mark. Studies have shown that: normal development of male plants is controlled by AA dominant gene; single females are controlled by aa recessive gene; when single female genes mate with normal sexual development, half of the offspring are hybrids which are strains developing normal male flowers and the other half are female plants. Further studies showed: single females are shaped by nuclear genes showing an additive effect of multiple genes, if there are suppressor genes that make use of integrated single breeding female castor seed. The development of male flowers and no marks character are influenced by two dominant genes controlled by a tight chain, whereas single females and sign character are controlled by two pairs of tight chains of recessive nuclear genes. Their genetic performance is single female plant with mark character, and show variety test cross with other lines. Additionally, F1 are all normal strains, while all the sexes are represented by formula one. The normal sexual strains and symbol character have the female ratio of 3 : 1 ($P > 0.995$). F1 backcross in females with mark character sheet (or normal strains in F1 and single sisters with logos traits) having normal strain and symbol character female ratio of 1 : 1 ($P > 0.995$).

2.3.3.3.3 Castor heterosis utilization

Castor heterosis is obvious, and in comparison to conventional hybrid yield, it shows an increase of more than 30 %. Since the second half of the 20th century, many countries have conducted castor heterosis utilization research.

The combining ability between strains and tested hybrid was studied by different combination of three female and eight male castors. The results showed that the additional gene on yield and three yield-related traits showed no obvious advantage, whereas the other three traits were found to have additional genes. Female parent SKP4 consumed up to 50 % flowering time and the seed, which had a kernel weight of several hundreds, showed good general combining ability. The VP1 varieties of plant height, yield, several hundred kernel weight and effective branches have the same effect. Male parent SPS43-3, J169, V19, J116 and J121 for production and some production factors show high general combining ability. The hybrids' oil content combining ability was studied, which pointed out different genotypes along with the combining ability of hybrids in 12 genotypes. Additionally, the hybrid genetic analysis of the generation of oil content for the studied hybrid was also presented. TMV5, JM3 and 240 varieties have the highest general combining ability, while 2-73-11 × SH38, SH15 × 2-73-11 hybrid F1 showed the highest special combining ability.

One of the ways to use heterosis is by choosing a female strain producing hybrid seed. N-female strains can isolate 1 F (f monoecious): 1 ff (female) planting in the cross-field. After purifying the monoecious plants, the remaining plant crossbred with the selected inbred line to produce hybrids. Female strains were kept by the sister plants. In 1950, Americans bred a single nuclear recessive gene inheritance N145-4 type female line (about 50 % of the population are female plants, while 50 % are bisexual strain), and proposed two types of female lines as female. One was the use of an artificial way to remove gender lines producing F1 hybrid seed, while the other was the bred hybrids used in the production. Ithe recessive gene and temperature-sensitive mosaicism male genetic independent genetic characteristics was studied, which produced temperature-sensitive bred female line. The average daily temperature in Californiain July is 90 °F, where small amounts of males can be produced in isolation from a fertile female line. In July, the temperature is 75 °F in the Davis, there is little or no males that are suitable to produce hybrid seeds. The achievement and combined with their climatic conditions was further developed, which presented the production of hybrid seeds in the same area at low season (October–February). In the hot season (July to October), female line 240 was bred to promote the rapid production of Indian castor. Then they bred SKR (such as new VP-1) with many temperature-sensitive female lines, and several hybrids were also bred for production applications, in which VP-1 was used as the maternal parent. Gauch-1 and GCH-2,3,4 hybrids' yields were in the range of 9–60 % more than those of Gauch-1, which showed strong heterosis. Two types of female plants N145-4 obtained from the United States were bred to keep the whole female temporary strains. The researchers bred three crosses and the control varieties' yield was found to be 10 %.

Cytoplasmic female line was found and bred in Romania and the obtained material can make offspring recover from hermaphroditism. Huantai county and Shandong province Institute of Microbiology in China bred Hengza No. 1 and Hengza No. 2 by using hybridization between inbred lines. Castor was applied in the five provinces and two cities became the main producing areas. This increased the production around 26.9–62.0 % more than the local varieties. Inner Mongolia's Tongliao Agricultural Institute and Shanxi Academy of Agricultural Science applied "a series of dual-use", "two-line" heterosis utilization pathways and bred locally adapted plants of hybrid castor biza No. 1, Zhe 1 Fen bi No. 4, and Luliangshan No. 1. The production of these hybrid seeds significantly reduced the volume of investment, while the emasculation to remove gender lines, purity and yield of the hybrids also showed an increasing trend.

The research about castor high polymerization breeding techniques and high oil yield castor varieties has not made much progress in China. Although there have been great advances since the 1980s, basic research still requires more attention. Presently, it attaches great importance to deepening germplasm resource collection, conservation, character identification and utilization, strengthening the diversity of genetic resources, and related molecular marker research. the results from basic research are vital to developing research on high oil, high yield and key characters of general combining ability and special combining ability to provide a scientific basis for selection and testing cross parents. In order to improve breeding efficiency, utilization of modern genetics and breeding technology is needed. Furthermore, establishment of efficient polymerization breeding systems to carry out a single female like "a series of dual-use" or "two-line" high oil, high yield heterosis research is also needed. These steps are vital to improve the level of China's castor breeding research and production levels.

2.3.3.3.4 Breeding castor's resistance to high temperature and humidity

In nature, temperature and humidity always exist at the same time, and therefore, show a mutual and comprehensive influence. High temperature and humidity can easily cause castor's premature aging, shorten its growth duration, result in plant diseases and encourage growth of pests, and decline in production quality. Therefore, improving castor's resistance to high temperature and high humidity is one of the most important aims of castor bean breeding research. Hunan Academy of Forestry has carried out fruitful work in this respect, and has bred castor varieties which have improved resistance to high temperature and high humidity. The work has won first prize in science and technology progress of Hunan province in China.

High temperature and high humidity resistance can be achieved through genetic breeding, which combines castor's resistance to high temperature and humidity and high yield into a breeding cultivars. Recently, Hunan Academy of Forestry conducted research about the theory, methods and techniques of castor's resistance identification and physiology to identify resistance in a high temperature and humidity environment, and develop a physiological and genetic breeding strategy, which can help quickly develop resistance to high temperature and high humidity and high genotype of varieties.

Firstly, Hunan Academy of Forestry proposed three ways to foster resistance to high temperature and humidity, yielding new varieties (combination). These included:

(1) hybrid high temperature and humidity resistance with high yielding varieties;
(2) using “three hybrid ways” which combines castor’s high temperature and humidity resistance with high yield varieties and get a cross product;
(3) using a compound hybridization method to cultivate seeds having resistance to high temperature and high humidity.

Secondly, they also conducted research on the requirements of culturing under high temperature and rainy areas and greenhouses, on the parent matching method to choose the variety which will have high yield, high quality, thermal and moisture resistance, disease resistance and other characteristics better than the parent. At the same time, different genetic background and geographies can be chosen, which directly influence the varieties available locally and abroad as a parent. This way, a better offspring with excellent characteristics can be chosen. According to the agronomic traits, reasonable selection of the parent castor is important. The authors analyzed a lot of hybrid combinations to choose different varieties of the hybrid, and bred new varieties of high yield and resistance to high temperature and humidity genotypes.

Thirdly, research was conducted on different growth stages to breed high temperature and humidity resistant castor by making it sensitive to high temperature and waterlogging periods to avoid the stress of high temperature and humidity. During bud stage, the authors paid attention to the ability of the resistance to high temperature and high humidity of castor bean sprouts. During the seedling stage, the researchers should not only focus on seedling’s ability to resist high temperature and high humidity, but also observe development under adverse conditions. For adult plants, the researchers should focus more on production capacity under adverse situations (economic yield, and biological yield) and the ability to reproduce. Comprehensive breeding of high temperature and high humidity resistant plants not only considers the morphological characters of castor and growth characteristics, but also considers its physiological and yield traits.

Lastly, taking the idea of backcross breeding and establishing ecological education to improve the new breed’s resistance to high temperature and high humidity and their production is another way forward. Previous studies have found that stress resistance and disease resistance as well as fruit type do not have genetic linkages in castors. However, some castors have excellent resistance properties, though a bad economical character. Then backcross breeding was applied to transfer the resistance of genes in these materials to the breeding materials and seed in the high temperature, high humidity and arid areas at the same time or through alternative selection. This means investigating the resistance to high temperature, high humidity and diseases, and the quality of breeds in the high temperature, high humidity areas, while high yield, stability and economic characteristics (such as plant height) are investigated in the dry areas. This way, the researchers can select some materials that have favorable properties, including resistance to high temperature and high humidity, and the ability of high production. Through many years of multipoint ecological breeding, breeding has resulted in comprehensive, stable, high yield varieties having resistance to high temperature, high humidity and disease.

2.3.3.4 Soybean with high oleic acid

Soybean oil, which is currently used as an industrial raw material, is essentially a fatty acid that has not been genetically modified. Using biotechnology and breeding technology to change the fatty acid composition of oil, one can produce more suitable species for industrial purposes (such as biodiesel) from soybean oil. High oleic soybean has attracted much attention in various industrial applications. The use of different 1,2-oleic acid desaturase gene (FAD2) mutant breeding can improve the contents of oleic acid. Typical FAD2 enzyme is responsible for the conversion of oleic acid to linoleic acid. The enzyme mainly uses oleic acid molecules as the substrate to generate phosphatidylcholine (PC). The content of oleic acid in soybean seeds can be improved by FAD2 mutation or by inhibiting its expression, which is the main component of seed oil. Biotechnology can help inhibit the FAD2 gene and reduce the palmitic acid acyl carrier protein thioesterase gene (*FatB*), which can further increase the oleic acid. By this method, the oleic acid content of soybean oil can be as high as 90 %. Inhibition of *FatB* expression also reduces the content of these oils to around 4 % or less, while simultaneously producing a low saturated fatty acid content of the oil.

High oleic acid (HO) soybean oil not only has high content of oleic acid, but also reduces the content of polyunsaturated fatty acids (e.g. linoleic acid). For example, the 90 % oleic acid content of soybean oil contains less than 4 % of the polyunsaturated fatty acids and palm acid contents. Most of the remaining polyunsaturated fatty acids can be removed by breeding, and the content of the flax acid is lower than 1 % of the soybean. High oleic acid and low polyunsaturated fatty acids greatly increase the oxidation stability of liquid oil. For example, oleic acid content of 85 % soybean oil's oxidation stability (to the value of unity) is more than 12 times that of traditional soybean oil. If vegetable oil is used as lubricating oil, including motor oil and hydraulic oil, oxidation stability will be very important. Compared with traditional soybean oil, it is more favorable for biodiesel production. The reduction in polyunsaturated fatty acids of HO soybean oil not only improves the oxidative stability of the soybean oil, but also reduces the nitrogen oxide emissions (NO*). The condensation point of high oleic soybean oil was improved due to the decrease in content of palm acid (about

12 % of the traditional soybean) and about 4 % of high oleic soybean. For example, with high oleic soybean oil, the production of methyl cloud was undertaken at pour temperatures of −5 and −9 °C. In comparison, the traditional oil cloud and pour temperature are 0 °C and 1 °C. Undoubtedly, transgenic high oleic soybean varieties as parents, and others as obtained by the mutation breeding of fatty acid content change (such as, high stearic acid) of soybean hybrids can breed more and hence can generate different varieties of soybean oil which can be used in various industrial applications.

Changing the relative proportion of five common fatty acids in soybean seeds can produce higher economic value. High oleic soybean oil with high performance and wide industrial use is one of the high value industrial fatty acids. In addition, some foreign gene can be introduced into the synthesis of novel fatty acid by the transgenic method. This way, oil having special industrial use can be obtained. These genes are generally obtained from nonagricultural species containing abnormal fatty acids in seed oil. The enzymes encoded by these genes can change the structure of the fatty acid carbon chain, and obtain fatty acid with changes to the position and configuration of the hydroxyl group, epoxy group or the double bond. These can even produce a fatty acid that has more than 18 carbon atoms. These genes can not only encode FAD2-like enzymes, but can also have other enzymatic functions. For example, the castor oil acid hydroxy enzyme, which is a typical FAD2 substrate, is a lecithin, but is also the product that further produces a hydroxyl group, not in Δ2 or 1 position to produce a cis double bond. Ricin oleic acid (OH-18:1Δ9) is a kind of hydroxyl fatty acid that has a wide range of industrial uses. It can be used as lubricating oil, hydraulic oil, surface active agent, and in cosmetics and nylon production. Hydroxy acid castor can also increase the lubricating properties of fatty acid methyl ester in biodiesel. In order to produce castor acid from soybean, one of the promoters controls the enzyme gene in castor seed specific hydroxyl conversion of soybean. Furthermore, the ricin oleic acid content in the genetically modified soybean oil is around 15 %. At present, the ongoing assessment of this genetically modified seed oil, and in-depth understanding of hydroxylated fatty acids increases the value of grease. Additionally, these also increase the oxidative stability of oleic acid content and improve the oil.

Cyclic fatty acid is another variant of fatty acid, which can increase the industrial value of soybean oil. At present, chemical methods to epoxidate soybean oil, plasticizing agent and precursor substances (such as polyol) can be used for producing coatings, adhesives and biological polymers. Fatty acid epoxidation of soybean oil is produced by the reaction of double bond of fatty acid with hydrogen peroxide under acidic conditions. The reaction is nonspecific in the presence of Δ9, Δ12, and Δ15 double bonds in the fatty acids of soybean oil. Some nonagronomic plant species have evolved a specific enzyme that can convert linoleic acid Δ12 double bonds to epoxy fatty acid vernolic acid. Vegetable oil containing vernolic acid can not only be used for producing cyclic oxidation of soybean oil, but can also be used for producing low volatile organic compound (VOC) paint solvents and thus, garners much research interest. A new method for industrially producing vernolic acid is the chemical transformation of useful materials. Vernolic acid Δ12 epoxy can be produced by linoleic phosphatidylcholine (linoleoyl-PC) under different FAD2 cyclooxygenase, which can also be converted to cytochrome P450 epoxygenase. The traditional FAD2 epoxido gene was obtained from soybean in which the vernolic acid content was about 7 % of the genetically modified soybean oil. Soybean somatic embryo expression of Euphorbia cytochrome P450 oxidase gene in the plant ring is a similar level of vernolic acid.

One of the main uses of soybean oil in industry is the production of soybean ink. Soybean oil is widely used in colored newspapers' printing ink. Soybean oil used in newspaper printing ink dries slower. In order to improve the drying rate of soy ink, one can add a conjugated fatty acid, which is very high in soybean oil in tung oil. The double bond of conjugated fatty acid is located on the adjacent carbon atom, while the double bond of soybean oil and linoleic acid is separated by methylene. Recently, soybean production of conjugated fatty acid isomers of eleostearic acid and calendula acid has been reported. The two kinds of fatty acids are produced under the action of a FAD2-like enzyme, which is a fatty acid conjugated enzyme. These enzymes will be combined with a cis double bond in the lecithin on the linoleic acid to be converted to two conjugated trans double bonds to get a conjugated three. Calendula acid enzyme, conjugated fatty acids, and linoleic acid convert the Δ9 double bond into Δ8 trans and Δ10 trans double bond, and produce eleostearic acid fatty acid conjugation enzymes to convert linoleic acid Δ12 double bond to Δ11 trans and Δ13 trans double bonds. The Δ9 modified conjugate enzyme cDNA is converted to soybean import from the produced Calendula officinalis. Additionally, the calendula acid content is around 5–10 % of the soybean oil. Similarly, from bitter gourd, balsam and cocoa plum, Δ12 modified enzyme conjugates cDNA by somatic embryos of soybean, in which the eleostearic acid content is around 20 % of the oil.

Technically, it is a breakthrough in the fatty acid composition of soybean oil to change the gene of other species through a metabolic engineering approach. However, the metabolic engineering of the new fatty acid content and accumulation of natural varieties of abnormal fatty acid content are much lower compared to most cases. For example, the content of castor oil is up to 90 %, while the content of castor acid in transgenic soybean can only be around 15 %. Abnormal fatty acid content is too low, and therefore, it is difficult to carry out the commercial development. Therefore, improving the abnormal fatty acid content of genetically modified soybean is the major technical obstacle to be overcome in future. The accumulation of abnormal fatty acids in transgenic seeds is a bottleneck in the accumulation of abnormal fatty acids in FAD2 enzyme (FAD2), which is due to the deficiency in the outflow of PC. The expression of the seed of fatty acid conjugated enzyme proved to be so. Expression of Δ9 and Δ12 type conjugate enzyme of arabidopsis and soybean seeds are not only in the form of triacylglycerol accumulation, but are also in equal or higher proportion in the form of PC accumulation. For example, the expression of Calendula officinalis conjugate enzyme in transgenic soybean and calendula acid in triglyceride gan accounted for 20 % of the fatty acid, but also to PC fatty acids formed by abnormal accumulation and having content as high as PC fatty acids of 25 %. On the contrary, calendula acid content of three glycerols in the form of calendula seeds accounted for about 55 %, which is less by 1 % in the form of PC. Calendula evolved a mechanism for abnormal accumulation of limited marigold acid in PC. However, such a mechanism does not exist in soybean seeds. The seeds of other species that naturally produce conjugated fatty acids have also evolved the ability to effectively remove these fatty acids from PC. This is due to the fact that the conjugated fatty acids accounted for more than 80 % of the seed oil fatty acid, while the content of conjugated fatty acids in PC is little higher than 2 %. Some plants can accumulate abnormal fatty acids due to the activity of FAD2 related enzymes. The present study focuses on the discovery of different types of phospholipids from these plants. Presumably, this enzyme has obtained the ability of effective abnormal metabolism of fatty acids. These metabolic enzymes and FAD2 synthetase along with the Chinese soybean expression will have soybean varieties, which may have very high contents of abnormal fatty acids. This can help to achieve viable economic and industrial production.

2.3.3.5 High erucic acid rapeseed oil

Rich in erucic acid, this vegetable oil is a kind of typical industrial raw material. The erucic acid derivatives and erucic acid hydrogenation produce behenic acid, which has 22 carbon grease compounds and has excellent adhesion, softening, hydrophobic and lubrication properties. Therefore, it has a wide range of industrial applications. They can be used as biodiesel, food additives, cosmetics, hair care elements, surface active agent, detergent and plastic additives, lubricants and fuel auxiliary materials. Additionally, these can also be used as a raw material for photography and recording.

With the emergence of low erucic acid rapeseed cultivar, the traditional production of high erucic acid rapeseed declined rapidly in the world. Since it contains about 45–50 % erucic acid, old rape varieties can produce higher seed yield and oil. Therefore, high erucic acid rapeseed breeding can rise again. Due to this, breeders, biochemists and genetic engineering scientists are trying to improve the erucic acid content through genetic engineering. Although many research based projects have been introduced, a breakthrough in this regard will take time.

2.3.3.5.1 Application of microspore culture technology and a double haploid system in cultivation of high erucic acid rape

The improvement of the classic pedigree breeding method of Brassica napus rapeseed fatty acid from hybridization to breed varieties would take at least 10–12 years. The cultivation of double haploid microspore culture technology can accelerate the improvement of the process systems. Luhs and Friedt [13] used erucic acid content, which was higher in the winter pool of vegetable varieties in inbred hybridized combination, parents and F1 generation plants of microspore culture and plantlet regeneration. They analyzed the small sporelings of vernalization and colchicine doubling. Additionally, many double haploid plants were obtained on seed generation during 31 doubled haploid line field experiment. The results showed that the erucic acid contents increased to around 60 %.

2.3.3.5.2 In vitro selection of microspore embryos for cultivating high erucic acid rape

Cabbage-type rape pollen embryos can accumulate lipids. In the later stage, the fatty acid composition of the small spore embryo is almost the same as that in the embryo and the mature seed. Therefore, the pollen embryo-like body has become a tool for various biochemical and molecular research efforts. Since the three acyl glycerol ester is present only in the developing seed of the neutral lipid fraction, it is a good marker for the initiation of lipid synthesis. Due to high enzyme activity, the homogenate of the pollen embryo-like body can produce triacylglycerides. it has been proved that in 1,2-dierucoylglycerol and erucoyl-CoA, the homogenate of the pollen embryo-like body produces three acyl glycerine ester.

In order to cultivate specific fatty acids in rapeseed, which have half the size of a grain of seed, erucic acid analysis methods can be used. The fatty acid analysis of the group of the embryo was carried out, and the ideal shape of the embryo was selected. To make the selection more accurate, the culture conditions must be appropriate, so that the development of a population of embryos (size, age and ploidy level) and synthesis of fatty acid could take place. Additionally, in the late microspore embryo cotyledons, erucic acid accumulation is lower than that in zygotic embryos and mature seeds. In the breeding study, using the microspore embryo as a volatile object is still a good method for rapid screening of high erucic acid material. it has been reported that the fatty acid content of the seeds of a plant, which was determined by a single leaf of the embryo and the regeneration of the plants, was determined to be about 70 %. Furthermore, embryos can be eliminated and therefore do not have to be cultured into plants.

2.3.3.5.3 Applying biotechnology to create new variations in fatty acids

Brassica chinensis is a diploid hybrid formed by a natural cross between Chinese cabbage and cabbage. The largely artificial hybrids of Brassica napus produce oils such as Sweden rape and forage rape. On the contrary, the types of cabbage and Chinese cabbage are very important and are rendered as important vegetables, oil and feed type. These diploid species provide a rich parent material for the improvement of Brassica species. Over the past 40 years, a lot of work has been done to find new germplasm resources and on the synthesis of bridge materials by means of cabbage*cabbage. Now the isozymes and molecular markers are being studied. The results show that, unlike natural B. napus, the artificial synthesis of various cabbage type rape strain system's genetic composition is biparental diploid species in the middle. In ancient diploid species, there is a high degree of variation of erucic acid content. Cabbage is 30.1–61.4 %, while brassica (including wild species) is 28.2–63.4 %. Especially in broccoli, erucic acid content is 46.6–63.4 %, with an average of 57.9 % + 0.3 %. The erucic acid contents of the hybrid cabbages are about 55–60 %, and is determined via the synthesis of ovule culture in Brassica napus. Genetic studies confirm that erucic acid synthesis is controlled by two alleles in the additive model, where each gene controlled the synthesis of erucic acid by around 16–17 %. However, through hybridization, recombination and accumulation of efficient alleles increased the probability of erucic acid synthesis composed of three acyl glycerides rich in erucic acid, especially the synthesis of three erucic acid glycerol esters was blocked and reduced.

In the Brassicaceae, protoplast fusion has become a kind of advanced technology for the improvement of drought resistance, anti-falling grain, insect resistance and disease resistance of wild species of Brassica napus rapeseed or Brassica juncea, Brassica napus and Brassica vine. Interspecific somatic hybrids of Cruciferae and different genera have been produced. However, the more distant somatic hybrids are rarely reported. Recently, the cabbage Brassica napus, Arabidopsis thaliana, Brassica Rape, and Thlaspi arvense genus Thlaspi perfoliatum have been found to be fertile somatic hybrids. The genetic pattern of fatty acid is not as controlled by the cytoplasm as in the male sterile line, however the aim of the resynthesis of Brassica by somatic hybridization is to induce the extensive variation of fatty acids. Several research groups have tried to achieve this through high erucic acid rape, Thlaspi arvense genera and ornamental plants in satin genus (lunaria annua somatic hybridization and improvement of Brassica napus long chain fatty acids). However, about 20 % of these wild species of seed oil contained in the somatic cell hybrid seeds were not detected.

2.3.3.5.4 Molecular markers and their application in the breeding of oil rape

Using traditional methods it will take many years to achieve good characteristics of the mutant or wild species. In recent years, the selection efficiency of molecular markers of backcross breeding has shown great effect. In many biochemical and molecular markers, RFLP, RAPD and microsatellite DNA have a significant impact on crop improvement. Recently, Uzunova [14] used the RFLP linkage map of Brassica napus (Marashodts hamburger raps × Samourai) F1 of small hold double haploid subsystem to control the erucic acid synthesis in both, to gene map in Article 6 and Article 12 linkage groups. The markers linked to the gene can be used for breeding erucic acid rape. Using the double haploid system, the control of 3 quantitative trait loci of oil content is positioned at 6, 10 and 12 linkage groups. One of the two loci and loci controlling erucic acid content is in close linkage. This shows that the erucic acid gene directly affects the seed oil content. This is consistent with the results reported by Klassen [15].

2.3.3.5.5 Gene engineering of three erucic acid and glycerol ester of rapeseed oil

Although erucic acid is the main component of triglycerides in rapeseed oils, erucic acid (long-chain fatty acids) only exists in esterification of first glycerol backbone and third hydroxyl groups, but not with second hydroxy esterification, so that rapeseed oil was not detected in three erucic acid glycerol esters. This means that theoretically, the erucic acid content in rapeseed oil has the highest value of 66 %. it was believed that through the improvement, the ratio of erucic acid content in rapeseed oil can be increased to about 95 %. In fact, in some kinds of Cruciferae, especially in broccoli oil, the erucic acid content is 60–63 %. Recently in some genotypes of cauliflower, the erucic acid was found to be esterified in the central three hydroxy acyl glycerides. However, these three erucic acid glycerol esters were not found in the seed oil. The reason for this is not clear, and should be studied further.

In rapeseed oil and erucic acid synthesis, the main obstacles are the specificity and selectivity of assembly associated with acyl coenzyme A (acyl CoA) hemolytic phosphate acyltransferase (LPA-AT). The erucic acid cannot enter the glycerol backbone of the 2-hydroxyesterification. So, the synthesis of three erucic acid glycerol ester was blocked. Molecular biologists have studied Limnanthes douglasii plant’s seed and have isolated the cDNA of code 1-acyl glyceride-3- phosphate acyltransferase (AGPAT). This enzyme gene controls the production of erucoyl-CoA. Thus, the study aims at trying to achieve the substitution of rapeseed LPA-AT enzyme gene by IAGPAT enzyme gene. The glycerol backbone central hydroxyl esterification of erucic acid forms three erucic acid glycerol ester.

2.3.3.6 Cassava

Cassava (*Manihotesculenta Crantz*) belongs to the Euphorbiaceae genus of cassava, which originated from dry regions of Brazil and Columbia in tropical America. Cassava is one of the world’s top three potato crops, and has a planting area of 1,700 million hectares, which is second only to potato. The plant is located between 30 degrees north and south latitude, at an altitude of 2,000 meters in the tropical regions and is an important source of energy.

Cassava has a unique biological adaptability and economic value due to following reasons:

(1) It has extraordinary light, heat and water resource utilization capability. Its per unit area yield is higher than almost all other crops, while the ten month period of cassava fresh tuber yield can reach 90 tons/ha. Additionally, the root average drying rate is 42 %, while the starch rate is about 30 %. The economic coefficient is 0.55, which is equivalent to 37.8 tons/ha dry matter production of roots, 30 tons/ha starch and 68.7 tons/ha of total biomass.

(2) It is drought resistant, barren resistant, and widely adaptable. Cassava has prominent soil nutrient and water use efficiency, and can grow in poor soil. It can with-

stand a severe drought period. Furthermore, it shows rapid growth of genetic characteristics at the arrival of the rainy season.

(3) It has a high root starch rate and starch particularity. The root starch content is generally around 26–34 %, which is higher than sweet potato and potato. The starch grains have greater transparency, high viscosity, and are suitable for manufacturing high quality modified starch.

Cassava introduced in China has 180 years of history, and is mainly distributed in Guangxi, Guangdong, Hainan, Yunnan and parts of Fujian. In the traditional sense, it is the underground barn in the tropical and subtropical regions of China, and is also a cheap raw source of starch. In recent years, the planting area of cassava in China was maintained at about 40 million hectares, whereas the fresh tuber yield was more than 700 million tons, which accounts for 90 % of the total production of starch. Cassava has become an important dryland crop and industrial commodity in the tropics. About 90 % of China's cassava production is concentrated in two provinces of Guangxi and Guangdong.

Cassava is mainly distributed in Guangxi, Guangdong, Yunnan, Fujian, Hainan and other provinces in the south of the country. In Guangxi, cassava planting area and production account for more than 60 % of the countryside, and it is the country's largest cassava production area. The total cassava planting area of China was around 408,400 ha in 2010, while the total output was 9,022,500 tons. Due to the benefit from the improvement of varieties and other types of scientific and technological progress, the yield of cassava in China has increased from 14.71 tons/ha in 2000 to 18.83 tons/ha in 2008.

The breeding and cultivation of cassava production and field management department has been committed to improving China's cassava products and planting modes. Furthermore, the institute is trying to improve the varieties. After decades of efforts, China bred Southern China No. 5, Southern China No. 6, Southern China No. 7, Southern China No. 8, Southern China No. 9, GR891, GR911, and Nanzhi 199 have independent intellectual property rights of fine varieties. Some varieties have an average fresh sweet potato yield of around 30–45 tons/ha, which is 30–80 % more than the old varieties. Additionally, the fresh sweet potato starch content can reach up to around 30 % (Tab. 2.13).

2.3.3.7 Sweet potato

Sweet potato (*Ipomoea batatas* (L.) Lam) is an annual or perennial crop, while the vining plant is a cultivated variety of family Convolvulaceae [16]. Its stem and leaves, which are above the ground, may be used as a vegetable, while dried stem and leaves are used as animal feed. The underground root tuber is the main part utilized in food. Sweet potato has a high yield of biomass, has good abiotic stress resistance and good adaptability. Yields of 19.5–37.5 ton/ha can be normally obtained, which can be in-

Tab. 2.13: Main varieties of China's cassava.

Varieties	Characteristics	Per mu yield (ton/acre)	Starch content (%)
Southern China 205	High yield, high powder, fertilizer, soil fertility is higher the higher the yield.	2 ~ 3 (Intensive cultivation of up to 5)	28 ~ 30
GR891	High yield, early maturing, high powder, low toxicity, suitable for planting cultivation.	2 ~ 3 (Fertilizer and water management of good conditions of up to 3 ~ 4.5)	30 ~ 33
Southern China 124	High yield, stem storage resistance, wind resistance; suitability for planting cultivation is a bit poor.	2 ~ 3 (Intensive cultivation of up to 4 ~ 5)	24 ~ 27
Nanzhi 199	High powder, high yield, low toxicity, strong wind resistance, pest and disease resistance, suitable for medium fertility above soil cultivation.	2 ~ 3 (High yield up to 3 ~ 5)	28 ~ 32
Southern China No. 5 (Southern China 057)	High yield, wind resistance, suitable for cultivation on a slope, no high requirements for fertility.	2 ~ 3	27 ~ 29
Southern China 6068	Plant height and stem diameter is moderate, the bifurcation angle is small, dense plant type, suitable for planting and intercropping, poor wind resistance ability.	1–1.5 (High yield up to 3 ~ 5)	30 ~ 35
Southern China 201	Adaptability is strong, cold, barren resistant, starch viscosity high.	1.5 ~ 2.5	25 ~ 28

creased up to 60 ton/ha in high yielding land with good management. The starch content is about 20 %, which means 9 tons of sweet potatoes can produce 1 ton of ethanol fuel. Sweet potato is extremely drought resistant, so that even in land where other crops cannot survive, considerable yield can be obtained. Sweet potato is therefore regarded as a pioneer for land reclamation [17].

As a raw material to produce ethanol fuel, sweet potato has the following advantages:

(1) It has highly economic production. China's sweet potato per hectare average yield is 21.3 tons. Reports on pilot production have suggested a yield of more than 75 tons per hectare, while the average yield of 45 tons per hectare in a large area is relatively easy to reach. It has around 30 % dry matter, while 13.5 tons dry matter per hectare can be produced [18].

(2) It has high energy yield. Energy per unit area for sweet potato production reached 10.4×10^4 kcal/(ha · days), which is much higher than potato, soybean, rice, cassava and corn. In fact, the value is about three times that of the corn [19].

(3) It has wide adaptability. Hainan in South China, Heilongjiang in North China, coastal provinces in the East, from Shaanxi to Longnan in the West, Sichuan Basin and Yunnan-Gizhou Plateau in the Southwest, Turpan in the Northwest, Xinjiang, Hotan and other places can grow sweet potato, while the crop is especially suitable for dry land, hillside ground and saline planting.

(4) It has high efficiency of conversion to ethanol. Three tons of dry sweet potato can produce one ton of ethanol.

Sweet potato was introduced in China in 1594, and therefore, has a cultural history of more than 400 years. China is the world's largest sweet potato producing country. Among various crops in China, sweet potato is in fourth place with respect to production, following rice, wheat and corn. For China, the sowing area and gross output of sweet potato in 2011 was 3.49 million ha and 75.56 million tons, respectively. Unit area yield has been reported at 21.65 t/ha, which is far more than the global level. Sweet potatoes are widely planted in Sichuan basin, Huang-Huai-Hai, Yangtze River basin, and in the southeastern coastal provinces. Surveys show that 50 % of the sweet potatoes produced in China are used for animal feed, while only 15 % are used for further processing. Additionally, 14 % are directly eaten, 6 % for seed, and 15 % become musty/spoiled due to improper storage.

2.3.3.8 Jerusalem artichoke

Jerusalem artichoke belongs to *Helianthus tuberosus* L. in Compositae family and is also called the sunroot or sunchoke or topinambur. It is a species of sunflower native to North America. It is a herbaceous perennial plant whose underground root tubers are rich in synanthrin and other fructose polymers, and consist of 3–60 fructose units and one glucose unit. The dahlin content in fresh tuber is about 10–20 % with an average of 15 %.

Jerusalem artichoke is strongly adaptable, resistant to barren, cold, drought, flood and saline conditions. Planting of Jerusalem artichoke is very simple, such that repeated harvests can be obtained after sowing once. The tuber yield can reach 4–8 t/mu on normal land, whereas it can even reach 5–8 t/mu if more suitable conditions are provided. The tubers germinate at 6–7 °C, and generate seedlings at 8–10 °C. The seedling can resist low temperatures of 1–2 °C. Studies have shown that temperatures of 18–22 °C combined with 12 hours of sunshine will facilitate the growth of tubers. The tubers can stay safely in frozen soil through winter where temperatures are at −25 to −40 °C. Introduction of Jerusalem artichoke to waste lands and hillsides not only helps avoid occupying arable and fertile land, but can also protect the ecological environment.

Jerusalem artichoke originated from North America, and was introduced to China via Europe. Nowadays, it is widely grown in both North and South China in scattered plantings. Jerusalem artichoke in the past was mostly used for small-scale pickle processing which created little added value. Products from enterprises in Inner Mongolia, Gansu and Xinjiang of Jerusalem artichoke are much poorer in quality than similar European products. Furthermore, these are poor competitors and use poor technologies.

2.3.4 Woody oil plants

Plant oil is a kind of energy stored in the organs of plants. After processing, it can be extracted as plant fuel oil, instead of the fuel oil substances obtained from fossil fuels. Oil energy plants are a kind of plant species (or variants) that contain the element of energy plant oil, and are also a kind of renewable resource. They represent the utilization of plants as an energy resource. Biodiesel is an excellent substitute for petroleum and diesel.

With depleting world oil resources and increasing awareness about environmental protection, biodiesel is getting a lot of research attention all over the world due to its superior environmental protection and renewable characteristics. However, the materials are the key to the development of the biodiesel industry. Biodiesel's main component is the fatty acid triglyceride, which has 7–21 carbon atoms in the carbon chain, while there are mostly 11–19 carbons. From the beginning of the last mid-century, many countries and regions in the world began research on the selection and use of biodiesel plant materials. Some available plant species have been chosen, and are established as the base materials to be utilized as biodiesel raw materials. At the end of the 1970s and early 1980s, the USA carried out a great deal of research and development on fuel oil plants, and focused on the fuel oil plant resources which are rich in latex. Twelve kinds of hydrocarbons were selected, such as Euphorbia lathyris and green Yushu and were studied for cultivation. Additionally, the USA established a "Biological fuel oil forest farm" in southern California. After the Gulf War broke out in 1990, the United States began to attach importance to studying the composite production of biofuel. In 1999, the US Department of Energy organized a meeting, in which France, Netherlands, Germany, Austria, Malaysia and other countries participated. Scientists from these countries carried out research on oil palm, algae, parts of tropical plants, and concluded that by 2050, 80 % of the global liquid fuel oils will come from wood or oil plants cultivated from herbaceous species and algae. Currently, all countries are choosing materials that have their own advantages in developing biodiesel. EU countries use canola oil as the raw material, while the raw material for the production of biodiesel in the US is mainly transgenic soybean. The main raw material in Brazil is castor oil and transgenic soybean, while that in Malaysia and Indonesia is palm oil. At present, China lags behind in biodiesel resources, whereas the supply of the raw materials is also unstable.

China has a vast territory, located in the temperate zone and subtropical zone, which is rich in plant resources. More than 400 species of oil plants including rape, peanut, soybean, cotton (seed), sunflower, sesame, castor, tung oil, palm oil, *Swida* *wilsoniana*, coconut, eucalyptus, and sasanqua are found in these regions. However, the plant oil resources used in energy are very limited. In 2011, China's cultivated area for oil plants was 13.79 million hectares, while the total output was 32.79 million tons. The main products were beans, peanut, rapeseed, and sesame. These oil plants are the main sources of edible oil, which cannot be used for energy purposes. Therefore, the development of the biofuel industry in China must take place so that there are no disputes with the utilization of edible resources. Woody oil plants have the characteristics that these do not occupy arable land, they green barren hills, can fix carbon and reduce emissions, improve the ecological environment and others. Nearly 70 % of the land in China is occupied by mountains, hills and plateaus. Since it is rich in woody oil plants, it has the conditions to develop woody oil energy plants.

A study by the Academy of Forestry of Hunan Province shows that the oil plants that have been identified in China belong to 151 families, 697 genera, and 1,554 species. Among them are 154 species having seed oil content of more than 40 %. The plants having oil content over 10 % in their available organs and tissues constituted 138 families and 1,159 species. With further studies in plant fuel, the development in research and utilization of plant species to produce biodiesel will surely continue to increase. Our scientists focus on the feasibility of some wild plants and their fuel energy utilization. Table 2.14 lists several oil components of the oil plants, which may become suitable for China to produce plant oil feedstock for biofuel oil.

2.3.4.1 Jatropha curcas

Jatropha curcas L. is a member of the family *Euphorbiaceae*, which is originally found in tropical zones of Central America. It was naturalized in Southeast Asian countries. *Euphorbiaceae* consists of 200 species, which are distributed in the areas of Guizhou, Sichuan, Guangdong, Guangxi, Hainan province and southern Tibet. There are about five species in China: *J. curcas, J. podagrica, J. multifida, J. gossypifolia and J. integerrima*. Its oil content is about 40–60 %, and sulfur, carbon monoxide, lead emissions and other quality indices of the biodiesel transformed from *Jatropha curcas* seed are superior to #0 diesel. Its bark, leaf and fruit (including by-products from the oil-pressing) can be applied in medicine. Moreover, it can also be used to produce vegetable protein, biological pesticide, biological fertilizer, refining glycerol and some fine chemical products.

2.3.4.2 Swida wilsoniana

Swida wilsoniana is also known as *swida* dogwood, and is a kind of deciduous tree of *Cornaceae* and *Awida Opiz*. Wang Jingping named it *Cornus Swida wilsonian* in Latin. Cornus has 42 species in total and 24 of these are available in China. The main cultivation areas are Hunan, Jiangxi, Hubei, north of Guangxi, and north of Guangdong. There are five other species of Cornus plants, excluding *Swida wilsoniana*, which are

Tab. 2.14: Analysis of the oil constituents of potential oil plants.

Fatty acid (%)		Lauric acid	Myristic acid	Palmitic acid	Stearic acid	Arachidic acid	Hexadecenoic acid	Oleic Acid	Linoleic Acid	Linolenic acid	Eicosenoic acid	Special fatty acid
Varieties												
Woody Plants	Oil tea	–	0.8	10.6	1.7	–	–	77.333	9.167	0.267		–
	Pistacia chinensis	–	0.013	20.867	1.5	0.567	1.2	46.4	29.367	0.007	–	–
	Idesia polycarpa Maxim.	–	0.007	12.8	3.3	–	2.867	9.2	71.133	0.467	–	–
	Swida wilsoniana	0.007	0.067	16.533	1.767	–	0.973	30.5	48.5	1.6	–	–
	Palm	19.5	18.6	27	12.3	–	–	22.6	–	–	–	–
	Eucalyptus	–	–	5.5	2.4	0.7	–	12.8	78.5	–	–	–
	Caper euphorbia	0.01	–	5.8	1.9	0.3	1.1	70.25	16.2	2	–	–
	Symplocos Paniculata	–	–	20.733	0.873	–	–	48.233	30.167	–	–	–
	Tung oil tree	0.167	0.007	1.8	1.9	–	0.007	7.1	6.9	0.3	–	eleostearic acid 72.9
	Tallow Tree	–	27.4	13.7	1.37	–	–	9.59	21.92	26.06	–	–
	Soapberry	–	–	4.75	1.52	6.14	–	55.62	6.88	1.15	21.83	–
	Jatropha curcas	0.09	–	17.25	7.42	0.22	–	40.31	32.69	0.4	0.23	–
	Xanthoceras sorbifolia	–	–	10.4	2.6	–	–	31.81	42.36	–	6.08	–
	Walnut	–	–	4.69	–	0.43	–	1.43	31.85	49.54	–	–
Herbaceous Crops	Castor bean	–	–	0.72	0.64	–	–	2.82	0.27	–	–	Castor acid 90.85
	Rapeseed	–	0.04	3.567	1.133	0.007	0.14	14.5	15.467	13.6	–	–
	Soybean	–	–	13	2.9	–	–	19.35	58.05	6.7	–	–

Swida paucinervis, Swida macrophylla, Swida waten, Swida oblonga and *Swida austrosinensis*. *Swida* is a newly developed woody oil plant which is peculiar to the South of China. It has strong adaptability, early fruit, short fruit period, high yield, and high oil content (about 30 %). The oil of *Swida wilsoniana* can be used as edible, pharmaceutical, biodiesel raw material and as other raw materials in the chemical industry. *Swida wilsoniana* is a dominant species for limestone, while the hard wood has a dense, beautiful texture which is a kind of good material. It is widely distributed in the south of Yellow River. In addition, *Swida wilsoniana* is an ideal tree species for soil and water conservation due to its trees' deciduous layer thickness. It can be used to control rocky desertification, for greening of barren hills, roadsides, housing borders, and urban gardening. At present, *Swida wilsoniana* is mainly cultivated in Hunan, Jiangxi, Guangdong, Guangxi, Jiangsu, and Zhejiang regions of China.

2.3.4.3 Pistacia chinensis Bunge

Pistacia chinensis Bunge is also called Pistacia sinensis Bge, Jieshu, yellow neem, medicine wood, Huang Hua, encrinite, yellow wood, wood smartweed tree, comb wood, Yang Yang, rotten wood, and Coptis chinensis tea, and is one kind of cashew deciduous woody species. The oil content of the shell is 3.28 %, while the oil contents of seeds and kernel are 35.05 % and 56.5 %, respectively. The tannins content of leaves and pulp are 10.8 % and 5.4 %, respectively, which can pick up tanning extract. The wood of *Pistacia chinensis* Bunge is ring-porous wood, whereas the sapwood is wide, and gray-yellow. The heartwood is heavy and hard, while its structure is fine and even. The air drying capacity is 0.713 g/m^3, so corrosion prevention is high. It can be used in areas of architecture, vehicles, farm tools and furniture. The crown of *Pistacia chinensis* Bunge is wide, while its leaves are lush and become bright and orange red in autumn. Its leaves and bark can be used for medicine, while its root, branches, leaves and bark can be used to make pesticides. Aromatic oil can be obtained from its fresh leaves, tender leaves can be used for tea and pickled food. *Pistacia chinensis* Bunge is an excellent tree species for timber, aesthetics, medicine and oil plants, and is also an excellent tree species that can drive the development of a variety of industries.

2.3.4.4 Xanthoceras sorbifolia Bunge

Xanthoceras sorbifolia belongs to *Sapindaceae (Sapindaceae)* yellowhorn (*Xanthoceras*), and is also known as Wenguanhua and Yamugua. It originated in the Loess Plateau of Northwest China. Wild *Xanthoceras sorbifolia* is widely distributed in Inner Mongolia, Shanxi, Gansu, Hebei and other provinces. It is a unique woody oil plant and is also regarded as a precious ornamental tree species of China. Additionally, it is commonly used in Chinese medicine in the treatment of high blood lipids, hypertension and other cardiovascular and cerebrovascular diseases. It has high economic value, medicinal value, and ecological benefits. The State Forestry Administration has reported that the biomass energy tree species are suitable for development in China, whereas woody plant *Xanthoceras sorbifolia* was identified as the only suitable biomass energy tree in the North of China. The relevant departments of the state made it one of eight species for producing biodiesel. *Xanthoceras sorbifolia* Bunge has far-reaching developmental prospects in different sectors, such as industry, edibles, medicinal, greening of barren hills, soil and water conservation.

2.3.4.5 Sapindus

The plant *Vernicia euphorbiaceae* is collectively called *vernicia*, and is an important industrial oil plant variety. The seed kernel's oil content is about 60 %, which is either squeezed or extracted from the seed kernel. The extracted oil is called Chinese wood oil, and is the highest quality drying oil in the world. It is widely used in industry, agriculture, fishery, construction, transportation, printing and national defense industry. *Vernicia* has a long cultivation history in China, and is widely planted in the highlands of southern China. Historically, *vernicia* is mainly used for lighting, painting farm tools, furniture and ships, and treating scabies pyogenic infections.

Sapindus mukorossi Gaerth is also called soapbark or soapberry, and is a kind of deciduous trees, which belongs to *sapindus linn*. The *sapindaceae* is distributed in Southeast Asian countries, Taiwan province of our country and the provinces south of Huaihe river. Sapindus mukorossi Gaerth's aril is rich in saponin, which has good foamability and decontamination performance. It can be used in shampoos and various kinds of cosmetics for dermatological purposes. The aril also has a physiological antibacterial effect and relieves itching. It can be used for athlete's foot and heel ringworms. Saponin is a good agricultural pesticide emulsifier, which has good effectiveness in killing cotton aphid, red spider and sweet potato jinhua worm. Pharmacological studies have shown that saponin has the function of antidermatophyte and anticandida and a variety of biological activities, such as inhibition of tumor, cell proliferation, activity of antihelicobacter pylori and hepatoprotective effect. Moreover, this type of tree is beautiful. For its development, the root can absorb harmful gases like automobile exhaust and sulfur dioxide in the air. With regards to landscaping, water and soil conservation, and environmental protection, the plant has important value. As a kind of multifunctional plant, the development and utilization of Sapindus mukorossi Gaerth has received more and more research attention.

2.3.4.6 Tung oil tree

At the end of the nineteenth and start of the twentieth century, due to the rapid development of the world paint industry, tung oil emerged as the best paint raw material, and was exported from China to other countries. It became the biggest export commodity traded out of China. The increase in export volume has greatly stimulated the production of tung oil in China. By the 1980s, the planting area of tung trees had reached 1.8 million hm^2. The main cultivation areas include Chongqing, Guizhou, Hunan, Hubei, Guangxi, Guangdong, and Fujian.

2.3.4.7 Sapium sebiferum (L.) Roxb.

Sapium sebiferum is a kind of deciduous tree that belongs to euphorbiaceae tallow and can be used as an ornamental plant. Its shape, leaf and fruit all have high ornamental value. The seed of *Sapium sebiferum* contains white waxy aril like a black ball in the outside. The oil can be made into paint and the aril can be used as raw material for making candles and soap. Usually, the seed's wax content is between 30–40 %, while the seed's oil contents are about 40 %. At the same time, *Sapium sebiferum* is regarded as a unique economic tree species in China. The history of its cultivation is more than 1,400 years old. It originated in the Yangtze River and Zhu River basin. *Sapium sebiferum* are mainly distributed in various provinces and regions located in south of the Yellow River in China, such as in Shangxi, Gansu, and Zhejiang regions. This plant is also cultivated in East Asia, South Asia, Southeast Asia, Europe, United States and Africa.

2.3.4.8 Elaeis guineensis Jacq.

Oil palm (*Elaeis guineensis* Jacq.) is a perennial woody endogen oil crop, and has become the world's most efficient oil-producing plant. As an oil-producing plant, *Elaeis guineensis*' average annual output is as high as 4.27 tons per hectare, which is 5–6 times higher than that of peanut, and 9–10 times that of soybean. It is rightly titled "the king of the world's oil". Its original production areas include south of the equator (10 ° to 15 ° north latitude), and African damp areas on the edge of forest at an altitude below 150 m. The plant is distributed widely in Asia, Malaysia, Indonesia, West and Central Africa, South America, and North and Central America. In China, palm oil is cultivated in Hainan, Guangdong, Guangxi and Yunnan provinces. *Elaeis guineensis* has huge potential as a woody energy tree species, and is one of the major energy tree species designated by the State Forestry Administration. The development of *Elaeis guineensis* industry can provide raw materials for biofuel development in China and therefore has vast development and utilization potential.

2.3.4.9 Symplocos paniculata (Thunb.) Miq.

Sandalwood [*Symplocos paniculata* (Thunb.) Miq.] is commonly known as subtree, and is also known as broken seed tree, WuZi, cocobolo, ZiMu, and kink wood. *Symplocos paniculata* belongs to the mountains' alum section and is a kind of deciduous shrub or small tree, which is widely distributed in the northeast and south of the Yellow River region in China. It is especially seen in the provinces and regions south of the Yangtze River basin. Born in an altitude of 200–1,000 m in hilly areas, *Symplo-*

cos paniculata is often planted with woodlands, shrubs and red soil on a slope. Its growth is good in plain fields and valleys. *Symplocos paniculata* has a large number of distributed varieties in the Dawei Hills of Liuyang and the Heng mountain area in Hunan, China. Its developed roots, lush foliage, strong adaptability, drought resistance, cold resistance, and resistance to barren make it one of the finest tree species for soil and water conservation. *Symplocos paniculata* has a white flower, whose fruit is violet. Therefore, it has great prospects for development as an ornamental plant. *Symplocos paniculata* fruit is full of oil (both fruit and seed). The oil content is more than 36 %, which consists of fat oleic acid and linoleic acid and can be used to make cooking oil. At the same time, it has a wide range of valuable applications in industry. Examples include machine industries, where it can be used as a harmonic agent in lubricating oil, the ink and textile industries, where it can be used to soften and administer anti-electrostatic treatment of wool, and in the chemical industry to manufacture soap. Most importantly, the oil of *Symplocos paniculata* is also an ideal fruit raw oil for biodiesel production.

2.3.4.10 Idesia polycarpa. Maxim

Idesia polycarpa is a hydnocarpus table genera deciduous tree, which is mainly distributed in Zhejiang, Hunan, Shanxi, Gansu, Sichuan, Anhui, Jiangxi, Yunnan and other provinces of China. It is found at an altitude of 300–1,200 m on either side of hills, valleys or savanna forest edge. It has a straight trunk, gray bark with no cracks, and the tree is beautiful. It also has cones and yellow flowers. The berries or elliptic strings hang like grapes. The mature fruit is red or orange. *Idesia polycarpa* grows fast, and has strong adaptability. After three years, it can produce seeds. Its aesthetic ornamental value is high, which makes it one of the major urban afforestation tree species in South China. Studies have found that the content of fruit oil of *Idesia polycarpa* is high (30–45 %), and contains unsaturated fatty acids and compound vitamins for hyperlipidemia and cardiovascular disease prevention. The fruit oil of *Idesia polycarpa* has a bitter taste and can very easily be oxidized. For this reason, it cannot be developed as edible oil. *Idesia polycarpa* has important developmental value and has been included in the 10 kinds of biomass energy plants.

2.3.5 Hydrocarbon energy plants

Not only oil can be obtained naturally from plants, but sometimes these can be grown to obtain other valuable liquids that, without processing or with simple processing, can be used as fuel for internal combustion engines. Plants grown to obtain this liquid are called “oil plants” or “hydrocarbon energy plants”. Prof. Melvin Calvin is an American noble laureate and is devoted to finding this kind of plant. During a visit to Brazil in 1979, he found that one can produce “diesel” from a tree in the jungle. The researchers drilled a 5 cm hole in its 1 m trunk and then shut it. After six months, the stopper was removed. From the hole, around 15–20 L hydrocarbons were collected, which can be directly used in a diesel engine without further processing. In Brazil, several Euphorbiaceae have also been found. An example is *Euphorbia lathyris*, whose stems and leaves can be squeezed to produce a milky sap that can be used as the raw material to produce fuel and chemicals.

At present, scientists have found more than 40 kinds of “hydrocarbon energy plants” and more than 200 other energy plants. Experts are selecting varieties, optimizing their quality, and preparing to implement commercial production as soon as possible. Britain had set aside 1,590,000 acres of land for planting oil forest, while Brazil has planted eucalyptus forest having an area of around 2,000,000 mu (1 mu = 666.7 m^2). Furthermore, Switzerland plans to fulfill 50 % of its annual oil consumption with biodiesel in the next 10 years. The University of California in the United States has successfully bred new “hydrocarbon energy plants” by means of genetic engineering. The oil of the emulsion is similar to natural crude oil. By dehydration, it can be converted to gasoline and kerosene.

Thousands of “hydrocarbon energy plants” have already been found and new species are still being found. This marks a new field for humans to get liquid fuel from nature. Before crude oil runs out, sufficient “hydrocarbon energy plants” can be planted to fulfill energy needs.

2.3.5.1 Eucalyptus robusta Smith

The eucalyptus has a high content of flammable oil. An Australian eucalyptus has fuel content as high as 4.1 %, and coupled with high boiling point fuel, has a total fuel content of around 8.7 % of its fresh weight.

Due to characteristics such as low viscosity, high octane number, low ignition temperature, calorific value close to diesel, ability to undergo mixed combustion with gasoline, harmfulness of ethanol fuel, and less harmful components in exhaust gas, eucalyptus oil is an ideal substitute for diesel. Some of its characteristics are shown in Tab. 2.15.

Tab. 2.15: Characteristics of eucalyptus oil.

Item	Density (kg/m^3)	Ignition Temperature (°C)	Octane Value	Calorific Value (kJ/kg)	Dynamic Viscosity (30 °C) (Pa.s)
Characteristic Value	910–920	54	100.1–100.2	39,265–40,060	$2.07–10^{-2}$

Note: Dynamic viscosity = kinematic viscosity × liquid density

2.3.5.2 Euphorbia tirucalli L.

Euphorbia tirucalli belongs to Euphorbiaceae, or Euphorbia, and is also known as rubber Euphorbia, Euphorbia tirucalli, pencil tree, and milk bush. It consists of erect shrubs or small trees without thorns, which are 2–10 m tall. *Euphorbia tirucalli* has a long history of cultivation, and originated from Africa, America, Malaysia, India, Britain, France and many other tropical and subtropical regions. China's Yunnan, Hainan and other provinces cultivated it as an ornamental and medicinal plant. *Euphorbia tirucalli* contains a white emulsion, which is rich in hydrocarbon. The main component of the hydrocarbon is sterol (which can be mixed with other substances to make crude oil). The combustion value of *Euphorbia tirucalli* oil is high, whereas the dry wood's combustion value is 17.6 MJ/kg. Additionally, ash-free dry material of its combustion value is as high as 19.0 MJ/kg. So, *Euphorbia tirucalli* oil is a promising alternative to fossil oil. In Okinawa, Japan, 62,500 plants per hectare can produce about 7,570 liters of oil.

2.3.5.3 Sindora glabra

S. glabra is the only species of Caesalpiniaceae which is found in China. There are dozens of other species in this family. *S. glabra* is mainly found in tropical and subtropical areas, while in China it is scattered in the forest regions of Hainan Island. There is one kind of yellow-brown light oil in its trunk, which can be used for lighting, spice production and the treatment of skin diseases. The light oil is reserved to parts of the trunk. If drilled to "oil position", oil will flow out automatically. The oil can be used directly as engine fuel.

2.3.5.4 Simmondsia chinensis

S. chinensis is a kind of wild bush belonging to Simmondsia of Buxaceae, and is native to America, Israel, Mexico and other places in the tropical desert region. Resistance to drought and alkali are strong. The seeds of *S. chinensis* contain a kind of pale yellow liquid wax, which is around 50 % of the seed's weight. The artificial cultivation of *S. chinensis* can produce 10.50 kg of wax per hectare per year.

2.3.5.5 Pinus massoniana

P. massoniana is richly distributed in the South of China. After being used for refined rosin, turpentine, activated carbon, the waste can be used to obtain pine diesel by fractionation. The main component of pine diesel is the aromatic hydrocarbons with cyclic molecular structure. These aromatic hydrocarbons account for about 85.6 % of the pine diesel. Pure pine diesel does not solidify above −60 °C, while no black smoke is generated on burning. Its calorific value, flash point, and viscosity are similar to those of diesel. It has wonderful thermal stability and is not easily oxidized. However, high gum content should be removed before putting it into the refining process.

2.3.5.6 Copaifera reticulate

C. reticulate trees can be as high as 30 meters, while their diameter can reach 1 meter. They originated in the Amazon River Basin. By drilling a small hole in the trunk of *C. reticulate*, around 10–20 L gold yellow oily sap will outflow in two or three hours after drilling. The composition is almost the same as that of oil. Therefore, it can be used directly for most agricultural machinery, trucks, generators and trains as fuel.

2.3.5.7 Euphorbia lathyris

E. lathyris is a plant of *Euphorbiaceae,* and is about 1 to 2 meters high. It can produce an emulsion When the bark is cut with a knife, the liquid flows out. It can be used as a fuel just like gasoline. Artificially cultivated *E. lathyris* can produce 50 or more barrels of oil every hectare per day. According to the data from *E. lathyris* forests in southern California, America, annual liquid production per hectare is about 4,680 liters. Its heating capacity is 39,307 kJ/kg. In China, the cultivation of *E. lathyris* has a long history. Its seeds have about 50 % oil. There are several promising energy plants in *Euphorbiaceae*. Recently, some countries have been extensively searching for highly productive new varieties. With the application of genetic engineering technology, a breakthrough is expected in 5–8 years, after which these plants can be put into practical applications.

2.3.5.8 Oil-producing herbs

Widely distributed in United States, wild oil grass can be refined for about 1 ton of vegetable oil per hectare. Through hybridization breeding, oil production of artificially planted oil grass can be increased by around six times. In addition, the following two kinds of herbs also show good application prospects as oil plants: *Cryptostegia grandiflora* and *Corydalis davidii*. Both of these are highly oil productive.

In addition to land, large areas of water are also wonderful places for the development of bioenergy. Some kinds of marine algae have been proven to produce oily substances. In the USA, large-scale tests are ongoing at present. On the west coast of the United States, giant kelp has been found and developed. It grows fast, and after processing, oil-like substances can be obtained from it.

2.3.6 Wood energy forests

Wood energy forests have no fixed species and include almost all trees (Tab. 2.16). They are a source of renewable energy that can be obtained in a short time and have the main purpose of producing fuelwood and providing fuel. In practice, we usually generally choose hardwood trees to create and cultivate in coppices. The trees must be tolerant of drought and barren, have adaptability with powerful budding force, fast growth, strong regeneration ability, resistance to cutting and high value burning.

Wood energy forests are strategic forests for development in China, and are an important measure to alleviate the imbalance between supply and demand of fuelwood that causes rural energy shortages. The main traditional types of wood energy forest in China include oak energy forest, coniferous energy forest, poplar and willow energy forest, leguminous energy forest and shrub energy forest. Researchers in China have formed a set of advanced plantation technologies, which range from selection of species to cultivation and management and are considered to play a key role in the development of wood energy production, technological progress, and accumulation of experience. These factors will provide favorable conditions for the development of wood energy forests and the expansion of grass covered areas, protecting vegetation, reducing soil and water loss, reducing regions of sand and alkalization, and expanding the sources of biomass fuel.

The development of wood energy forests was included in the National Forest Project in the Sixth Five-Year Plan. Since the 7th Five-Year Plan, there have been 50 pilot projects to plant wood energy forests in the country. Furthermore, another 50 pilot projects have been included in the 8th Five-Year Plan, which increase the number to 100, distributed across 29 provinces. This way a lot of work has been done on the research and popularization, and macroeconomic management, which contributed to the steady growth of national forest planting. Between 1981 and 1995, the area of wood energy forest reached 4.948 million Hm^2, while the production of biomass from wood energy forests reached 20–25 million tons per year, which is equivalent to 11.43–14.29 million tons of standard coal.

In 1995, a new goal was put forward after it was decided to comprehensively promote the “energy forest” project in China. The goal was to build a scientifically laid out and rationally structured rural energy system (including increasing the forest energy base area and to 12 million Hm^2 in about 20 years). There are three phases to the whole project. The first phase was from 1996 to 2000, while the next was from 2001 to 2010. The third phase started from 2011. The first phase included the development of 3 million Hm^2 of wood energy forest during the 6th Five-Year Plan. The task of the second phase was to plant 6 million Hm^2 of wood energy forest, while that of third was to develop a further 3 million Hm^2 of wood energy forest. 100 counties were selected as key projects in the first phase. Their task is to create a wood energy forest having an area of 333,000 hm^2, with an average area of 667.7 hm^2 per county.

There is 304 million Hm^2 forest in China. The available energy consists of wood energy and the “three residues” of forestry and wood processing, which altogether constitute around 350,000,000 tons per year. This would be equivalent to 300 million tons of standard coal, provided the firewood, forestry and wood processing waste were effectively utilized. Biomass energy capacity will be more than 50 million tons of standard coal by 2015, however, China can utilize biomass resources for energy production, which are equivalent to 460 million tons of standard coal per year. However, China has been using around 22 million tons of standard coal at present and about 440 million tons can be used as energy sources. With the development of social, economic, ecological, agricultural and forestry-related factors, biomass energy utilization will further increase in China.

According to the principle of “ without sacrificing food, and without sacrificing the land for food” and the characteristics of land resources, agricultural and forestry production, nongrain raw materials have been combined with developments in modern agriculture, forestry and ecological management to establish a reasonable selection and scientific planting of energy forest in the bioenergy forest planting areas. According to the local conditions, both the marginal land and large-scale cultivation of inedible plants are explored and developed in order to establish a biomass raw material supply base.

According to “renewable energy development of 12th Five-Year Plan”, ecological development has been combined with planting wood energy forests in shrub dominated marginal land of the three-north region (including semi-desert and sandy regions). The wood energy forest base will reach 5.2 million Hm^2 by 2015, while energy crops and energy forests can meet raw materials demand equivalent to 1 million tons of biodiesel production per year, thus amounting to around 1.4 million tons of standard coal energy.

2.4 Oleaginous microalgae

Energy shortages have become a major issue in recent years. The global energy supply mainly depends upon fossil fuels. However, fossil fuels belong to the nonrenewable energies, which are not sustainable. Therefore, the development of environmentally-friendly renewable energy has become an important research field. Biodiesel is a new form of energy that has attracted widespread attention.

The raw materials for biodiesel production include waste oil, vegetable oil and microbial oil. Oleaginous microorganisms include bacteria, yeast, mold and microalgae. Microalgae are considered the raw material for biodiesel production with the highest production potential. They have a number of advantages, such as higher photosynthetic efficiency, faster growth rate, shorter growth cycle, smaller land area, no competitiveness with humans for land and grain use, and higher lipid content.

Tab. 2.16: Classification of main wood energy forests.

Number	Region	Main type of energy forest
1	Greater Khingan Range mountainous area	Mongolian oak
2	Xiao Xingan Ling mountain of Changbai Mountain	Mongolian oak, maple, locust
3	Songliao Plain	Willow, Liu Songjiang, Mongolian Liu, Lespedeza, sea buckthorn, Amorpha fruticosa
4	The eastern part of Inner Mongolia and the plateau of North Hebei Province	Mongolian oak, sea buckthorn, Lespedeza, Salix
5	Plain of Central Plains of North China	Willow, acacia, Amorpha fruticosa, Qi Liu
6	Taihang Mountain, Yanshan mountain	Robinia pseudoacacia, Quercus acutissima, Salix, Lespedeza, sea buckthorn, apricot and peach, Huang Lu
7	Southern Liaoning and Shandong hills	Robinia pseudoacacia, Quercus acutissima, Lespedeza, Salix, Amorpha fruticosa
8	Hilly Loess Plateau	Caragana, sea buckthorn, apricot, locust, Tamarix, Hu Zhizi
9	Mountainous region of Loess Plateau	Robinia pseudoacacia, Salix, Caragana, sea buckthorn, Liaodong oak, Prunus armeniaca
10	Central China Mountainous Region	Ma Sang Le oak, Quercus acutissima, Robinia pseudoacacia, bolt
11	Tongbai and Dabie Mountains, Mount Huangshan, the Shogunate,	Cork oak, Quercus acutissima, Robinia pseudoacacia, Lespedeza, Castanopsis, p. rigida, quassia wood
12	Middle-Lower Yangtze plains	Willow, alder, acacia, Amorpha fruticosa, Xuan Lingmu
13	Sichuan hills	Cork oak, Quercus acutissima, Robinia pseudoacacia, Schima superba, Qingfeng oak, alder, Eucalyptus camaldulensis, coriaria
14	Southern Mountain Region	Oak, Quercus variabilis, Schima superba, Robinia pseudoacacia, gallery eucalyptus, alder, Eucalyptus camaldulensis, Castanopsis fissa and others
15	Tropical area of Southern China	Eucalyptus exserta, Lei Lin, Eucalyptus urophylla, Schima superba, Taiwan Acacia, Acacia mangium, Acacia, Casuarina
16	Yunnan plateau region	Eucalyptus globulus, Eucalyptus maideni, Quercus variabilis, Schima superba, Cyclobalanopsis glaucoides, silver wattle
17	Sichuan, Yunnan, Tibet Alpine Canyon Area	Qinggang, sea buckthorn, Jatropha, DAL
18	Inner Mongolia Plateau hilly land	Caragana microphylla, Hippophae rhamnoides, tops, Salix matsudana, Robinia pseudoacacia, Tamarix chinensis and others
19	Northwest desert and semi-desert region	Caragana, Tamarix, Sha Guaizao, Haloxylon persicum, flower sticks, Russian olive
20	Irrigated agricultural oasis in Northwest China	Willow, acacia, Tamarix, Caragana, sea buckthorn, Guan Muliu

2.4.1 Strains of oleaginous microalgae

Oleaginous microalgae refer to microalgae in which oil accounts for more than 20 % of the dry cell weight under certain conditions. The Aquatic Species Program, initiated in 1978, achieved the collection, screening and identification of microalgae. Ultimately, around 300 strains of oil-rich microalgae were obtained. Most of these oleaginous microalgae belonged to *Chlorophyceae* and *Bacillariophyceae*. The oleaginous microalgae studied included *Bacillariophyceae*, *Rhodophyceae*, *Chrysophyceae*, *Phaeophyceae*, *Chlorophyceae*, *Dinophyceae*, *Cryptophyceae* and *Xanthophyceae*. In general, the lipid content is different in different kinds of microalgae. The lipid content of the same microalgae changes under different growth conditions. Furthermore, the lipid content of different strains belonging to the same species can vary significantly.

2.4.2 Isolation and selection of microalgae

Microalgae obtained from the natural environment need to be isolated and purified. Several common methods are employed to isolate microalgae including serial dilution method, water separation method, micropipette separation method, and solid medium separation method [20]. However, it takes a long time to isolate microalgae with traditional isolation methods. High-throughput automated isolation techniques such as fluorescence-activated cell sorting (FACS) [21] and flow cytometry cell sorting [22] have received extensive attention for large-scale isolation and screening. When comparing many algal species, it is difficult to accurately identify the strain based only upon the traditional taxonomy due to their morphological similarities. Presently, strain identification should be based on molecular methods, such as 18S rRNA sequence identification [23] or other molecular technology.

The isolation of microalgae is affected by the following major factors: growth conditions, capacity of metabolite production, and adaptability. The growth conditions could be reflected in several factors, such as maximum specific growth rate, maximum cell density, tolerance to adversity, and nutrient requirements for growth.

Screening for metabolite production needs to assay the cellular component (proteins, lipids and carbohydrates), and analyze the precursor metabolites (lipids and carbohydrates) for biofuel generation. Oil production should measure the content and composition of neutral and polar lipids, fatty acid profiles, and the content of polyunsaturated fatty acids in detail. Production of carbohydrates should assay the content and composition of monosaccharides, oligosaccharides and polysaccharides, and distinguish pentose and hexose. Meanwhile, there is a need to determine the high value-added products in microalgae to reduce production costs, since the production costs of microalgal biofuels are very high at present.

The adaptability of algae includes culture consistency, resilience and susceptibility to diseases and insect pests. For mass culture, it is very important to consider the adaptability of algae. Previous studies indicated that the performance of algae in outdoor mass cultures was always inferior to that in the laboratory [24]. Therefore, there is a need for conducting small-scale cultures to investigate the adaptability of algae before undertaking outdoor mass cultures.

Breeding methods of microalgae include selective breeding, cell fusion breeding, mutation breeding and genetic engineering breeding. The breeding method should be determined according to actual conditions, since all breeding methods have their own advantages and disadvantages. Selective breeding involves isolating excellent natural mutants from the germplasm community, and amplifying the propagation to breed new cultivated varieties.

Cell fusion breeding involves preparation of protoplasts and cell fusion. The vigorous heterotrophic microalgae *Tetraselmis* sp. and autotrophic *Pavlova viridis*, which are rich in EPA/DHA, were fused by chemical fusion methods [25]. The fused microalgae were screened based on the growth characteristics, appearance and color of the colonies, and fatty acid profiles. Compared with the parent *Tetraselmis* sp., the performance of the fused microalgae was excellent in every respect. However, the content of total lipids and EPA/DHA were less than that of the parent *Pavlova viridis*.

Mutation breeding is the process of exposing microalgae to chemicals or physical effects to generate mutants with desirable traits and hence breed new varieties. *Crypthecodium cohnii* ATCC30772 was exposed to different doses of ^{60}Co radiation in order to generate mutants with high DHA content [26]. The results indicated that the mutant with high yield of DHA was obtained under 2.4 kGy dose, while the DHA content of the mutant was 39.04 %. Compared with the control strain, the lipid yield, lipid content and DHA content in the mutant increased by 51.66 %, 66.37 % and 3.39 %, respectively.

Genetic engineering breeding manipulates an organism's genome using in vitro DNA recombinant technology. Firstly, the target gene was cloned into the vector. Secondly, this construct was inserted into a somatic cell of the host organism to replicate the expression in the recipient cell. Lastly, the cell with new genetic traits was obtained. This method has received extensive attention because of its purposeful design and short breeding time. During genetic engineering breeding, the factors needing to be considered include selective marker, transformation protocol and promoter.

A selectable marker is a marker gene that isolates transformants from the community. Generally, selectable markers are resistance genes. However, some selectable markers are auxotroph markers. Common selectable markers include resistance genes for neomycin, kanamycin, zeocin, chloramphenicol and nourseothricin in current microalgal genetic engineering.

The expression vectors need to be introduced into algal cells. Common transformation methods include microinjection (gene gun), electroporation, vortexing with glass beads and silicon carbide whiskers for microalgal genetic engineering. The gene gun method and electroporation method are the most widely used approaches. The gene gun method is effective for both nuclear and chloroplast transformation [27].

A promoter is a DNA sequence that drives the expression of the target gene. The expression level of the target gene is determined by both the promoter type and the recipient cell. The promoters used for microalgal genetic engineering include CaMV 35S, Ubi, UbiΩ, promoter of the nitrate reductase gene and the carbonic anhydrase gene. The promoter of the nitrate reductase gene is an inducible promoter, whose activity was regulated by nitrate and ammonium salts. This inducible promoter can accurately control the time and intensity of gene expression, which are important for actual production.

The genes *STA6*, *SSS2* and *AMYB1* of *Chlamydomonas reinhardtii* in the metabolic pathway of starch were regulated through artificial microRNA technology [28]. The results indicated that the gene silencing of *AMYB1* and *SSS2* could obviously improve the content of neutral lipid, however the effect on the content of neutral lipid by the gene silencing of *STA6* was not obvious. The *E. coli ACS* gene encoding acetyl-coenzyme A synthetase was introduced into *Schizochytrium* sp. TIO1101 by the electroporation method [29]. The results indicated that the overexpression of exogenous *ACS* gene could obviously reduce the concentration of acetic acid in the medium, improve the content of acetyl-coenzyme A in the cell, and significantly enhance the biomass and fatty acid content. Compared with the biomass of wild *Schizochytrium* sp. TIO1101 (14.9 g/L), the biomass of transformants ACS1 and ACS3 (18.54 g/L and 19.36 g/L, respectively) increased by 24.3 % and 29.9 %, which indicated that the overexpression of *E. coli ACS* could significantly enhance the biomass of *Schizochytrium* sp. TIO1101. Meanwhile, the fatty acid content of transgenetic *Schizochytrium* sp. TIO1101 (44.74 % and 46.76 %) was slightly higher than that of the wild type (41.96 %).

Along with the advancement of molecular biology techniques, a number of techniques can be used for microalgae genetic engineering. These techniques include RNA interference, directed evolution of proteins, protein tagging technologies, and omics approaches (such as genomics, transcriptomics, proteomics, metabolomics and lipidomics). These techniques can be useful for genetic modification of microalgae.

2.4.3 Culture of microalgae

Microalgae are diverse, but they are all autotrophic. A handful of microalgae are heterotrophic under special conditions. The photoautotrophic microalgae can be cultivated in closed photobioreactors or open ponds. The heterotrophic microalgae can be cultivated in fermentation tanks.

Microalgae grow and accumulate metabolite by photosynthesis in photoautotrophic cultivation. Costs for open pond raceway constructions are currently less than those for closed photobioreactors. The open ponds have been widely used for large-scale cultivation of microalgae. The advantages of open ponds include lower capital costs and simpler technical requirements. However, open ponds are subject to seasonal changes, illumination, temperature and humidity, which result in unstable cultivation conditions. The closed photobioreactors have various advantages, such as maintenance of monocultures, higher cultivation density, easily controlled cultivation conditions, simplicity of harvest and lesser loss of water [30]. However, the construction costs of closed photobioreactors are higher, which means that these can only be used for producing high value-added products. Closed photobioreactors used for producing microalgal biofuels have suffered from problems of higher costs. In order to tackle this, hybrid systems were suggested, which consisted of combinations of closed photobioreactors and open ponds. Firstly, closed photobioreactors would provide high cell density microalgal inoculum for open ponds. Secondly, the microalgal inoculum was cultivated for large-scale production in open ponds.

A handful of microalgae, such as *Chlorella* can be fed exogenous sugars to grow and accumulate metabolite under dark and special nutritional conditions. Heterotrophic cultivation can achieve high cell density and biomass, however the costs of appropriate raw materials, such as lignocellulosic sugars were higher. In addition, the utilization of sugars is limited and it is easier for microalgae to be contaminated when they are in large-scale production in heterotrophic cultivation.

2.4.4 Harvesting and oil extraction

The density of microalgae cells reaches its peak as the microalgae grow in the later phase of the exponential stage or the early phase of the stable stage. At this time, different methods can be selected for harvesting based on the characteristics of the microalgae. Common methods included centrifugation, superfiltration, dissolved air flotation and flocculation.

Centrifugation is a common method of separation. A disk centrifuge is widely used for centrifugation, and is easier to operate and can collect continuously. However, it has some disadvantages, such as high costs and high energy consumption, which limit its application for large-scale harvesting at present.

Superfiltration is a membrane separation technology. Substances of different molecular weight are separated when the treated liquid passes through the membrane under the driving force of pressure difference between the two sides of the membrane. Superfiltration can be used for concentrating the microalgae culture. However, the costs of this method are higher. Microalgae pass through larger pores, which results in the loss of some cells. However, decreasing pore size leads to the blockade of filter pores, and reduces the filtering rates.

The method of air flotation involves introducing microbubbles into water to form a three-phase mixture of water, gas and material to be removed. Then, microbubbles are promoted to attach to the flocs, and force flocs to float in order to separate them in water under the action of interfacial tension, buoyancy and static water pressure.

The harvesting efficiency of *Dunaliella* and *Chlorella* has been found to be 80 % to 94.3 % by air flotation method. The subsequent processing could be affected, since less flocculants and surfactants were added in air flotation method.

Flocculation is a process wherein aerosols come out of the suspension in the form of flocs to achieve the separation of solid and liquid materials. Flocculation is achieved by adding chemicals to destroy the electrostatic repulsion among particles or by bridging up the particles by linear high-molecular compounds to disrupt the system's stability, and realize the coalescence of particles. According to their composition, flocculants can be divided into inorganic flocculants and organic flocculants. A series of flocculants have been utilized for the collection of microalgae. Flocculation can be divided into chemical flocculation, bioflocculation and electroflocculation. The common chemical flocculants include alum, lime, cellulose, salts, polyacrylamide polymers, surfactants, chitosan and manmade fibers. Controlling the pH of suspension is very important in chemical flocculation. Microalgae are cocultured with other organisms which promote aggregation of cells in bioflocculation.

The lipids need to be extracted from harvested microalgae cells to prepare biodiesel. The lipid extraction methods include mechanical disruption, organic cosolvent mixtures, accelerated solvent extraction, supercritical fluid extraction, subcritical water extraction and enzyme extraction.

Mechanical disruption is a method for extracting lipids from plants using mechanical force. This method was only used for dry microalgal powder. Furthermore, this method has the advantages including simple craft and perferable adaptability has simple craft and preferable adaptability. However, drying microalgal cells increases energy consumption and costs of the extraction process.

The organic cosolvent mixtures method is a classical means for lipid extraction. The theoretical basis of the method is the similarity-intermiscibility theory. The common organic cosolvent mixtures include chloroform/methanol, hexane/ethanol, and hexane/isopropanol. This method has an obvious effect on the environment. Furthermore, this method is not suitable for wet microalgae. The lipids are extracted using organic solvent under high temperature and high pressure in the accelerated solvent extraction method. Accelerated solvent extraction can improve yields, reduce extraction time and remove co-extractable material. This method requires dry microalgal powder, which increases energy consumption and costs.

The solvating power of fluids significantly increases under supercritical conditions. In addition, the change in this solvating power is associated with the changes in temperature and pressure. This technology can isolate chemical materials (such as lipids) from solid and liquid feeds [31]. Generally, CO_2 was used as the supercritical liquid. In addition, other supercritical fluids used included ethane, water, methanol and n-butane [32]. Supercritical fluid extraction can be utilized in both batch and continuous modes. However, the disadvantage of this method is higher energy consumption. This method is mainly used for analytical tests. Furthermore, scaling up the process has not yet been achieved.

Subcritical water extraction is a technology for extracting lipids using liquid hot water [33]. This technology was initially applied to pretreatment of cellulose and hemicellulose. Subcritical water extraction has several advantages, such as shorter extraction time, higher extraction quality, environment-friendliness, and treatment of wet microalgae. However, when this method was used for large-scale design, it encountered operational difficulty, and incurred higher energy consumption.

Enzyme extraction is a burgeoning lipid extraction method, which degrades the cell wall using mechanical force and enzymes to promote the release of lipids. This method utilizes cellulase, hemicellulase, pectinase, amylase and protease for treatment of microalgae based on mechanical disruption. The method can handle wet microalgae and the lipid can be obtained after enzymolysis and centrifugation. This technology can simultaneously separate lipids and proteins, whose reaction is mild. In addition, this technology is environment-friendly, and suitable for wet microalgae.

2.4.5 Comprehensive utilization of microalgae

The cost of microalgal biodiesel production is high at present, which limits its commercial production. It is necessary to combine microalgal biodiesel production and high value-added product extraction to reduce production costs.

Potential high value-added products include carotenoid, flavone, polyunsaturated fatty acid, and active polysaccharide. In addition, production costs could be decreased through absorption of CO_2 emissions of power plants, treatment of agricultural and industrial wastewater, and using algal residue as bait in aquaculture.

With the depletion of fossil resources, renewable energy will play an increasingly important role in the energy system. As a kind of new energy, biodiesel has attracted extensive attention. Microalgae lipid is a very promising kind of material for biodiesel production. Technically, biodiesel production using microalgae is completely feasible. However, given the economic considerations, it is necessary to further reduce the production costs of microalgae biodiesel, and to combine it with the comprehensive utilization of microalgae to achieve the commercialization of microalgae biodiesel production.

2.5 Biomass resources forecast

2.5.1 Crop straw

In recent years, China’s grain production development and supply-demand situation have been in a good situation. However, China’s food security faces some new challenges with the advancement of industrialization and urbanization, including increased difficulty of steady increases in grain production, tight grain supply-demand situation in the long term, apparent trade deficit regarding agricultural imports and exports, gradually increased import demand of soybeans and cotton, and sharply rising major agricultural prices. These issues are becoming prominent problems for sustainable economic development. From the long-term development perspective, due to factors such as population, arable land, water resources, climate and energy, reversing these trends is hardly possible. China will face serious challenges in the areas of food and food security.

2.5.1.1 Consumer demand growth

It is predicted that the per capita food consumption of residents was 389 kg, while total demand reached 525 billion kilograms by 2010. It is expected that per capita food consumption will be 395 kg, while total demand will reach 572.5 billion kilograms in 2020.

The food consumption structure can be upgraded, which will reduce food consumption. It is predicted that the total use of grain for people was 258.5 billion kilograms, representing around 49 % of total consumption in 2010. It will reach 247.5 billion kilograms and 46 % in 2020. According to various reports, food grain demand will rise. Total use of food grain was 187 billion kilograms, accounting for 36 % of total consumption demand in 2010. It will reach 235.5 billion kilograms and 41 % in 2020. Nevertheless, demand for industrial uses of grain has a stable trend.

Edible vegetable oil consumption continues to increase. It is predicted that China’s per capita consumption was 17.8 kilograms of edible vegetable oil, while total consumer demand was 324.1 million tons in 2010. It is expected that per capita consumption will increase to 20 kg, while total consumer demand will reach 29 million tons in 2020.

2.5.1.2 Decrease in arable area

Due to adjustments to agricultural structure, ecological restoration, natural disasters and nonagricultural development, arable land resources have declined. According to a survey, the country had 1.826 billion mu of arable land in 2007, which was 125 million hectares less than that in 1996. Additionally, average annual reduction in land was 11 million acres. Currently, the national per capita arable land is 1.38 acres, which accounts for 40 % of the world average level. Owing to many factors, such as drought, incline, barren, flooding and salinity, relatively poor quality land (which is low yielding) accounts for about two-thirds of total arable land. Land desertification, soil degradation, and “three wastes” pollution have become serious problems. With the acceleration of industrialization and urbanization, arable land will continue to decrease in area. The growing scarcity of arable land reserves can result in a limitation to the future expansion space for grain acreage.

2.5.1.3 Water shortages

At present, China's per capita water resources are about 2,200 cubic meters, which represents 28 % of the world average level. The water use for annual agricultural production is more than 20 billion cubic meters, whereas uneven distribution of water resources and imbalance between the land and water resources are two of the other problems related to water. More serious water shortages are occurring in the North of China. Northeast and Huang-Huai regions account for 53 % of national food production, and their commercial production accounts for 66 % of the country's total production. However, Sanjiang Plain and many other parts of the North China Plain overexploit groundwater for irrigation. Sanjiang Plain groundwater level has declined by 2–3 meters over the past 10 years. Additionally, a part of the region has faced a water-level drop of around 3–5 meters. The North China Plain has formed more than 90,000 square kilometers of the world's largest mining groundwater funnel area (including shallow and deep groundwater). In addition, in recent years, serious natural disasters, many adverse weather factors, continuous below average precipitation in the northern areas, more severe drought trends and global warming could pose a greater threat to long-term food security of China.

2.5.1.4 Low profit for grain

In recent years, due to more expensive agricultural production materials, such as chemical fertilizers, pesticides and diesel oil for agriculture and rising labor costs, agricultural profit has declined. With the rapid development of China's industrialization and urbanization, rural migrant workers have increased in number. It is worth noting that more than half of the migrant workers in major grain producing areas are young workers. Therefore, a structural shortage of agricultural labor has occurred, whereas food production in some areas has shown a "sideline" trend. Compared with the salary of migrant workers, agricultural profit is significantly lower. The difficulty of protecting farmers' enthusiasm for growing grain and maintaining stable development has increased significantly.

2.5.1.5 Tight global food supply-demand situation

The growth of global food production is difficult to meet the needs of consumer demand growth. According to estimations, the global cereal demand has increased to 220 billion kg in the past 10 years. The growth represents an average annual growth of 1.1 %. However, production has increased up to 100 billion kg with an average annual growth of 0.5 %. Currently, the ratio of world cereal stocks to consumption was close to its lowest level in the past three decades. Since 2006, the international food market prices rose sharply, and the prices of wheat, corn, rice, soybeans and soybean oil have hit record levels. Global population growth, less arable land, water constraints and climate anomalies may cause a tight supply-demand situation in the long term.

Especially against the background of energy shortages and high oil prices, the global trend to turn food into biofuels will accelerate, whereas the conflict between energy and food will become more severe, resulting in further tensions in global food supply and demand. Topping up domestic individual varieties of grain and oil by purchasing these on the international market has become more difficult.

The domestic situation is a tight balance between supply and demand for food, so there is little room for developing corn-based fuel ethanol. People have reason to fear that this grain-based ethanol production model could pose a threat to China's food security. Therefore, the basis of biofuel development must insist on the principle of "taking public food security as a priority".

According to the national food security and long-term planning framework (2008–2020), grain production capacity was stable at 500 billion kilograms in 2010, and is expected to reach more than 540 billion kilograms in 2020.

Edible vegetable oil is an important necessity for urban and rural residents. In recent years, oil production profits have dropped and consequently the enthusiasm of farmers has decreased. The national oil acreage has continued to decline, whereas the gap between domestic edible oil production and demand has increased. In order to fully mobilize the enthusiasm of the farmers and promote rapid development of oil production, the country made it a priority to expand production of soybean, rapeseed and other major oil crops without jeopardizing the production of subsistence crops, making sure to stabilize the edible vegetable oil self-sufficiency rate. The northeast continued to build a high-oil soybean production base, while the Yangtze River continued to construct a "double low" (low erucic acid, low glucosinolate) rapeseed production base. The government encouraged developing rapeseed production in fallow fields in the southern region, strengthening the crops' irrigation infrastructure in the main oil producing areas, accelerating the breeding of fine varieties of oil crops, promoting new varieties of high yield and high oil, and focusing on improving the yield and quality of soybean oil crops, such as rapeseed and peanuts. Oil yields improved by 6 % from 2006 to 2010 and average oil production increased by 2 %.

Cotton is an important material for people's livelihood, and plays an important role in national economic development. China is the world's largest cotton producer and consumer, and is also the largest producer and exporter of textiles and garments. In 2005, the national cotton acreage was 5.06 million hectares, whereas the total yield was 5.71 million tons. Future global fiber consumption will continue to grow. It is expected that by 2020 the annual consumption of cotton will reach 32 million tons. The rapid development of China's textile and garment industry can promote domestic demand for cotton. Currently, the state has opted to optimize the structure and quality of cotton, develop the regionalization and specialization of production, and achieve quality standardization, thereby promoting cotton production. The cotton regional distribution plan (2008–2015) proposed the following goals: by 2015, cotton-growing area will stabilize at about 85 million acres; lint yield will reach 95 kg/mu; total lint production will reach about 8.1 million tons; efforts would be made to meet more than 50 % of domestic demand.

Based on National Agriculture and Rural Economy's 12th Five-Year Plan (2015), gross agricultural mechanical power should reach 10 million kilowatts in 2015, whereas the quantity of primary agricultural equipment will steadily grow. The infrastructure for the equipment should become more rational and well-coordinated. The mechanization level with respect to staple crops, such as sugar, cotton and oil, should significantly increase; whereas utilization should reach more than 60 % (the national crop mechanization level should reach 52.3 %). China's agricultural mechanization will enter the advanced stage, whereas utilization will reach about 70 % in 2020.

2.5.2 Forestry residues

2.5.2.1 Felling, logging residues bucking lave

Forest resources are an important natural and strategic resource. The demand for products derived from forest materials must be studied to ensure social and economic development, development of modern forestry, and ecological security. The resource is an important carrier of the construction of ecological civilization. To strengthen the protection and manage forest resources, a forest cutting quota system in accordance with the law has been introduced. Additionally, strict controls on the consumption of forest resources have been introduced in China. Additionally, other factors, such as improving the efficiency of utilization of forest resources, establishing and implementing a forest management plan for the system of the forestry industry the forestry ecological system, constructing a perfect development and prosperity plan for the ecological and cultural systems, and dealing with global climate change have important and far-reaching significance in promoting economic and socially sustainable development.

According to national 15th Five-Year Plan, the annual forest cutting quota is estimated to be 223.1032 million cubic meters. The national 11th Five-Year Plan put the forest cutting quota at 248.155 million cubic meters, while the 10th Five-Year Plan had 25.053 cubic meters more forest cutting quota than the 11th. According to the 12th Five-Year Plan, the annual forest cutting quota (not including bamboo cutting quota) is 27.1054 cubic meters, while compared to 11th Five-Year Plan, it shows an increase of 22.899 cubic meters, which equates to an increase of 9.3 %.

If calculated in accordance with the five-year average annual growth rate of 10 %, China's felling and logging residues available resources or dry weight will reach 11.962 million tons in 2015, 13.158 million tons in 2020, 15.921 million tons in 2030, and 23.311 million tons in 2050.

2.5.2.2 Forestry processing residues

If calculated in accordance with the five-year average annual growth rate of 10 %, wood processing residue resources in China or dry weight will reach 6.1 million tons in 2015, 6.71 million tons in 2020, 8.1191 million tons in 2030, and 11.0128 million tons in 2050.

2.5.3 Wood energy

According to the objective proposed by the national forestry biomass development plan (2011–2020), the area of wood energy forests will reach 5.24 million hectares in 2015, of which around 4 million hectares is unused, providing about 24 million tons of biomass feedstock. These materials can substitute around 12 million tons of standard coal.

The area of wood energy forest will reach 9.43 million hectares in 2020, of which around 7.5 million hectares is unused, providing 45 million tons of biomass feedstock per year. These materials can substitute around 22 million tons of standard coal.

A key area is in the “Three North” regions (Northwest, North and Western Northeast region), combining ecological development, and planting 24 wood energy forest bases. The total area for wood energy base is 9.43 million hectares, of which 4.59 million hectares will consist of new forests.

China has 1.7 million hectares of firewood forest which are distributed in Yunnan, Liaoning, Shaanxi, Hubei, Sichuan and fifteen other provinces. The area accounts for 97 % of the national firewood forest area. The total growth in existing shrubbery is more than 53 million hectares per year, which can provide approximately 100 million tons of wood fuel. The country has about 70 million hectares of young forest, which can provide around 20–40 million tons of raw materials per year through normal thinning. In addition, forest pruning, and pruning urban greening can provide more raw materials. The potential of existing forest resources can be used to obtain about 350 million tons of wood energy, which is equivalent to 200 million tons of standard coal.

Wood energy forests can provide 100 million tons of biomass feedstock per year in 2030, which will be equivalent to 50 million tons of standard coal in 2030. Wood energy forests can provide 200 million tons of biomass feedstock per year in 2050, which will be equivalent to 100 million tons of standard coal.

2.5.4 Nonfood energy crops

Since the shortage of arable land in China causes a tight balance between food supply and demand, corn-based fuel ethanol development space has become extremely limited, although the diversification of raw materials is imperative [34].

Sugarcane is one of the best raw materials for fuel ethanol production. However, China's sugarcane area is very limited. With the rapid economic growth and rapid development of the food processing industry, a substantial increase in domestic sugar consumption has caused a shortage in supply. Additionally, the profit for producing sugar from cane is higher than that for alcohol. This factor hinders the further development of raw materials to produce fuel ethanol. Under the conditions of stabilizing sugar demand, one can achieve sugar-alcohol production as an effective measure.

Sweet sorghum, cassava and sweet potatoes, and other nonfood energy crops can be used as raw materials for producing fuel ethanol, and have the advantages of high yield and low cost of production. This method is the most recent viable direction [35]. The method consists of planting sweet sorghum and cassava intercropping. The seeds make use of the features of high-yielding, high starch content and strong resistance, combined with the scientific management measures to improve yields.

Of course, agricultural production is obviously regional. Different crops have their own specific growing conditions, particularly light, heat, water, soil and other environmental conditions. Agricultural production must be based on land and natural resources.

The vast territory of China has many agro-ecological zones characterized by climate, altitude, terrain, soils and varieties of crops that can be grown in a range of farming systems. Dense population and limited land in China determine the intensity and complexity of the farm systems, and hence, lead to diverse crop species and uneven distribution of straw/stubble resources. Generally, China is divided into eight major regions, which do not include Hong Kong, Macao and Taiwan. The division has been undertaken according to the planning based on farming systems [25] and the level of economic development. The crops grown in each of the regions are listed in Tab. 2.17.

Tab. 2.17: Crop planning based on farming regions in China [36].

Divisions	**Regions**
Northeast	Sweet sorghum
North China	Sweet potato, sweet sorghum, Jerusalem artichoke
Loess Plateau Area	Sweet sorghum
Lower Yangtze Valley	Sweet potato, Jerusalem artichoke
Southwest	Sweet potato
South China	Sugarcane, cassava
Inner-Mongolia-Xinjiang Region	Sweet sorghum, sugar beet
Qinghai Tibet	Not developed temporarily

Note: Jerusalem artichoke is only planted in coastal areas.

Marshland and reed beds are one of the most important wetland resources, and accommodate abundant species of living creatures. These are also an essential habitat for animals. Even though there is potential for arable land use, marshland and reed beds are not considered as arable lands because of the need for ecological protection. Therefore, marshland and reed bed areas are excluded when calculating the area of arable land reserves.

Step-by-step measures have been planned to strategically develop energy crops in arable land reserves taking into consideration ecological protection, dynamic balance of arable land, urbanization, reclamation ratio, adaptability and yield increase of energy crops. According to an estimate, approximately 10 % and 50 % of arable land reserves will be made accessible in 2015 and 2020, respectively, which will help achieve capacities of fuel ethanol production of 2.61 million tons in 2015, 14.25 million tons in 2030, respectively.

Most of these arable land reserves are located in Northwest China [37]. Development and utilization of these reserves is costly due to the constraints of heat, water resources, wind, extreme cold, and sand and saline conditions. The area of arable land reserves is based on the current level of technology, which makes these financially feasible to be developed. Land which is not currently financially feasible to develop may become financially feasible to develop in the future due to the development of new technologies. It is expected that transportation and fuel costs will increase to a point where the development of these lands will become viable. Thus, there remains some flexibility for their utilization.

2.5.5 Oil-bearing energy forest

According to the “National Forestry Biomass Energy Development Plan” (2011–2020), the area of oil-bearing energy forest will reach 2,120,000 hectares, whereas currently around 500,000 hectares is under use. These are equivalent to about 700,000 tons of standard coal.

By 2020, the area of oil energy forest will reach 4,220,000 hectares, and if this is realized, then it would be equivalent to 5,800,000 tons of standard coal.

The transformation of palm oil needs to be developed, using soapberry, Jatropha curcas, light skin tree, Wen Guanguo, Pistacia species. Further, species like Yama Kiriko, Litseacubeba, Rhuschinensis, Ou Li, Chinese tallow tree, Tokyo jasmine and the other kinds of trees can also be developed. The planning and development of oil-bearing energy forest aims to have around 4,220,000 hectares of oil-bearing energy forest by 2020, of which the new afforestation area will be 3,970,000 hectares. The existing Lin Gaipei is around 250,000 hectares.

The realization of these projects would mean that oil-bearing energy forest will be equivalent to about 10,000,000 tons of standard coal. Additionally, by 2050, oil energy forest will be equivalent to about 20,000,000 tons of standard coal.

2.5.6 Waste edible oils and fats

Since the 1990s, with the continuous improvement of living standards, China’s total edible oil consumption and per capita consumption of edible oil have shown a growing trend. Edible oil consumption in China in 1997 was 10,470,000 tons, whereas consumption in 2011 increased to 25,150,000 tons. This number has doubled in the past ten years, with an average annual growth rate of 1,533,000 tons. In the past five years, annual edible oil consumption has increased by around 10 %. Current annual consumption per person is close to 20 kg/year, whereas the global average is 22–23 kg/year per person. With consumption gradually reaching the global average, edible oil’s growth rate is bound to be difficult to sustain.

The values in 2015, 2020, 2030 and 2050 can be estimated. China’s edible oil consumption will be 27.89 million tons in 2015, 28.49 million tons in 2020, 28.83 million tons in 2030, and 27.66 million tons in 2050. Recyclable waste edible oil will be 2.685 million tons in 2015, 2.992 million tons in 2020, 3.532 million tons in 2030, and 3.872 million tons in 2050.

2.5.7 Industrial organic wastewater

According to the 12th Five-Year Plan, China’s GDP is expected to grow to around US $ 4,000 billion in 2020, which is more than twice the value of 2010. With the development of industrial enterprises to carry out energy savings, emission reductions and undertake cleaner production, wastewater and emissions of other pollutants are expected to increase. It is expected that industrial wastewater and waste residue emissions will increase by 50 % of the value from 2012. However, organic wastewater discharged by industrial enterprises can be transformed into biogas, which will have a volume of 56.655 billion cubic meters. Similarly, organic waste residue can be transformed into biogas having a volume of 4.637 billion cubic meters.

2.5.8 Livestock and poultry manure

With the increase in population and the acceleration of urbanization, meat consumption will continue to increase, however the meat consumption rate shows a declining trend. It is expected that Chinese families will be consuming 62.96 kg/year of meat in 2020, 68.62 kg/year in 2030, and 68.62 kg/year in 2050. The per capita egg consumption for 2020, 2030 and 2050 are estimated to be 19.85, 21.13, 21.13 kg/year. Based upon these numbers, it is estimated that China’s livestock and poultry manure can be converted to methane, which would be equivalent to 1,548 billion cubic meters (in 2020), 1,815 billion cubic meters (in 2030), and 166.9 billion cubic meters (in 2050).

Jinsong Zhou*, Xinshu Zhuang, Hanping Chen, Chunjiang Yu,
Jie Xu, and Xuesong Tan

3 Biomass direct combustion technology

Since the invention of fire, humans have used biomass as fuel for combustion. Direct combustion is the most primitive and most direct way of biomass energy conversion and utilization. With social development and advances in technologies, biomass combustion facilities and methods are constantly improving. With increased public awareness that biomass belongs to clean renewable energy sources and that effective reduction of greenhouse gas emission can be achieved via large-scale use of biomass, the adoption of advanced combustion technologies and efficient large-scale use of biomass have received wide attention for nearly two decades, and a booming new industry has formed across the globe. This chapter mainly introduces the basics of biomass combustion and utilization, the use of traditional biomass stoves, and modern technologies of large-scale industrial applications.

3.1 Principle of biomass combustion

Biomass consists of various types of substances produced via photosynthesis either by direct or indirect use of air, water, soil, and other resources. Organic solid fuels are widely available. In contrast to coal and other fossil fuels, biomass is subject to the influence of resources and the external environment since it has not undergone extensive diagenesis and metamorphism; therefore, it will exhibit some special combustion performance. To understand the special nature of biomass fuels and the process of biomass combustion, characteristics of combustion organization and the emission of

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***Corresponding Author: Jinsong Zhou:** State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027
Xinshu Zhuang: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Hanping Chen: State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China
Chunjiang Yu: State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027
Jie Xu: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Xuesong Tan: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China

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pollutants are of important significance for biomass combustion and utilization at different occasions.

3.1.1 Biomass combustion process

3.1.1.1 Characteristics of biomass fuels

Generally, biomass (in a narrow sense) mainly refers to lignocellulosic materials such as straws and trees as opposed to foods and fruits in the agricultural and forestry production process. For example, leftovers of agricultural product processing, agricultural and forestry wastes, feces of livestock and poultry in the livestock production process, and wastes. Since the variety, sources and way of formation vary, different biomasses will have great variance in their physical and chemical characteristics, mainly reflected in appearance, shape, structure, texture, moisture, and content of impurities. From a fuel perspective, the differences in the characteristics of biomass exert a significant influence on the whole process from fuel collection, transport, drying, and pretreatment up to combustion. Therefore, it is critical to understand the relevant characteristics of fuels for the design of an improved combustion process. In terms of solid fuel, industrial analysis and elemental analysis are important indices to describe combustion characteristics. Using lignocellulosic biomass as an example, relevant analysis data and other physical and chemical properties are shown in Tab. 3.1. The data of typical coals are used for comparison.

Tab. 3.1: Physical and chemical properties of biomass fuels and coals [38].

Item	Biomass	Coal
Density (kg/m^3)	150–500	~ 1300
Size (mm)	~3	~100
C (mass percentage, by dry weight)	42–54	65–85
O (mass percentage, by dry weight)	35–45	2–15
H (mass percentage, by dry weight)	5–6	3–5
S (mass percentage, by dry weight)	Max 0.5	0.5–7.5
SiO_2 (mass percentage, by dry weight)	23–49	40–60
K_2O (mass percentage, by dry weight)	4–48	2–6
Al_2O_3 (mass percentage, by dry weight)	2.4–9.5	15–25
Fe_2O_3 (mass percentage, by dry weight)	1.5–8.5	8–18
Ash (mass percentage, by dry weight)	4–14	65–70
Volatiles (mass percentage, by dry weight)	65–70	7–38
Ignition temperature (K)	418–426	490–595
Peak temperature (K)	560–575	–
Fragility	Low	High
Calorific value in dried basis (MJ/kg)	14–21	23–28

As shown in Tab. 3.1, the main characteristics of biomass fuels are as follows:

(1) Low density and low calorific value. Biomass is loose in texture. Its calorific value in dried basis is only 14–21 MJ/kg. Its density and thermal values are significantly lower than those of coal, causing a significantly lower energy density per unit volume than coal. This factor will significantly influence the design of transport cost, fuel storage, silos, and feeding in the biomass combustion and utilization process.

(2) Less carbon content and high oxygen content. Lignocellulosic biomass composition determines the most remarkable feature of high oxygen content for fuel element composition. The main characteristics in the conversion process from biomass to coal are the removal of oxygen and hydrogen. The low carbon content of biomass would cause a lower calorific value than that of coal, while the oxygen in the biomass exists in a combined form, which is an invalid element of fuel.

(3) Low sulfur and ash contents. The sulfur content of biomass is lower than that of coal by an order of magnitude; however, the desulfuration degree of the combustion process is usually higher than that of coal. Therefore, the emission concentration of sulfur oxides when burning is far below than that of coal. The ash content of biomass is low, which is conducive to burning semi-coke and controlling dust emissions.

(4) High volatile content, easy to ignite, strong combustion activity. The volatile content of biomass on a dry basis is typically above 65 %, which is far higher than that of coal, and as such, very conducive to ignition of biomass fuels. Its semi-coke pore is developed, and reaction activity is significantly higher compared to coal. It can burn quickly after ignition, with a low burnout temperature.

(5) High content of alkali metal in the ash. Most biomass contains potassium, chloride, and other inorganic impurities. This portion of alkali metals and related substances easily causes slagging and deposition corrosion under combustion temperature conditions, which should be handled very carefully.

The above biomass characteristics decide the particularity of the combustion process. The parameters that require specific consideration are: fuel collection, pretreatment, feeding, selection of combustion parameters, design of combustion equipment, pollutants discharge control, ash characteristics, and handling.

3.1.1.2 Typical combustion process

For biomass fuels, a process of vigorous oxidation reaction occurs between the organic substances that comprise the biomass and the oxygen in the air, and releases heat energy. Energy conversion is a process where chemical energy is converted to heat energy. Biomass burning is essentially a heterogeneous reaction of the gas-solid phase. However, due to natural complexity, its combustion process contains the drying, pyrolysis, and combustion of volatiles and semi-coke; therefore, it couples a number of processes of chemical reactions: heat transfer, mass transfer, and fluid flow. At a macrolevel, and considering the balance estimate of relevant substances for biomass burning, this can be calculated from the perspective of elements balance. Generally, complete combustion of biomass in air can follow the Eq. (3.1):

$$\begin{aligned}C_{x1}H_{x2}O_{x3}N_{x4}S_{x5} + n_1H_2O + n_2(O_2 + 3.76\,N_2)\\ = n_3CO_2 + n_4H_2O + n_5N_2 + n_6NO_x + +n_7SO_2 + +\text{Energy}\end{aligned} \tag{3.1}$$

The second term on the left of the equation represents water entering together with fuel and air in the combustion process. The water evaporates from liquid to join the smoke in the combustion process. Although it is not directly involved in combustion, it has a high latent heat of vaporization; thus reducing the content which is conducive to combustion. The third term of the equation represents air, consisting of 21 % oxygen and 79 % nitrogen. The composition of the combustion products is complex. The equation provides only the macrocomponents and the major gas phase pollutants. The smoke in the actual combustion process typically contains O_2 introduced by excessive air, the incomplete combustion of CO, HC, and alkali metal chlorides, sulfates, carbonates, silicates, and other complex ash components.

Fig. 3.1 is an overview scheme of the biomass combustion process. The combustion process can be divided into the following stages: preheating and drying (evaporation of water) – pyrolysis (devolatilization) – gas phase combustion – coke (fixed carbon) combustion – and flue gas. The heat energy of high temperature flue gas generated in the combustion can be used for heating, steam, power generation, or other forms of energy demands.

In the actual combustion process, the above stages continuously occur with varying degrees of overlap. In addition, since biomass volatiles have a large share, volatile combustion is very important. When volatile gas is ignited, it will continue to flow upwards; and its flow and reaction occur simultaneously to form diffusion flames. In these diffusion flames, air mixes with the combustible gas in different mixing ratios, thus flames of different temperatures are forming. For an appropriate ratio, the speed of burning is fast, and the temperature is high. For an inappropriate ratio, the speed of burning is slow, and the temperature is low. Therefore, during the process of biomass combustion, feeding an appropriate ratio of combustion air to appropriate places, at the appropriate time, and in an appropriate form is very important. Too much or too little air or a poor mixture will negatively influence combustion and even cause combustion extinction.

According to the above, the biomass combustion process can roughly be divided into two stages: combustion of volatiles and coke combustion. In general, the former accounts for about 10 % of the combustion time and the latter accounts for 90 % of combustion time.

According to the above analysis, the direct combustion of biomass fuel is characterized by fast volatile escape, low ash content, light semi-coke texture, and high

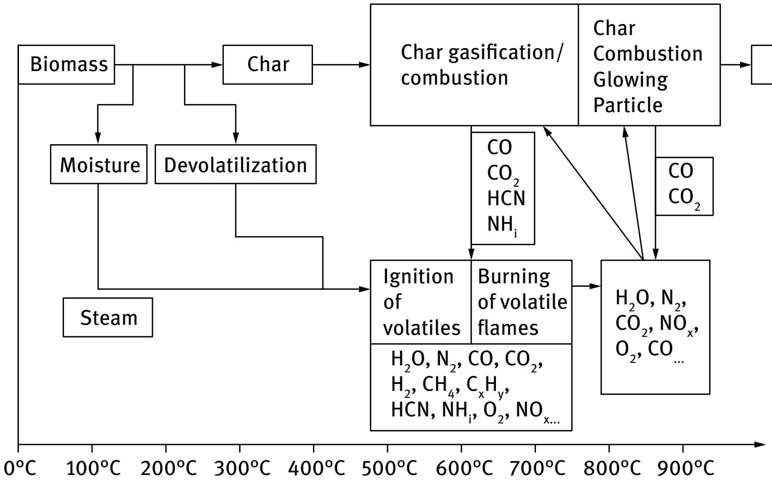


Fig. 3.1: The combustion process of biomass fuel [39].

combustion activity, which is significantly different from coal. These factors should be well designed to organize combustion.

3.1.1.3 Characteristics of pyrolysis

Pyrolysis is defined as thermal degradation under the condition of oxygen isolation. Pyrolysis itself is an important means of biomass thermochemical conversion, either directly or indirectly converting biomass into high-grade fuel or valuable chemical raw materials. However, pyrolysis is also an important stage process in biomass combustion and gasification, which has a significant effect on the combustion and gasification processes of biomass. The products of such pyrolysis are gaseous volatiles, condensable volatile matters (tar), and solid phase cokes. Among the components of biomass, the pyrolysis products of cellulose and hemicellulose are mainly volatile components. Lignin pyrolysis can produce coke. For oxygen-rich biomass fuels, pyrolysis gaseous products are mainly CO and CO_2. The type of biomasses, pyrolysis temperature, pressure, heating rate, and reaction time, will significantly affect the quantity and characteristics of pyrolysis products.

Fig. 3.2 shows thermogravimetric analysis experiments (TGA and DTG) under an inert atmosphere for four types of timber. With temperature change, the change in weight of the four types of timber and the accompanying change in pyrolysis rate with temperature resulted in a similar trend. When temperatures rose, the samples started to dry. Sample pyrolysis began at 473 K and the pyrolysis rate accelerated with rising temperature. The shoulder peak in the low-temperature zone in the DTG graph represents the decomposition of hemicelluloses, and the peak of the wave in the high-temperature zone represents the decomposition of celluloses. Hardwoods (such

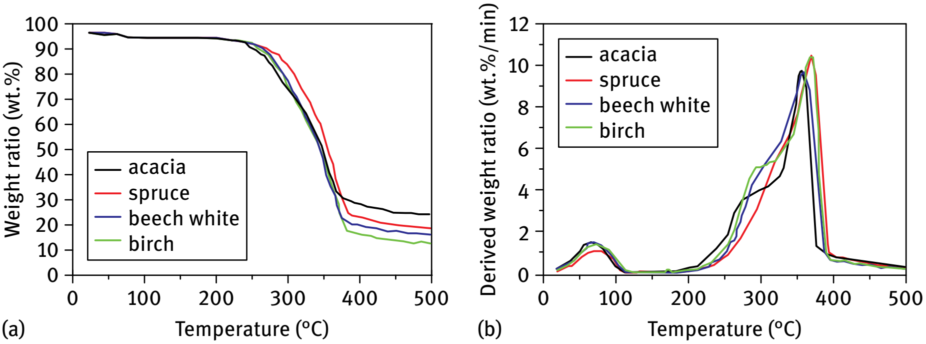


Fig. 3.2: Thermogravimetric analysis of a 5 mg timber sample when heating rate was 10 °C/min.

as birch, American beech, and locust) contain more hemicellulose than softwood (spruce), thus the shoulder peak of hemicellulose was more pronounced. When the temperature reached 673 K, most volatile matters were released and the pyrolysis rate rapidly decreased. The low-speed pyrolysis phenomenon still existed at temperatures of 673–773 K, which may be caused by the decomposition of lignin.

3.1.1.4 Combustion characteristics of coke

Coke combustion generally occurs in the late stage of pyrolysis of volatiles. During the pyrolysis process, the released volatile gas is mixed with air. When temperature and concentration conditions are met, the volatiles and the multipore solid phase substances firstly burn to release energy, which can promote the combustion of semi-coke. During coke combustion, the heat energy released on the surface will be gradually accumulated and diffused to inner biomass particles through conduction and radiation, thus releasing inner volatiles, which continue to mix with oxygen. At this time, semi-coke is surrounded by volatiles and oxygen cannot easily access the coke's surface, making it difficult to burn. Semi-coke gasification at the combustion of volatiles is a dominant process. When the released volatiles are reduced, external oxygen will be diffused to the surface of coke, to increase the proportion of coke combustion. With the combustion of coke, the residual ash may cover the remaining semi-coke, thus hindering further combustion. The residual carbon in the ash is typically produced at this stage.

Coke combustion is the reaction between carbon and oxygen in air. The following two types of reactions may occur depending on the oxygen content at the hot coke surface [2]:

$$C + O_2 == CO_2 + 408.86\,\text{kJ} \tag{3.2}$$

$$2C + O_2 == 2CO + 246\,\text{kJ} \tag{3.3}$$

When the reaction temperature is high (exceeding 700 °C) and the generated CO diffuses outside, it will continue to react with oxygen in air to generate CO_2, namely:

$$2CO + O_2 == 2CO_2 + 570.87\,\text{kJ} \tag{3.4}$$

When there is no oxygen available for the coke during the combustion process, a gasification reaction may occur with the surrounding water vapor and CO_2 at high temperature, namely:

$$C + 2H_2O == CO_2 + 2H_2 \tag{3.5}$$

$$C + H_2O == CO + H_2 \tag{3.6}$$

$$C + 2H_2 == CH_4 \tag{3.7}$$

$$C + CO_2 == 2CO \tag{3.8}$$

Coke and elemental carbon (such as graphite) generated from biomass fuel pyrolysis greatly differ from the coke generated from coal pyrolysis. With developed pores and large reaction surface area, active inorganic substances, such as potassium in the biomass, have a catalytic effect on the semi-coke combustion and gasification processes. The reaction activity of biomass semi-coke is strong, thus having the ability to complete the combustion or gasification process in rapid response speed and at low temperature.

3.1.2 Characteristics of biomass combustion

3.1.2.1 Effect of moisture

Fuel type and storage method determine that different types of biomass fuels have varying moisture contents. The increased moisture content will produce adverse effects on biomass combustion:

(1) increasing the energy required for combustion;
(2) lowering the calorific value, while reducing the possible maximum combustion temperature (adiabatic combustion temperature);
(3) increasing the water vapor content in the flue gas, thus increasing the heat loss of the combustion apparatus and reducing the thermal efficiency of the combustion apparatus;
(4) extending the residence time of the fuels, requiring enlarged combustion space.

Fig. 3.3 presents the relationship between adiabatic combustion temperature, moisture content and excess air coefficient. The fuel components include C (50 %), H (6 %), and O (44 %) (calculated on dry basis).

For high moisture biomass fuel combustion, it is particularly necessary to ensure smooth ignition of fuels, maintaining the required temperature in the combustion region. To compensate for heat absorption during the water evaporation process after

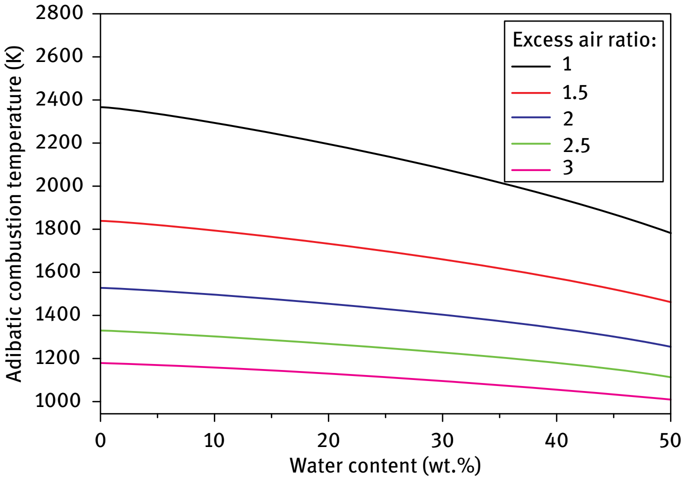


Fig. 3.3: Relationship between adiabatic combustion temperature, moisture content (wet basis), and excess air coefficient [40].

high moisture biomass fuels enter the hearth, it is necessary to consider the reduction of heat absorption area. This reduces or cancels the heat transfer area in part and ensures fire heat supply via utilization of a furnace arch, laying castables, or placing heat retainers. In addition, enhancing the temperature of primary and secondary air is also an effective response to excessive moisture in fuels.

3.1.2.2 Burnout of volatiles

Biomass fuel has a high content of volatiles, which begin to release at temperatures above 200 °C in the process of pyrolysis and becomes very active at 325 °C. When the temperature is 350 °C, most of the volatiles have been released. Since the volatiles are released very quickly, the air required for combustion should be provided timely; otherwise, volatiles will not be well combusted, and when severe, the flue gas will be thick and yellow, causing severe pollution.

When common small-scale biomass combustion is restricted by air distraction condition and furnace design, and when most of the fuel volatiles are released, the pressure close to the feeding port instantly increases. Consequently, the air supply and oxygen concentration in the local space are reduced. This situation can become particularly severe especially when relying on natural ventilation. Furthermore, the gas expansion formed by volatiles after release lies in the furnace space of the fixed volume, which will hinder sufficient mixture of volatiles and combustion air. Based on these reasons and when the design is poor, it will often be difficult for volatiles to burn out. Volatile components, especially heavy components, are decomposed to release carbons under oxygen deficiency conditions at high temperature, which will form carbon black smoke that is discharged with the flue gas. This will not only significantly reduce combustion efficiency, but also cause severe environmental pollution. For extreme cases, the volatiles that are released in a centralized manner are directly discharged with the fuel gas without preceding reaction. At this time, the smoke will be thick and yellow, containing a large amount of condensable volatile tar in addition to incomplete combustion gas, causing severe harm to human health. The above conditions are particularly prominent when burning in a poorly-designed stove and for open burning.

To alleviate such problems, a simple alternative method is to burn biomass pellet fuel after compression forming. Pellet fuel has a dense structure due to mechanical compression. Upon entering the high-temperature furnace, the energy can be transferred from the outside of particles to the inside of particles. A significant temperature gradient can be found inside the particles, and the volatiles can be released from the outside to the inside layer, which greatly alleviates the centralized release of volatiles when heating the primitive biomass. Moreover, briquette fuels are even in particle size, with high and fixed porosity under the stacking condition, which can facilitate air ventilation and supplementation. However, it should be noted that the nature of briquette fuels' improvement of the burn conditions of volatiles is not to change the conventional combustion of solid fuel or the combustion apparatus. By changing the characteristics of the fuel, biomass becomes similar to traditional coal and other solid fuels, thus adapting to the original combustion mode or equipment structure.

From the perspective of combustion of high volatile content, low release temperature and high semi-coke activity are actually favorable factors for efficient combustion of biomass. In addition, the heat energy that is released by burning volatiles accounts for over 60 % of the total heat energy released from biomass combustion. Therefore, it is necessary to implement a specific design based on the characteristics of biomass in which particular importance has to be placed on to the burnout of volatiles. Most of the biomass combustion devices adopt the organization model of continuous feeding and fractional combustion. Under stable working conditions, the release and flow of biomass volatiles into the furnace is stable. A rational design ensures that biomass in the furnace can be quickly heated and thus release the volatiles. The primary air entering with the fuels provides oxygen for combustion. The heat energy released from combustion can be used to enhance and maintain a proper temperature in the furnace. A reasonable cross section of the furnace flue will ensure that unburned volatiles can flow at a reasonable speed and stay for an adequate time in the main combustion zone of the furnace. In this combustion zone, the appropriate arrangement of secondary air is the key. The arrangement of speed of secondary air and spaces can form a flow field, thus providing sufficient turbulence and mixing capabilities to ensure that the combustible components in the gas phase come fully into contact with oxygen to burn out.

3.1.2.3 Ash-related issues

The ash content of biomass fuel is far less than that of coal. The components of different biomass ash vary greatly, and are influenced by the sampling site, soil for crop growth, fertilizer supply, and climate. The ash component analysis data of different types of biomass are presented in Tab. 3.2.

Tab. 3.2: Ash components of different biomasses [41].

Fuel	Cl	SiO_2	Al_2O_3	Fe_2O_3	Mn	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3
Sawdust	NA	4.30	1.30	1.50	5.90	8.50	55.90	0.60	16.80	0.10	3.90	1.30
Sunflower	NA	2.90	0.60	0.80	0.10	21.60	21.60	0.24	22.80	0.10	15.20	14.00
Walnut shell	0.10	23.10	2.40	1.50	NA	13.40	16.60	1.00	32.80	0.10	6.30	2.20
Almond shell	0.20	23.50	2.70	2.80	NA	5.20	10.50	1.60	48.50	0.10	4.50	0.80
Olive skin	0.20	32.70	8.40	6.30	NA	4.20	14.50	26.20	4.30	0.30	2.50	0.60
Hazelnut shell	0.1	33.70	3.10	3.80	NA	7.90	15.40	1.30	30.40	0.10	3.20	1.10
Wheat straw	3.60	48.00	3.50	0.50	NA	1.80	3.70	14.50	20.00	NA	3.50	1.90
Beech	–	12.40	0.12	1.10	–	11.50	68.20	0.90	2.60	0.10	2.30	0.80
Tamarack	–	7.77	8.94	3.83	–	9.04	53.50	3.40	5.64	0.11	5.00	2.77
Switzerland grass	–	66.25	2.22	1.36	–	4.71	10.21	0.58	9.64	0.28	3.92	0.83
Straw	–	77.20	0.55	0.50	–	2.71	2.46	1.79	12.59	0.04	0.98	1.18

Compared to the ash produced from coal combustion, the contents of aluminum, magnesium, and other low melting substances in the ash of biomass are lower, while the contents and proportions of silicon, calcium, potassium, sodium, and chlorine are significantly higher. In general, the silicon content of herbaceous biomass ash is high, while the calcium content of woody biomass ash is high. When the contents of active elements such as potassium, sodium, and chlorine are high, the nature of the biomass ash is more active, and it is thus more likely to form depositions, slagging, and corrosion in the combustion process.

Biomass ash contains less aluminum, magnesium, and other high-melting substances that are easily melted at high temperature. In addition, since the biomass ash contains potassium, sodium, and other alkali metals, as well as chlorine, which act as flux in the ash, the melting point of biomass is dramatically reduced; therefore, it is necessary to pay special attention to the slagging or deposition problems caused by ash melting in the biomass combustion process. Generally, the contents of alkali metals of perennial, woody biomass are low and the ash melting point is high, while the contents of alkali metals of herbaceous biomass are high. Partial melting of biomass ash occurs during the fluidized combustion process, and adhesion of bed material particles occurs in the dense phase region, thus increasing the resistance of mutual movement between bed material particles. It is one of the major reasons for the agglomeration of biomass in fluidized beds in the combustion process.

Biomass contains a considerable amount of active alkali metal elements and chlorine, sulfur and other nonmetallic elements. During the combustion process, these substances will undergo a complicated gas-solid phase transition. Particularly when active alkali metal substances enter the gas phase through a complex approach, this will cause heating surface deposition, metal corrosion under high temperature, and small particulate emissions.

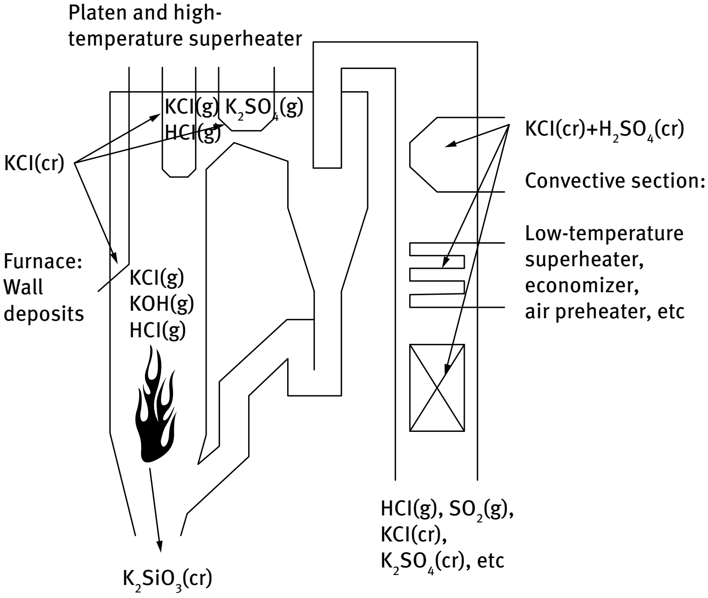


Fig. 3.4: The main routes of K, S, and Cl in the biomass of a direct-fired boiler [42].

Fig. 3.4 describes the major conversion and migration process of active inorganic components in the fuel of the biomass combustion process. The major volatile element in the process of biomass combustion is K, which exists in the flue gas in gas phase KCl vapor form during the biomass pyrolysis and combustion process in the presence of chlorine. As the temperature of the flue gas reduces, chloride homogeneous nucleation will occur, forming a number of fine particles or directly condense on the low-temperature heating surface. The alkali metal chloride that has condensed on the heating surface can trap the ash particles to induce deposition and growth. More severely, when the temperature of metal material is high, KCl will destroy the passive film on the surface of common alloy metal material, resulting in severe high-temperature corrosion problems.

3.1.2.4 Design calculation of the combustion process

The main combustible elements of biomass, as a solid fuel, are C, H, and very small amounts of S. The calculation principle and method of the required amount of air and production of flue gas are consistent with the coal combustion process, which are calculated via chemical reaction equations of combustible elements in the fuels under the complete reaction conditions. The calculation process is based on the basic assumptions: the air required for combustion contains oxygen (21 %), the carbons in the fuel are all converted to carbon dioxide, hydrogen is completely converted to water, and sulfur is completely converted to sulfur dioxide, all gases involved in the combustion process are ideal gases. Based on the above consumption, the theoretical amount of air required for the combustion of 1 kg of biomass can be calculated as follows:

$$V_0 = 0.0899(C_{ar} + 0.375\,S_{ar}) + 265\,H_{ar} - 0.0330\,O_{ar} \tag{3.9}$$

The amount of air calculated by Eq. (3.9) is the volume of dry air for the complete combustion of 1 kg of biomass (Nm^3). The actual amount of air fed into the furnace is generally higher than the theoretical value. Usually, the ratio of the actual amount of air that is being fed into the boiler to the amount of theoretical air is called excess air coefficient. For biomass fuel, although the content of volatiles is higher compared to coal, and the semi-coke combustion activity is strong, in the actual project, the excess air coefficient generally ranges between 1.15 and 1.2 for large-scale power plant biomass combustion, considering its nature of solid fuel combustion and poor broken features. For small-scale combustion, the excess air coefficient will be higher due to restrictions of furnace volume and height.

According to the calculation principle of combustion air, the flue gas volume produced from the complete combustion of 1 kg of fuel can be calculated according to the same principle. Utilizing the premise of complete combustion of the theoretical amount of air supply V_0, the amount of flue gas generated from 1 kg of biomass fuel can be calculated according to Eq.(3.10):

$$\begin{aligned} V_{py} = {} & [0.1866(C^y + 0.375\,S^y)] + 0.111\,H^y + 0.0124\,W^y + 0.008N^y \\ & + (1.0161\alpha_{py} - 0.21)V^0 \end{aligned} \tag{3.10}$$

Where:

- V_{py} is the actual amount of flue gas after complete combustion of per kg of fuel (standard state), m^3/kg fuel;
- C^y, S^y, H^y, W^y, and N^y are the as-received bases of carbon, sulfur, hydrogen, water, and nitrogen in fuel, % by weight, respectively.

It should be noted that the result obtained from the above equation is the exhaust gas volume of 1 kg of biomass after complete combustion. In the field of modern boiler design, it is generally accepted that the combustion process should be completed in the furnace. After unburnt fuel flows out of the furnace, the combustion portion of fuel after flowing out the furnace export is generally small, which can be ignored due to oxygen consumption in the fuel gas and cooling of the backend surface. Therefore, if the excess air coefficient at the smoke vent is substituted by the excess air coefficient at the furnace export, the amount of flue gas at the furnace export can be calculated.

Due to low calorific values and high moisture contents, biomass fuel can produce more flue gas when burning under the same combustion conditions compared to fossil fuels such as coal, which should be considered in the design of boiler flow area, selection of induced draft fans, and the evaluation and calculation of heat loss due to smoke vents.

The combustion of biomass volatiles plays an important role for the entire combustion process. Since mixing conditions and burnout speed of volatiles combustion are different from that of semi-coke, staged combustion, especially the optimization of air distribution for volatile burnout is a very important topic. Usually, biomass requires a high proportion of secondary air, and typically ranges from 45 to 65 %, which is far higher than coal. In addition, due to the large amount of volatiles generated by biomass quick devolatilization, a sufficient momentum and mixing capability should be considered for the design of secondary air. Good distribution of air inlet and outlet and enough air speed are key for design success.

Biomass has low ash content. After burnout, it will form a developed porous medium with very light texture. It can be easily carried and flowed by the flue gas, and even if there is some residual semi-coke ash, its density and intensity are much lower compared to that of coal semi-coke, which is very easy to break and flow with flue gas. For the above reasons, the proportion of fly ash in biomass combustion design is much higher than for coal. Under typical grate furnace combustion conditions, the ratio of fly ash can be over 55 %. In both fluidized combustion and suspension combustion, the ratio of fly ash is generally calculated as 100 %.

Since devolatilization forms a semi-coke with highly developed pores and very strong combustion activity, it is conducive to contact with air. Under the same condition, the burnout degree of semi-coke is higher than that of coal. Under well-designed combustion conditions, the carbon content of fly ash as the main body of coal slag is usually below 10 %. For a circulating fluidized bed, since there is unburned semi-coke multiple circulation, which can ensure the burnout mechanism, the carbon content of fly ash can be kept at 2–3 %. Typically the carbon content of fly ash of a typical grate ranges between 8 % and 10 %. It should be noted that sometimes the biomass ash content and the ash characteristics will exert great influence on carbon burnout. A typical example would be rice husk. Since it has high ash content and the ash is mainly dominated by silicon, the carbons in the rice husk semi-coke crosslink with the organic silicone in the ash in the combustion process, thus making it difficult to burn.

3.1.3 Pollutant emissions of biomass combustion

Biomass has low contents of ash and sulfur. Compared to coal, it is a clean solid fuel. Its pollutants produced via combustion can be divided into two categories: pollutants caused by noncombustion and pollutants caused by combustion. Noncombustion pollutants include CO, HC, tar, PAH, and C_xH_y, often caused by lower combustion temperature, uneven mixture of fuel and air as well as short fuel residence time. Combustion pollutants include particulate matter (PM), nitrogen oxides (NO_x, particularly NO, NO_2, and N_2O), sulfur oxides (SO_x, particularly SO_2), acidic gases such as HCl, and heavy metals (deposited within the ash or existing in the gas phase), and they are influenced by biomass fuel characteristics, combustion tissue, parameters, and craft.

3.1.3.1 Soot emissions

The ash-forming elements in raw materials exist in the form of inorganic impurities, or are connected to the organic macromolecular structure by a carbon chain combination, which is called inner ash. During the collection and transportation of biomass, soil may be mixed into the biomass. The ash thus formed is called entrained ash. Inner ash-forming materials are evenly distributed in the fuel and generally more active than entrained ash. They are also more likely to be volatile or participate in the reaction of the combustion process. The ash formation mechanism of biomass combustion is shown in Fig. 3.5.

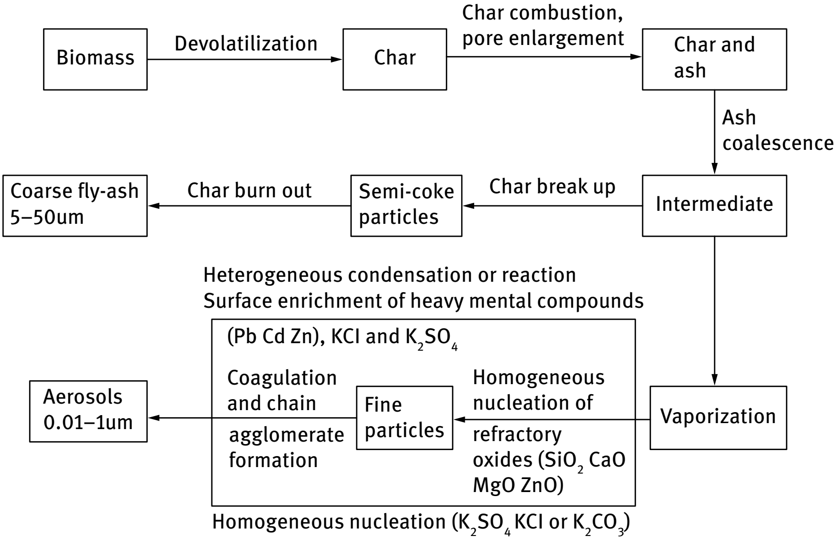


Fig. 3.5: Ash formation mechanism [43].

The surface or the interior reducing atmosphere and the high temperature of coke during combustion can strengthen volatilization of metals in ash such as Zn, Pb, and Cd. They may also produce refractory oxides such as SiO_2, CaO, and MgO, or transform into volatile SiO, Ca, and Mg. When these components are released into the gas phase, nucleation occurs due to condensation or chemical reactions, forming very fine particles in the boundary layer of coke in its combustion. Such particles are of a very fine size in the initial formation, approximately 5 to 10 nm. In flue gas flow, these tiny particles condense, aggregate, and gradually enlarge, forming the material basis of fly ash, with single particle sizes below 1 μm. However, during the semi-coke burning process, along with the development of semi-coke pores, particle collision, and mutual grinding effects, coarse particles are formed with inert biomass ash as the main material with some unburned carbon as addition. Under different combustion tissue conditions and biomass characteristics, such ash particles have a diameter on a macroscale, and the typical particle size ranges from 5 to 50 μm. This part of ash forms the main component of visible remnants after biomass combustion.

Biomass ash of the combustion system can be divided into two categories: inert components of fuel ash and coarse particles formed by products of incomplete combustion. The particle size of the latter depends on the breakage characteristics of semi-coke particles, or is formed by molten (agglomerate) nonvolatile components of the ash. The other type of small particles below 1 μm is made of nucleation or deposit of volatile ash components. Since such particles can directly move into the respiratory system, deposit in the alveoli, and are difficult to remove, they pose a greater hazard.

To reduce dust emissions, large-scale biomass combustion engineering has to take certain dust elimination measures into account. It is generally believed that ratio electrical resistivity of biomass ash is high, and it is difficult to guarantee the results of electrostatic dust elimination. Thus, an efficient dust elimination bag is preferred. The ash collection efficiency of a dust elimination bag for particles above 1 μm can reach more than 99.5 %, achieving effective collection of coarse particles in the biomass combustion process. However, both bag dust elimination and electrostatic dust elimination have low capture efficiencies for submicron particles, requiring further research.

3.1.3.2 Pollutants emissions in the gaseous phase

Plant roots can absorb NO_3^-, NH_4^+, and several soluble organic nitrogen compounds such as amino acids, amides, and urea from the soil, and turn them into part of their biomass. Thus, biomass fuel contains more or less nitrogen. The nitrogen in fuel can be precipitated by certain means in the combustion process, causing a nitrogen vapor emission problem. NO_x generated during the combustion process can be divided into thermal NO_x, prompt NO_x, and fuel NO_x. Fuel NO_x is the main component.

Fuel NO_x forms a large proportion of the outputs of the fuel combustion process. Its generation mechanism is very complex, as its generation and destruction process not only relate to fuel characteristics, structure, the nitrogen proportion of fuel, composition and distribution within the volatile content, and coke after thermal decomposition, but also closely relates to combustion conditions such as temperature and concentration of a variety of ingredients such as oxygen. Fuel NO_x is formed by oxidized N in the volatile part or in semi-coke. As biomass contains a relatively low content of semi-coke, most N comes from the volatile part (66–75 %). The production of fuel NO_x is often determined by the N content of the fuel, fuel reactivity, and oxygen concentration during the fuel combustion process. Most NO_x produced is NO and contains less than 5 % of NO_2.

Studies show that dominant volatile components with nitrogen in the biomass fuel combustion process are NH_3 and HCN. They can react with O_2, thus generating NO. However, NH_3 and HCN, as precursors of NO_x formation, have very complex reaction pathways in the combustion environment. As shown in Fig. 3.6, HCN can generate NH_3 via a specific reaction. NH_3 can react with NO and generate N_2 and water, and can also be decomposed into NH_2 and NH radicals; therefore, being oxidized by O_2 into NO, and can also generate N_2 with NO and OH radicals.

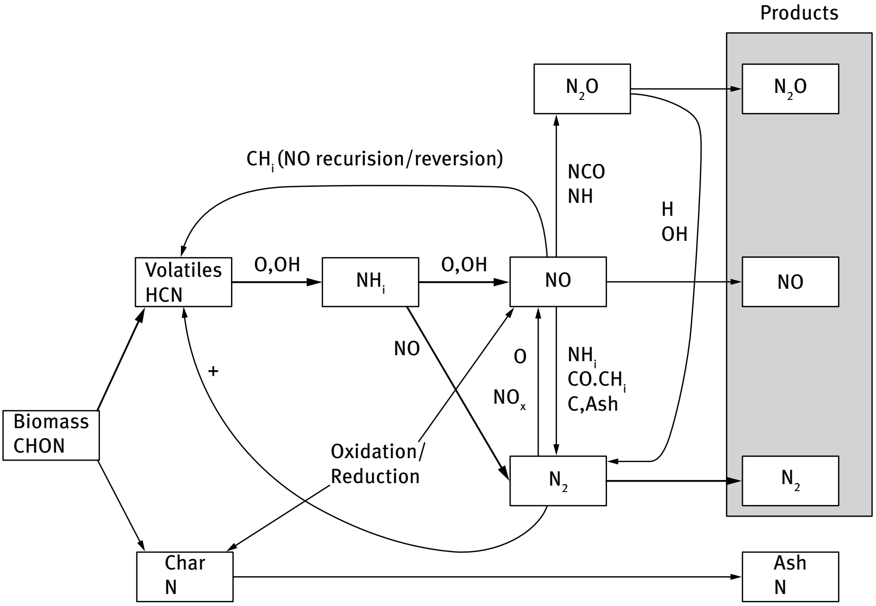


Fig. 3.6: Conversion route of fuel N [39].

For combustion, an effective air supply is very important to reduce NO_x emissions. To reduce NO_x generation, staged air supply and fuel supply can be used. However, combustion stability, reasonable distribution, and stability of the furnace temperature and atmosphere are also crucial for the reduction of NO_x emissions. If the above measures do not achieve such a reduction to a defined level, follow-up measures are necessary, such as SNCR technology of ammonia injection into the furnace, or a reburning technology. However, adopting the SCR $DeNO_x$ technology that is commonly used in coal-fired power plants for biomass combustion may be problematic, mainly due to the unavoidable presence of alkali metal substances in the biomass ash, which leads to a rapid and vast majority of SCR catalyst activation loss. Therefore, extra careful assessment is required.

In solid fuel combustion, emission of gas phase pollutant SO_x is not serious in biomass, mainly due to average sulfur content of approximately 0.1 % in biomass, which is far below the average sulfur content of coal.

3.1.3.3 Emissions of heavy metals

Trace metals in biomass fuel (As, Ba, Cd, Go, Cr, Cu, Hg, Mn, Mo, Ni, Sb, V, and Zn) play an important role in biomass utilization, involving biochemistry, nutrition, and clinical medicine.

The transformation and release pathways of heavy metals in the combustion process are affected by the element occurrence form, combustion conditions and other factors. In general, they are similar to the ash generation process of biomass combustion. Specifically, at proper combustion temperatures, volatile metals such as Cd, Pb, Ar, or Zn tend to be volatile with chlorides or oxides. Thermodynamic calculations reveal that, in combustion, Cd and Pb tend to turn into $CdCl_2/PbCl_2$. Zn has relatively poor volatility. A large amount of Zn is retained as oxide in ash. However, $ZnCl_2$ and trace metal Zn can be volatile. Other volatile metals such as Ar or Sb have a similar performance, mostly in the form of chloride appearing in fly ash. Mercury is a special volatile heavy metal. In chemically untreated biomass material, the amount of Hg is approximately 0.01 to 0.1 mg/kg db. Since the saturated vapor pressure is high, almost all of it exhausts in combustion in the gas phase. Other metals such as Fe, Cu, Cr, and Al have lower volatility and more stable oxides. Thus, most of them exhaust in the form of coarse ash particles.

3.2 Biomass ovens for domestic use

Biomass ovens include stoves that provide energy for civil use, required for cooking and heat supply, burning straw, core wood, or biomass briquettes mostly used in rural areas. In terms of the purpose of energy, biomass stoves for civil use can be categorized into three types: cooking stoves, heating stoves, and combined cooking and heating stoves. Since China is globally the largest developing country, straws and fuelwoods constitute primary life fuels in rural areas. Since traditional stoves in villages are mostly made of stones piped manually with rough construction technology, an enormous waste of biomass energy is caused due to insufficient combustion with simultaneous low heat efficiency. Furthermore, the dense smoke emitted as a result of insufficient combustion increases indoor air pollution. As the world has been keeping a watchful eye on energy efficiency and air pollution and with rural urbanization and concurrent improvements in living standards of the rural population, the traditional stove and its low efficiency combustion fails to live up to their demands. Highly-efficient and low-emission biomass ovens for civil use will not only reduce coal consumption and decrease emissions of pollutants, but also change wastes into wealth via utilization of otherwise wasted biomass resources. Furthermore, they help elevate living quality of peasants and thus propel socialism into the countryside [44].

The development of stoves has predominantly undergone three stages: the preliminary stage, the improvement and promotion stage, and the technological innovation stage. Before the 1980s, manually-built traditional stoves were mainly used in most rural areas, with heat efficiencies of approximately 12 %. During the early 1980s, the Chinese government began to work in pilot counties to improve stoves and save diesel, by purposefully promoting fuel-saving stoves (or energy-saving stoves) with heat efficiencies over 25 % [45]. Soon afterwards, semi-gasification biomass ovens for civil use that combined convenience and high efficiency were researched via technical innovation. Compared to traditional stoves with low heat efficiency, improved stoves drastically reduce indoor air pollution, decrease consumption of fuels, and greatly improve heat efficiency.

3.2.1 Cooking stoves

An oven is essentially nothing other than a stove. We would normally call something that is used to join a heatable brick bed an oven, and something that is independently fueled and does not join a heatable brick bed a stove.

Currently, most villages in China adopt traditional styles of cooking stoves. Insufficient air volume during the initial stage for feeding materials would cause gasification products inside the bed and insufficient combustion of a large volume of volatile substances that would change into black smoke smudge emitted into the air, causing energy waste, and environmental pollution. Excessive air quantity during a later period causes a rise of energy loss by exhaust gas. Moreover, it gives rise to uneven firepower inside a stove, periodically changing the burning temperature and leading to other deficiencies.

In light of the fundamental characteristics of biomass burning, biomass ovens for civil use should have the following characteristics [46]:

(1) They should make full use of volatile substances produced by biomass pyrolysis.
(2) They should effectively use thermal radiation of carbide during the combustion process.
(3) They should rationally organize the stove structure and ensure effective convection heat transfer of burning gases.
(4) The air can evenly, smoothly, sustainably, and stably access the stove.

Tab. 3.3: Partial technical requirements for biomass ovens for civil use according to Beijing Local Standards.

Item	Basic requirements or performance indicators
Stove structure	Reasonable design and easy to operate
Appearance	Elaborate shape, smooth and clean surface, free of burrs, rust proof, thermal insulation materials not exposed
Thermal performance index	(a) Rated heat is not below than the nominal value. (b) Thermal efficiency: Cooking stove: $\eta C \geq 35\,\%$; Heating Stove: $\eta N \geq 35\,\%$; Cooking stove: $\eta CN \geq 35\,\%$; (c) Cooking dynamic strength: $P > 2$ kW.
Flue gas emission index	(a) The average concentration of carbon monoxide $< 0.2\,\%$. (b) The average sulfur dioxide concentration $< 50\,\mathrm{mg/m^3}$. (c) The average concentration of dust emission $< 50\,\mathrm{mg/m^3}$. (d) Ringelmann emittance: grade 1.

(5) Firepower is sufficient, fire behavior is even, combustion is completed, black smoke is eliminated, and energy use efficiency is high.

To realize these technical requirements (Tab. 3.3), traditional ovens cannot live up to the demands; therefore, designing a new model biomass oven normally has to observe the following principles and a structural sketch is specified in Fig. 3.7.

(1) Design of secondary air inlet
Since volatile substances of biomass fuels are released fast and their combustion time is short, improper supply of air would result in emission of organic volatile matters that are not fully burned. Therefore, in designing direct-fire biomass ovens, a secondary air inlet should be added near the stokehole and fire door wall.

(2) Lengthening the length of flue combustion passage
During the burning process of biomass fuels, the release quantity of volatiles is enormous; yet, burning time is short. Lengthening the combustion passage of the flue will provide sufficient space and time for complete burning of volatile substances and thus improve the use ratio of fuels.

(3) Small primary air inlet
Oxygen content in biomass fuel is higher compared to that of coal; therefore, biomass fuels are easier to ignite and the oxygen supply can be comparatively reduced in burning.

(4) Big water jacket area of flue
Burning of volatile substances results in a temperature surge, increasing the heat absorption area of partial water jackets in flues, fully absorbing and utilizing the burning heat and thus reinforcing heat efficiency.

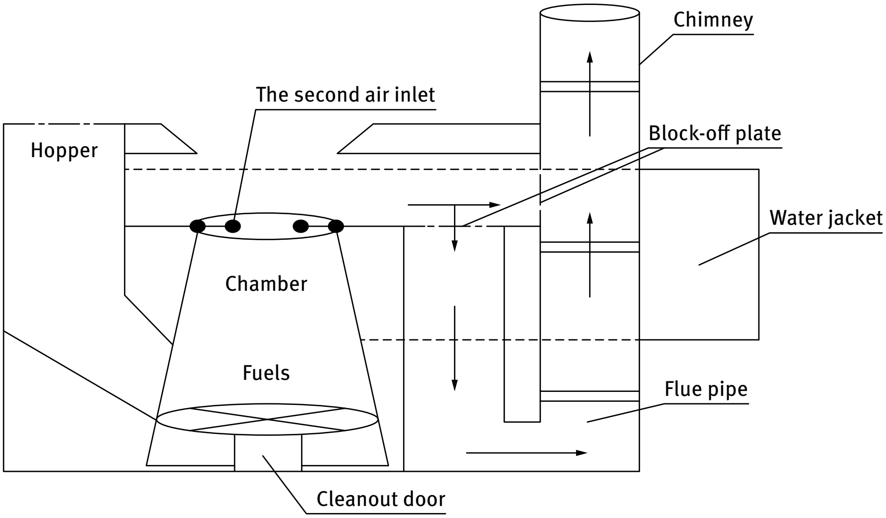


Fig. 3.7: Sketch of biomass oven for civil use.

(5) Use of biomass briquettes
Biomass is characterized by low carbon content and soft texture, and it is easy to ignite and burn, but frequent padding is required. The use of compact molding equipment compresses the incompact biomass into a mold, improves energy density, as well as some insufficiencies of biomass burning and thus is convenient for storage and transportation.

(6) Avoidance of burning coking phenomenon
Since biomass contains a high proportion of potassium, in an oven chamber with a burning temperature above 800 °C, large amounts of potassium oxide form a molten substance to be mixed with silicon, calcium, and other minerals contained in the biomass. Subsequently, as temperature drops, coking chunks of different sizes take shape, affecting the emission of stove ash and the supply of air. Increasing the water jacket heat absorption area in an oven chamber can help to control high temperature and avoid the formation of coking.

A blowing-type biomass cooking oven was designed based on these principles (specified in Fig. 3.8). This cooking oven adopts the updraft gasification technology (reverse flow gasification). Air is absorbed through a grid melter of the ash chamber with primary air and passes the burning zone from the bottom upwards. Fuels are added to the oven chamber at a time from the top of the fire door, which can also be padded while burning. Gasification is structured into three layers: the thermal decomposition layer, the reduction layer, and the oxide layer along the gasification height in the oven chamber.

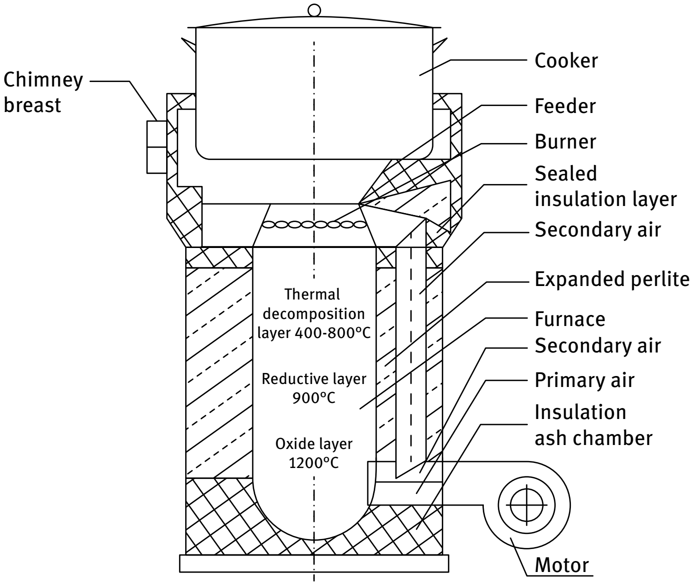


Fig. 3.8: Structure diagram of a blowing-type biomass cooking oven [47].

(1) Thermal decomposition layer. Pyrogenic decomposition of biomass refers to fuels being dried on top of a gasifier and entering the process of thermal decomposition after interaction with hot gas from the bottom of the gasifier, which is a key part of the whole gasification process. Its products include CO, H_2, CH_4, CO_2, tar, water vapor, and fixed carbon. Temperature is the key for completing thermal decomposition, since a high temperature renders shorter time to complete thermal decomposition, and hyperthermia (400–800 °C) facilitates the thermal decomposition process.

(2) Reduction layer. Chemical reduction reaction of CO_2 and fixed carbon is as follow:

$$CO_2 + C = 2CO + 172.46\,\text{kJ/mol} \tag{3.11}$$

The effective reduction temperature of CO_2 is above 800 °C. Consequently, raising the temperature facilitates the reduction reaction.

(3) Oxide layer. When thermal decomposition of biomass is accomplished, the remaining mass is fixed carbon in biomass. The transfer of fixed carbon to fuel gas requires gasifying medium (predominantly air) and a high temperature. With air, a mass of CO_2 is produced and abundant heat energy is generated when the temperature is higher than 1,200 °C. The reaction equations are:

$$CO + \frac{1}{2}O_2 = CO - 282.99\,\text{kJ/mol} \tag{3.12}$$

$$O + O_2 = CO_2 - 393.52\,\text{kJ/mol} \tag{3.13}$$

Mode-integrating biomass gasification with combustion can effectively overcome issues such as much tar in traditional updraft ovens and low energy utilization. The process of no cooling, no removal of tar, no filtration, no washing and no dedusting is known as a simple gasification or semi-gasification. Such a method of handling is both economical and environmentally friendly. Secondary air can be added in the gas-fired exit of the biomass cooking oven, and thermal fuel gas can be both energy saving, while burning tar when burning in the fire hole. After installing a miniature forced-draft fan in the biomass cooking oven, the oven temperature and supplied air rate can be thus controlled and primary and secondary air can be freely adjusted. Different air distributions in each combustion stage realize gasification of fixed carbon that enabled a significant breakthrough for improving heat efficiency of burning. A gasifier in its traditional way requires continuous feeding and the reaction of each burning zone is simultaneously achieved. However, such a biomass cooking oven requires full fuel added with slight primary air, ignition in the fire hole, and opening of secondary air valve after the oven chamber has been preheated. After normal gasification burning in the fire hole, gasification enters the first stage, dominated by thermal decomposition: the burning stage of volatile substances. The decomposition temperature is required to be above 400 °C. Then, the primary air valve can be closed or slightly opened. After opening the secondary air valve, biomass can naturally carry through gasification burning. When volatile substances of straw particles decrease, the second stage of gasification, namely the gasification stage of the oxide layer of fixed carbon, can be entered into. At this moment, primary air is gradually increased and secondary air is decreased so that the gasification reaction can be smoothly carried out. Gasification of the second stage is also important. Normally, the whole process of gasification is completed after volatile substances of biomass are gasified. In reality, a gasification peak for leftover fixed carbon exists in the follow-up stage.

Fig. 3.9 shows a structural diagram of an integrated biomass oven. Its body is a fixed-bed updraft structure and its burner and chamber for the gasification reaction are an organic whole. Biomass fuels are decomposed and gasified in the oven chamber, while the generated fuel gases are directly burned in the cooking range. The cooking range is designed to fit in the original feeding port. It can be hoisted alongside the axis direction of the secondary air hose and can rotate around it, to enable convenient feeding of materials.

The air supply system comprises primary air supply pipes, secondary air supply pipes, an annular air supply device, and a cooking range (Fig. 3.9). The primary air supply is guided into the annular air supply device in a tangential direction, forming an air supply platform to ensure maximum contact of primary air and materials for the gasification reaction. The remaining air is upcasted through a secondary air supply pipe and screws into the mixing chamber of gas and air in clockwise tangent direction before rapidly mixing with gasified gas screwing in with an anticlockwise tangent direction. The mixed gas is then ignited inside the big fire cover and forms a swingfire through the tangential screwing hole of the distributor before getting in

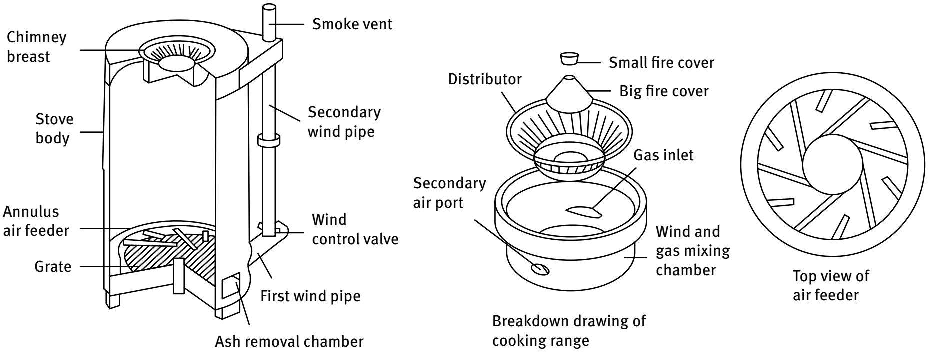


Fig. 3.9: Structural diagram of an integrated biomass cooking oven [48].

full contact with the bottom of the pan with convergence of big and small burner caps. During this process, tar in the gasified gas and partial unsaturated hydrocarbons enter high-temperature pyrolysis and burn within the cooking range, while soot of the burning process is discharged through smoke vents (connected with the cooking range). If air supply is sufficient, the adoption of such a semi-gasification method can lead to a thermal efficiency as high as 36 % and firepower intensity for cooking realizes 4.79 kW.

3.2.2 Cooking and heating oven

The principle of a cooking and heating oven is in essence not different from a cooking oven. By installing heat transfer, heat storage, and radiation appliances to the basic cooking oven, good heating function can be realized. The classification and use of thermal energy ensures comprehensive heat efficiency of the cooking and heating oven that is universally above 60 %.

Fig. 3.10 demonstrates the biomass cooking and heating oven integrating such functions as heating, cooking, and water boiling. The oven is designed in accordance with the design principles of a biomass fuel oven and maize straw briquettes fuel it. The combustion methods are chosen for grate firing, following combustion characteristics of fuels. Its main structure includes an ash chamber, air distribution pipes, grate dies, hearth, fire-drawing tank, circumferential water tank, water jacket, chimney, and a feeding mechanism.

This oven utilizes the model of traditional coal ovens to match and satisfy the cooking and heating habits of peasants. The ash chamber lies at the bottom of the hearth, the grate components are installed above the ash chamber, and the forced-draft fan is installed to the left of the hearth with stack air distribution pipes connecting them. The secondary air distributor is located directly above the hearth, the oven port lies in front of the hearth with natural ventilating ducts; the feeding apparatus

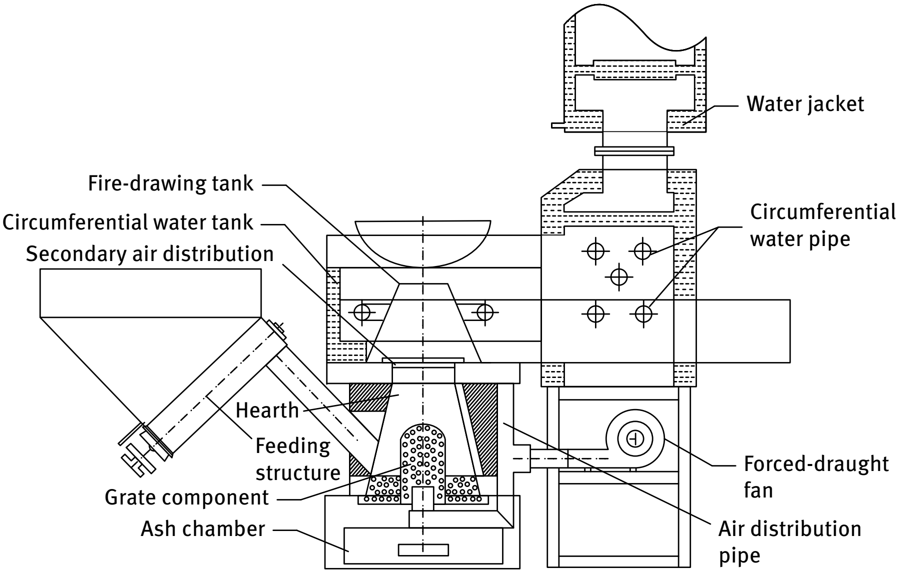


Fig. 3.10: Structural sketch of biomass cooking & heating oven [49].

is connected with the feeding port and hearth at a certain angle; the dismountable fire-drawing device is installed above the hearth and water tank and a heat-absorbing tube is arranged around the upper part of the furnace stack. The upper stack nozzle is located on the upper right of the furnace stack and is linked with the water jacket. The exhaust gas is emitted after entering the water jacket through the upper stack nozzle after heating the circumferential water tank and water pipes through the fire-drawing device. The exhaust gas can also pass heated absorbing tubes or heated water tanks and thus enter to the heated brick bed via smoking holes. Two exhaust gas outlets are equipped with switches to realize switchover of exhaust gas entering the flue of a kang and exiting from the heating and cooking oven. The method of installing a fire-drawing tank has been adopted for cooking to raise the height of a flame to satisfy the demands for dinner cooking. The furnace stack is equipped with a circumferential water tank and circumferential heat transfer pipes are installed between the water tank and inner walls. The annular water jacket is added to the stack nozzle above the furnace stack to utilize the afterheat of exhaust gas that does not enter the kang. Performance tests of the oven indicate that its rated thermal power is 8.0 kW, with a thermal efficiency of 69.7 %, and a thermal efficiency for cooking of 39.2 %, the comprehensive heat efficiency is 78.55 % and the index of flue gas emission is lower than the national standards.

3.2.3 Heating oven

The heating oven excludes the stove hole, and averts heat loss through the hole. It also adopts technologies of reverse heating and multiple air inlet fractional combustion to burn biomass fuels more completely. The use of multiple passage heat transfer technologies supplies the heating oven with increased efficiency, arriving at a heat use of 80 %.

Considering heat supply efficiency, the structural design of a biomass heating oven uses the burning characteristics of biomass briquette as basis. Fig. 3.11 shows a structural sketch of a classical biomass heating oven. The oven comprises the hearth, fire grate, radiation and heat convection platform, igniter, induced draft fan, crossflow fan, hopper, and spiral feeder.

The working process of a biomass briquette heating oven comprises the following phases: after starting its switch, the igniter begins to work. Simultaneously, spiral feeders deliver biomass particles inside a hopper to the fire grate in the combustor; then, the crossflow fan and induced draft fan are activated. After a brief while, fuel particles start to burn above the fire grate. Combustion air from the outside is introduced through a hole at the back of the combustion chamber and high-temperature flue gases are produced to heat the indoor cold air from the crossflow fan via the heat exchanger before exhausting it to the outside through smoke discharging pipes by the induced draft fan. The produced thermal air is emitted through the upper part of the furnace stack. After the heating oven has operated for a while, the power of crossflow fans and induced draft fans naturally increases.

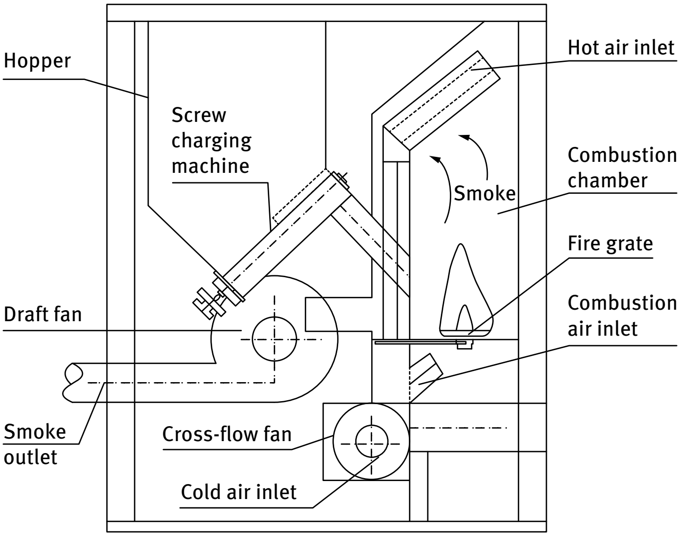


Fig. 3.11: Structural sketch of a biomass heating oven [50].

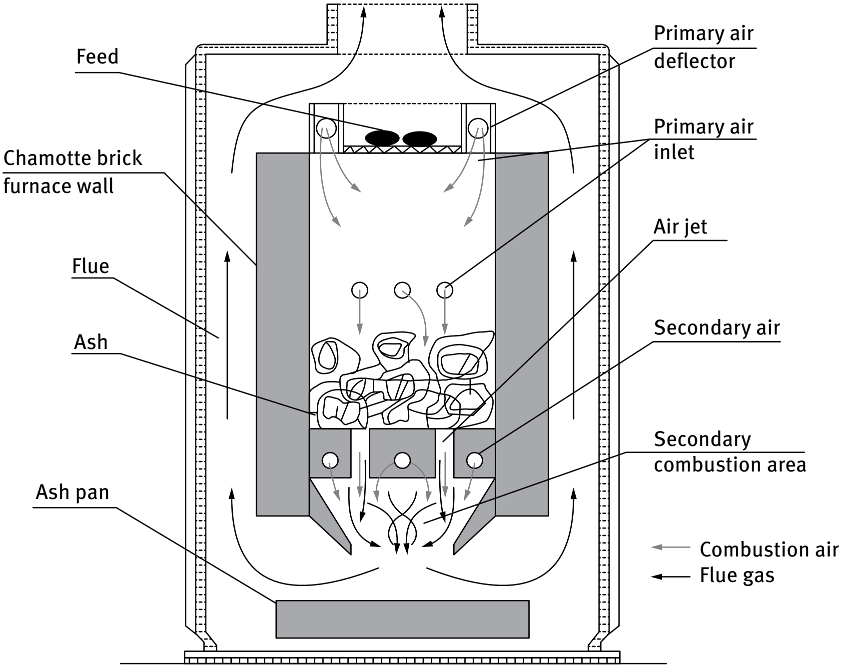


Fig. 3.12: Heat storage-heating oven.

A heat storage-heating oven normally either comprises a prefabricated slab or is made entirely of stones. Subsequent to the fray-out of flames, the stove can still emit heat to the living space for a long time. Fig. 3.12 shows a heat storage-heating oven with the combustion based on the principle of downdraft combustion. First, fuel is burned under the condition of slightly excess air coefficient before mixing with secondary air for full burning. The hearth is built of fireclay bricks with two smoke outlets in the hearth and a secondary air hole arranged in the grate. Fuels are fully burned in the secondary burning region and then flue gases flow upwards from the bottom of the stove, while exhaust gases deliver heat to the heat exchangers before flowing into the chimney. The heating devices make full use of most of the heat energy.

3.2.4 Energy-saving oven

In North China, particularly in Northeast China, most villagers have been using an old type of oven and heated brick beds for a long time. An oven is normally connected with a heated brick bed, known as oven kang (Fig. 3.13). However, in some regions of Northwest China, ovens are arranged separately from heated brick beds.

Fuels used in old-type ovens are usually straws of crops, core wood, herbage, dried animal manure, and similar items that are burned in the oven chamber (a space be-

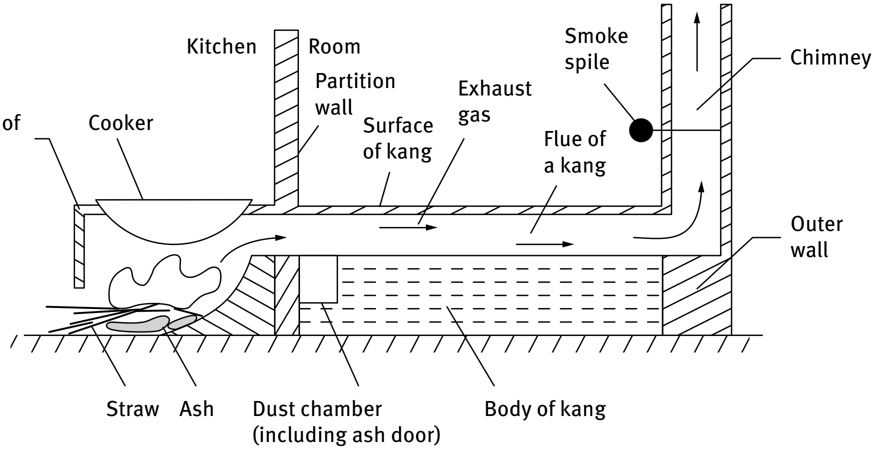


Fig. 3.13: Schematic diagram of an old-type oven kang.

low the cooking utensils). Due to the lack of a grate, air supply is insufficient, and fuels cannot be fully burned; since the oven hole is big, thermal insulation properties are low, the distance between cooker and fuels is far, and the standing time of high temperature flue gas is limited; consequently, thermal loss is enormous. Cooking heat efficiency of old-type ovens is low at approximately 12 %.

An old-type kang is usually called a ‘fire kang’ in Northeast China (middle part in Fig. 3.13), which is piped above the ground in a living room, and thus, it is also named a ‘floor kang’ (compared to the ‘overhead kang’ mentioned below). A kang, with the length of a living room and a width of about two meters, is normally made of soil, brick, and stone; a kang has four flues with depths of approximately 40 to 50 cm. High-temperature flue gas flows into the chimney via these flues from the exit of an oven before the surface of a kang is heated, dispersing the heat to the room for users to warm themselves. Two sides of a kang are usually clinging to the enclosure walls with one side as cellar wall inside the kang and the other side (the end of the kang) close to the outer wall of the chimney.

One major problem that dominates these old-type kangs is their low thermal insulation performance; consequently, their heating efficiency is not high. Thermal loss of exhaust gas originates due to four aspects: first, the thermal energy runs off from the sidewall (the wall below the cellar) inside a kang; second, it runs off from the sidewall of the end of a kang; third, it runs off from the group; and fourth, it runs off from the exhaust gas from the chimney. Considering thermal loss by all four ways, the comprehensive thermal efficiency of old-type oven kangs is normally approximately 45 % [51].

Energy-conservation ovens (or fuel-saving stoves) have varied forms; however, they share more or less the same basic structure, as specified in Fig. 3.14. The differences to old-type ovens are specified below:

(1) It is equipped with a grate and an ash chamber. The air supplied for burning is sufficient and ensures that fuels can be fully burned.
(2) It has a switchable door. Thermal loss can be reduced via closing the door after fuel padding.
(3) Fuels are situated near the base. Fire-drawing distance (from grate to the lowest point of the base) is short, normally at 12–16 cm (the actual data is 14–16 cm for burning soft fuels and 12–14 cm for burning hard fuels).
(4) It has a fire-prevention ring and flue return pass. The fire-prevention rings help lengthen the duration time of fire and high-temperature exhaust gas at the bottom of the pot. The fire-prevention interval is short in the exhaust gas outlet direction (left in Fig. 3.14) and is elongated in the direction of the oven door (right in Fig. 3.14). It is approximately 2–5 cm from right to left. The function of a flue return passage is to increase the route and time of exhaust gas spinning in the base. Via installing the fire-prevention ring and flue return passage, the pan can fully absorb the heat of burning.
(5) It adds heat preservation measures to the oven body. Materials with low thermal insulation properties are chosen for the oven body and appropriately increase thickness to reduce thermal loss.

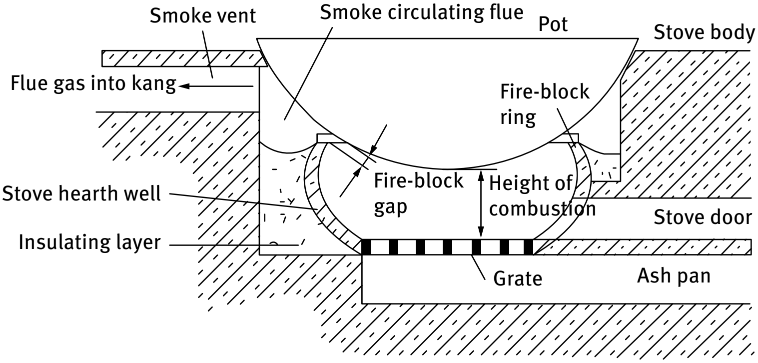
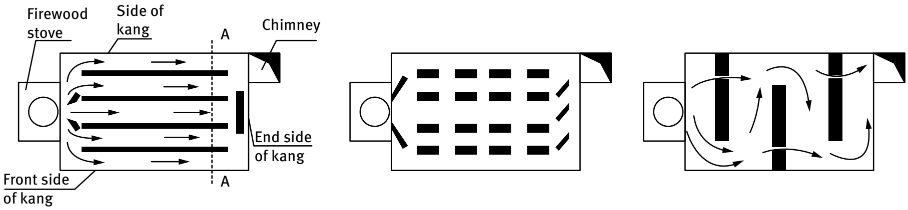


Fig. 3.14: Fuel-saving stove.

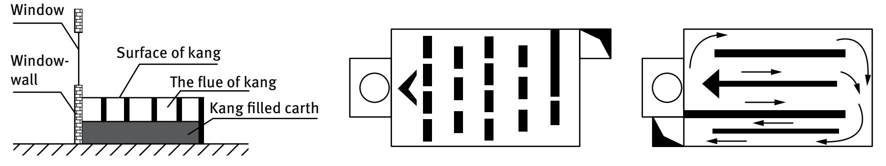
Moreover, a secondary blast pipe is arranged between oven chamber and oven body in some fuel-saving ovens, so that carbon particles that are not burned in the flue return passage can be kindled again to further release heat.

By adopting these measures, heat efficiency of cooking in a fuel-saving oven can increase to approximately 20 % from 12 % of the old-type oven. Some fuel-saving ovens with higher standards can reach a thermal efficiency of cooking of over 25 %.

Improvements to old-type kangs also aid in increasing comprehensive thermal efficiency: first, changing the flue form of a kang (Fig. 3.15) so that exhaust gas can



(a) Straight hole kang (b) Hua straight hole kang (d) Horizontal hole kang



A-A Profile (c) Hua horizontal-straight kang (e) Turning hole kang

Fig. 3.15: Schematic diagram of flue improvements to old-type kangs (floor kang) (from the top). (a) Flue of an old-type kang, (b)–(e) several forms of flue improvement to an old-type kang.

flow in a circuitous way into the kang flue; second, reducing the number of bricks used to support the surface of a kang inside the kang flue. These improvements help increase heat emitted from the surface of a kang to the room and result in more even distribution of heat over the surface of a kang.

The improvement measure specified in Fig. 3.16 is to arrange a flue return passage below the flue of a kang. The chimney is built within the room and two exhaust spiles are used to control the exhaust gas direction originating from an oven. When the kang surface releases heat into the room (heating is required when the outdoors temperature is low), the flow of the exhaust gas is specified in Fig. 3.16. This adds to the route and time of exhaust gas spinning in the flue of a kang and thus reduces thermal loss resulting from exhaust gas running off from the chimney; when heat release to the room from the kang surface is not required (for example, during hot summer days), a spile is used to intercept the exhaust gas that directly runs off from the chimney instead of accessing the flue of a kang.

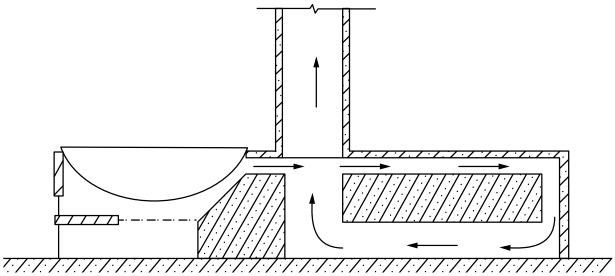
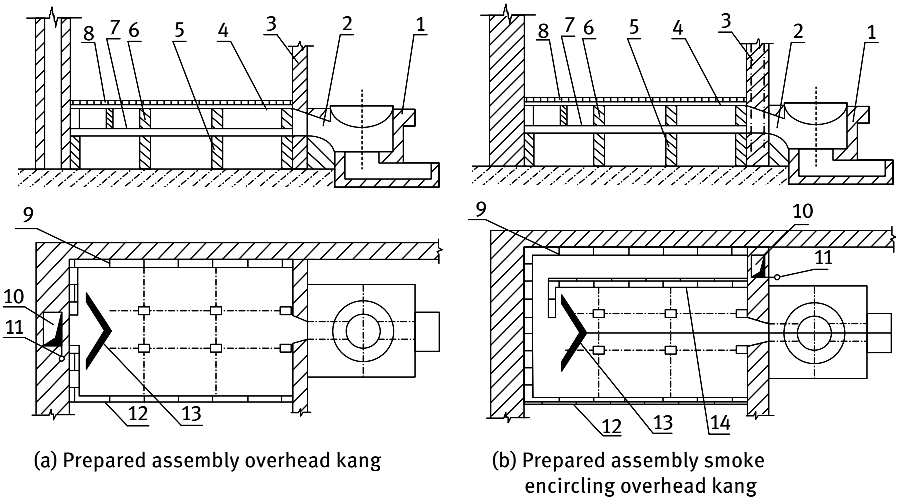


Fig. 3.16: Schematic diagram of gas flue arranged at the bottom of the flue of a kang [52].



(a) Prepared assembly overhead kang

(b) Prepared assembly smoke encircling overhead kang

Fig. 3.17: Structural diagram of an overhead kang.
1. Oven, 2.smoke inlet, 3. partition, 4. panel of a kang, 5. baseboard brace, 6. panel brace, 7. baseboard of a kang, 8. plastering mud, 9. thermal insulating layer, 10. chimney, 11. exhaust spile, 12. front wall of kang, 13. smoke-prevention board, 14. smoke-prevention wall

To cope with problems that exist in the floor kang, a new type of kang – namely the overhead kang (Fig. 3.17) – is being promoted following research in Liaoning, Jilin, and other provinces. This type of kang is not located on the floor inside a room but is fixed up with bricks. Its structural characteristics are as follows:

(1) The kang is similar to a flat box with four bricks lifting it up from the ground. The panel and the baseboard of the kang are connected via nine prefabricated cement slabs. Four small buttress panels are used to support the space between panel and basement of a kang (usually in bricks). The flue of the old-type kang is replaced by a wide hole (almost empty). Exhaust gas flowing from the oven to the chimney faces with low resistance, while the exhaust gas can be fully contacted with the panel and baseboard of a kang.

(2) The panel of a kang is slightly higher than the oven surface. This is so that the smoke inlet is uptilted in the flowing direction of exhaust gas to help the flow of smoke.

(3) Thermal insulation materials are added to the side where the kang contacts the maintenance wall to decrease heat transfer loss.

(4) Thickness of claying at the surface of a kang is different with its warmer end being thicker and the colder end thinner.

Since the surface and base of an overhead kang can release heat to the room, heat transfer loss to the side of a maintenance wall and to the floor is enormously decreased; full contact of exhaust gas with panel and baseboard inside the kang helps to lower the exhaust gas temperature and thus improve heat efficiency of the kang. Oven kangs combining the fuel-saving stove with an overhead kang enjoy a comprehensive thermal efficiency as high as approximately 70 %.

3.3 Industrial combustion technology and applications of biomass

Since the global oil crisis of the 1970s, biomass combustion technology has become an important measure for developed countries to adjust their energy structure and realize alternative energy and sustainable development. In the United States, Sweden, and Austria, biomass energy accounts for 4 %, 16 %, and 10 % of primary energy consumption respectively. Biomass energy is mainly used for regional and industrial heating (including regional heating networks, timber processing and drying, etc.) and used in steam engines, steam turbine power generation, or cogeneration. In the United States, the total installed capacity of biomass power generation has exceeded 10,000 MW and the stand-alone capacity has reached 10–25 MW. In China however, there are about 500,000 sets of industrial boilers and the coal consumption per year is approximately one third of the total coal production nationwide. To achieve the goal of “energy saving and emission reduction” during the “Twelfth Five-Year” period, the Chinese government has issued the Twelfth Five-Year Plan of energy saving and emission reduction, which explicitly aims to “support the transformation of units that have operated for less than 15 years and should be shut down to units usable for biomass energy power generation or cogeneration units in the regions that have identified the sources of biomass energy and implemented simultaneous construction of heating network and heat load according to the biomass energy development and utilization plan and urban centralized heat supply plan. In terms of centralized heat supply plan, biomass energy centralized heating should be adopted by the residents in large cities in Northeast, North, Northwest China.”

Therefore, making full use of clean energy and improving the energy utilization rate has become a strategic direction for the development of industrial boiler technology. Biomass energy is a renewable and clean energy. It is feasible to develop industrial biomass combustion technology in terms of technical, economic, and environmental benefits. In addition, according to the strategic requirements of limited mineral energy resources and environmental deterioration caused by increasing consumption, and in combination with the fact of rich biomass resources, it is of positive significance to develop industrial biomass boiler combustion technology, minimize conventional energy, and optimize the energy structure [53].

3.3.1 Combustion technology of biomass

Biomass combustion technologies include the biomass direct combustion technology, biomass briquette combustion technology, biomass and coal co-firing technology, and biomass gasification combustion technology.

3.3.1.1 Biomass direct combustion technology

Biomass direct combustion refers to the pure combustion of biomass, mainly divided into stove combustion and boiler combustion. Traditional stove combustion has particularly low efficiency, with a thermal efficiency of only 10–18 %. Even the energy-saving stoves that are being vigorously promoted have thermal efficiencies of only 20–25 %. For biomass boiler combustion, biomass is used as fuel of the boiler. Biomass utilization efficiency can be improved via advanced combustion technology, which is applicable to regions with centralized biomass resources that can be utilized at large scale [54]. According to the combustion mode, boilers can be divided into grate boilers and fluidized-bed boilers.

The grate boiler technology paves the biomass fuel on the grate to form a layer after mixing with primary air, gradually performing the drying, pyrolysis, combustion, and reduction processes. Combustible gas and secondary air can fully mix and combust on the space above the stoker. The boiler type is mainly a chain grate boiler and reciprocating grate boiler. The biomass grate firing technology is widely used for the development and use of agricultural and forestry wastes as well as for the incineration of municipal solid wastes, featuring very low investment and operating costs. Generally, the rated power is below 20 MW [54].

Fluidized combustion, with advantages of high combustion efficiency, low emissions of harmful gases, and improved heat capacity, is suitable for biomass fuels with high moisture contents and low calorific value. According to combustion mode, it can be divided into bubbling fluidized bed combustion and circulating fluidized bed combustion. For a bubbling fluidized bed, under a low gas velocity, biomass combustion reactions are realized via the bubbling fluidized process, which is mainly used in systems with a scale of approximately 20 MW. The biomass circulating fluidized bed combustion technology achieves turbulence fluidized state under the condition of high flow speed utilizing the gas-solid fluidized process, to make the most of fine particles forming circulations and returning to the bed. It is developed on the basis of improving the combustion performance of the bubbling fluidized bed. It is mainly used in a system with a scale exceeding 30 MW.

Compared to grate boilers, the raw materials of biomass fluidized-bed boilers have strong applicability, which can effectively improve the discharge of pollutants as well as fouling and slagging characteristics, and adapt to varying load operation. However, the bed material agglomeration problems in operation should be emphasized and considered in the design.

3.3.1.2 Biomass briquette combustion technology

Biomass briquettes feature small volume, high density, easy to store and transport, and are free of flying debris. Combustion can stably continue with a long cycle and high combustion efficiency. Both ash and flue gas after combustion have low content of pollutants. It is a clean energy source and its combustion technique is a very good way of utilization. However, since the cost is high and the briquette fuel pressing equipment is still immature, the scale of biomass briquettes in various countries is still not significant, and currently it is only used as a fuel for heating, cooking, and other special purposes, while its applications are to be expanded.

3.3.1.3 Co-firing technology of biomass and coal

In coal-fired industrial boilers, biomass is used to replace some of the coal, thus equipment does not need any or needs only minimal alteration. In terms of its economical scale, high thermal efficiency and effectivity to overcome the influence of raw material supply fluctuations of pure combustion of biomass boilers, it is still a way of combustion utilization with low costs and low risks. In many countries, mixed combustion is the most economical technical option for CO_2 emission reduction.

The main technical schemes for blended combustion of coal and biomass include three types: direct co-combustion, indirect co-combustion, and parallel combustion. The technological route is the following: on the basis of the original boiler equipment, the biomass receiving unit is added, as well as storage and pretreatment equipment, to enable biomass fuel to be added to the mixed combustion with coal powder in the boiler in the granularity. Furthermore, the original fuel delivery system and boiler pulverized coal burner should be partially transformed according to the characteristics of biomass fuels.

3.3.1.4 Biomass gasification combustion technology

The volatile content of biomass is high (70–90 %). Under a relatively low heating temperature, some solid fuel will be converted to volatile gases. The produced high-grade fuel gas can be utilized for both industrial and domestic purposes, or for power generation via an internal combustion engine or a steam turbine for cogeneration. The calorific value of a typical gas after biomass gasification is generally 2–6 MJ/m^3. At present, the main biomass gasification technologies are biomass-coal mixed combustion and IGCC technology of biomass. Widely used gasification devices are atmospheric circulating fluidized beds (ACFB) and pressurized circulating fluidized beds (CPCFB).

3.3.2 Biomass hot air furnace

A hot air furnace is the main auxiliary equipment for devices for pneumatic drying, spray drying, fluidized drying, tower type drying, tunnel drying, and rotary drying; it is also the main equipment used for warming greenhouses and livestock farms. This is widely used for industrial production, processing of agricultural products and food, metallurgy, building materials, and similar items [55]. The technological economy index of drying equipment will be directly influenced by the performance of a hot air furnace.

Biomass fuel has the following general properties: high moisture content; low ash content; high volatiles content; comparatively lower calorific value, and irregular shape. Therefore, at present, different combustion apparatuses of hot air furnace are developed based on the properties of biomass fuel.

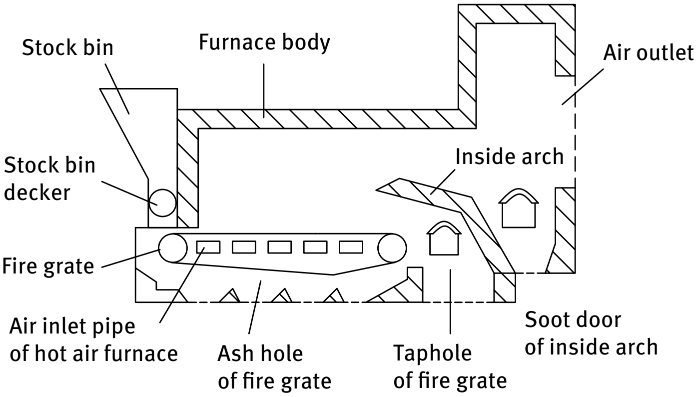


Fig. 3.18: Structural diagram of pre-drying hot air furnace [55].

A stratified combustion apparatus of biomass fuel, as shown in Fig. 3.18 [55], can adopt a stratified combustion technology that is similar to the form of lump coal. In the case that biomass fuel with an irregular shape is sent to the fire grate by the hopper, it may be hard for the air to be well distributed, resulting in low combustion efficiency. Furthermore, if the moisture content of the biomass fuel is high, the fuel will be hard to ignite on the bed surface or the ignition will be delayed and thus cannot burn out in time, resulting in low combustion efficiency and low heat efficiency of the heating apparatus. The actual operating heat efficiency of a stratified combustion apparatus ranges even below 40 %. Moreover, there will be no ash layer on the fire grate to prevent the overheating of the rear fire grate after burning out due to the shortage of ash content, which will easily result in the fire grate burning out.

3.3.2.1 Fluidized-bed combustion apparatus of biomass fuel

The fluidized-bed reactor has the following advantages: improved distribution of mix, greater heat and mass transfer coefficient, high combustion efficiency, less emission of noxious gases, easily controlled process, and high reaction capacity. However, biomass is irregular with shapes such as strips, polygons, angles and similar, with large differences between equivalent diameters; it is easy to deform and break under the effect of airflow and therefore cannot be used for fluidized combustion on a fluidized bed in singles. Generally, it can be mixed with inert material, which is easy to obtain at low price, such as sand and dolomite, to form a bi-component mixture with biomass fuel, which will solve the problem of biomass which is hard to be fluidized [56].

One of the crucial problems of fluidized-bed combustion of biomass fuel is how to choose the category and size of raw material and how to attain the fluidizing velocity when the fluidizing velocity of single biomass cannot be attained and the original correlation equation cannot be used. Moreover, there is a strong difference between different fluidization curve shapes of biomass bi-components, which makes it difficult to arrive at a general forecast equation. Therefore, the minimum fluidization velocity of a bi-component mixture of biomass and inert particle should be determined by a test [56]. A further problem lies in the mixture and separation of inert materials and biomass fuel. Both materials are required to be uniformly mixed without separation when the biomass is burning on the fluidized bed.

The current combustion technology of biomass on a fluidized bed has been industrialized. In Sweden, the branches, foliage, forest waste, bark, sawdust, and fragments of turf are chopped up and sent to a thermal power plant.

3.3.2.2 Apparatus for diffusive combustion of biomass fuel

The combustion mode of a diffusive combustion apparatus disperses the kibbling biomass fuel (rice husk, finely ground straw, and similar items) with mechanical power or wind power, and then burns it in air. In the combustion chamber of such a furnace, the biomass fuel will come into sufficient contact with the air and can thus be completely burned with a comparatively steady temperature. According to different structures, this can be divided into biomass multi-chamber combustion apparatuses, biomass concentric vortex combustion apparatuses, biomass two-stage combustion apparatuses, and biomass inclined fire grate vortex combustion apparatuses.

If dedusting can be conducted thoroughly, all these three biomass combustion apparatuses can be used to directly heat hot air. At present, the stratified combustion apparatus is mainly used in indirect heating hot air furnaces on account of incomplete combustion and that major noxious gases are contained in the resulting smoke. For the fluidized-bed combustion apparatus, it is mainly used for boiler and gasifier at present due to its comparatively high cost and comparatively complicated operational conditions. Combustion in the diffusive combustion apparatus is more complete; however, there is no actual application in China due to its high cost and complicated operational conditions; yet, it has been applied in other countries [24].

3.3.3 Heating industrial boiler

In general, the power of combustion systems of industrial boilers exceeds 100 kW, and fossil fuel or biomass fuel will be generally used as capacity resources that can produce high temperature flue gas to directly heat or produce high temperature steam by heating the flue gas used to heat. Generally, airflow or a mechanical feeding system is integrated into those systems, to meet the requirements of human cost and strict pollutants control. Typically, process control systems are included in the system, which will support full automatic operation. Fig. 3.19 shows a typical industrial heating system with biomass fuel.

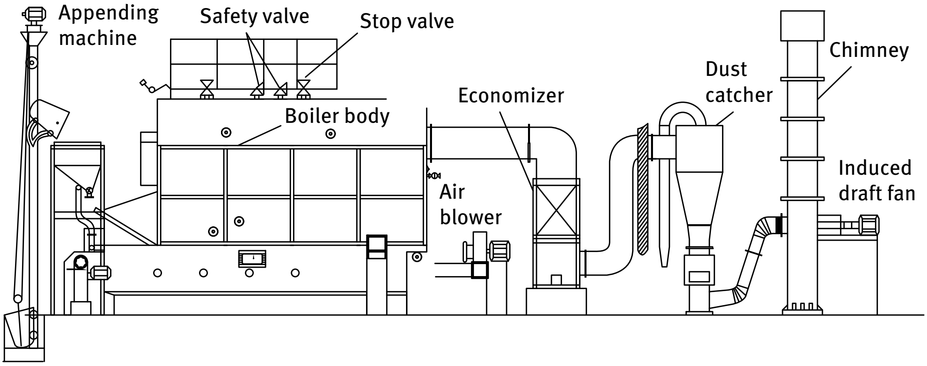


Fig. 3.19: Biomass industrial heating system.

3.3.3.1 Fuel characteristics of the biomass industrial boiler

Numerous experimental studies have revealed that the calorific value of biomass fuel is a little below that of secondary soft coal, which is typically used in industrial boilers. Compared to coal, the volatiles in biomass fuels are higher, which makes them easy to burn. Moreover, the ash content in biomass fuel is very low; therefore, the biomass burns out easily. There is basically no sulfur contained and few noxious gases are emitted after combustion, such as SO_X and similar. The CO_2 emitted during the whole period of growth and utilization of biomass is close to zero. The combustion of biomass fuels in boiler facilities does not exacerbate the greenhouse effect. Therefore, compared to coal, biomass is a clean fuel, which can be utilized efficiently. It is feasible to replace coal with biomass fuels as boiler fuel. However, there are still some features in biomass fuel that make combustion difficult, such as:

(1) If the air is insufficient or the temperature is low after many volatile components have been released, then the volatile components are easy to split and separate out carbon black, which will produce black smoke.
(2) The content of fixed carbon is low; thus, the duration time of combustion is short.
(3) The high moisture content will cause a low temperature inside the furnace, making it hard to combust steadily; at the same time, more moisture means more flue gas and more heat loss due to exhaust gas.
(4) The content of alkaline matter is high. For high temperature combustion, alkaline matter and the relevant inorganic elements may form slag in the furnace or deposit on the heating surface in the form of fly ash particles, which will negatively influence the heat efficiency of the boiler. At the same time, it will strongly corrode the heat-exchanging surface.
(5) The bulk density of raw biomass is low, which makes it harder to collect and store compared to coal. It also negatively influences the steady operation of combustion equipment.
(6) The raw materials of biomass, especially crop straws, are strongly seasonal. Moreover, the provenance is scattered. Therefore, it is hard to utilize biomass at large scale and with industrialization.

This allows the conclusion that the selection of combustion mode of biomass and the development of combustion technology must fully take the biomass fuel characteristics into account. Ultimately, it needs to ensure the economy and reliability of biomass combustion and utilization, and improve the efficiency of development and utilization of biomass.

3.3.3.2 Practical cases of biomass industrial boilers

The biomass burning and heat supply system generally adopts grate combustion, suspension combustion, and fluidized-bed combustion. Suspension combustion is generally used in boilers of power stations with a large evaporation capacity and such an industrial boiler often supplies steam or hot water for industrial and mining enterprises to meet the requirements of production technology, power, and heating. The evaporation capacity does not exceed 100–200 t/h. Considering the practical cost and burning features of biomass, most of biomass fuel industrial boilers in operation adopt the grate combustion boiler.

3.3.3.2.1 Palm kernel shell boiler made by Guangxi Wuguo Boiler Manufacture Co., Ltd. of China

The boiler is used as equipment in a palm oil refinery and it utilizes the waste material of palm kernels as fuel to produce steam for power and heating of the refinery. The boiler adopts either a dual-drum or a single-drum natural circulation plant for outdoor arrangement. It adopts the mode of reciprocating grate combustion. For this type of combustion, the air sprays the damp and loose palm waste from above the boiler to the hearth of the boiler, and forms part of suspension combustion and maintains a part of grate combustion, which ensures good burning conditions. The features of such a boiler are quick firing and flexiblity, which meets the need of loading adjustment.

3.3.3.2.2 Biomass briquette co-firing boiler made by BWE from Denmark

BWE is the world's leading biomass boiler manufacturer with a common application of biomass boiler products around the world.

The grate combustion technology mainly targets small boilers with fuel heat supply power below 150 MW. For boilers of large power stations, it often adopts the suspension-burning mode or circulating fluidized-bed combustion. The main advantage of grate combustion lies in the flexible requirement of fuel and it requires relatively simple pretreatment and grinding of fuel.

BWE mainly adopts a water-cooling vibrating grate and the grate has a wall with a cooling fin, which connects the flexible pipe for the vibration. After the fuel burns out, the ash is transported from the grate boiler to the ash bucket.

The temperature of steam can reach up to 540 °C. The last superheated pipe often adopts a suspension-pressing plate on the top of the boiler. The design can lead to ash shedding before reaching a certain thickness. Due to different fuels, the biomass grate boiler of BWE includes one for biomass raw material of packaged straw and another one for biomass raw material of small bits of wood.

In addition, BEW has developed the biomass briquette co-firing boiler, which is used for power stations. The co-firing proportion of biomass can range between 0–100 %.

3.3.3.2.3 PRO series biomass sawdust boiler of the British Treco Company

Treco is a British biomass industrial boiler manufacturer. Its PRO series biomass boiler can either use wood pellets or wood chips. The heat output can be adjusted from 175–1,000 kW. One of the key features of the PRO range is its market-leading efficiency in modulation, which means that the boilers are able to maintain a high efficiency of 96 % between 26–100 % of output. This leads to reduced fuel consumption, more heat generation, and a more complete combustion of fuel.

The boiler adopts an automatic hot air ignition system, which enables a fast and easy start and the lambda probe introduces exactly the right amount of oxygen to enable optimum combustion. Under stable burning conditions, the temperature of the gas in the hearth can reach up to 1,300 °C. A levelling auger helps to fit as much ash as possible into the ash bins. With only 0.5–1 % ash per volume of fuel, the PRO's large 240–960 liter ash bins only need to be emptied every 6–8 weeks. The vertical tabulator can move up and down to keep the heat exchanger clean, thus avoiding the deposition of ash on the heat exchange surfaces, while increasing heat efficiency. Due to the above mechanism, the boiler can run for long periods with minimal maintenance or cleaning.

3.3.4 Biomass-fired power generation boiler

3.3.4.1 Technical features of biomass-fired power generation

Biomass-fired power generation utilizes biomass as fuel. The professional boiler burns biomass directly to generate high temperatures and high-pressure steam, which will be converted into power by a turbine generator. The residue heat can be used as energy for industrial or domestic modern application technology. The technology is essentially mature and moves to large-scale commercial applications. It is one of the most important ways for large-scale highly-efficient clean application of biomass resources [57]. Without large transformation of current burning equipment, it can achieve relatively good burning effects. Its promotion and application plays a key role in enhancing the development of biomass technology, thus replacing fossil energy and improving the biological environment.

The biomass-fired boiler adopts biomass as fuel, which is an obvious difference from traditional coal fuels. Firstly, the volatile content of biomass is high with low calorific value and a low ignition point, which causes low burning temperature and the production and control of pollutants change as well. In addition, biomass contains a large amount of alkalis and alkaline earth with a low ash fusion point. It is easy to build up slag. Thus, the ash slag build-up, corrosion of heat surface, and blocking of the flue need to be considered. For a technical condition analysis, the biomass-fired technology can be divided into two types. The first type is for low alkaline biomass fuel, such as burning technology of wood, mainly including suspension, grate, and fluidized combustion. The second type is for high alkaline biomass fuel such as crop straw-fired technology [58].

Grate boilers are the most common type with the longest development history. These adopt a moving grate, which enables continued and automatic operation. The core of the boiler is the grate. The arrangement, size, and shape of the grate vary according to different water content of biomass, different heat value, and different manufacturer. The Danish water-cooling vibrating grate straw-fired technology adopts the grate with a special design, ensuring the burnout of biomass fuel and the elimination of low melting point ash. The design of both hearth and heat surface also considers the ash melting of biomass and the high- and low-temperature corrosion of inorganic impurities of biomass. After introduction of this technology, the operating condition is good except for the adjustment to domestic fuel types and the quality change with pretreatment of fuel and feeding. However, the comparatively high cost impedes its promotion.

The circulating fluidized combustion technology that emerged in the 1980s has many advantages, including high burning efficiency, even wind arrangement, easy control of harmful gas emissions, and large heating capacity, which is suitable for burning straw with high water content and low heat value. The technology meets the national conditions of China and has thus been rapidly developed during recent years. The ash slag within the hearth, corrosion of heat surface, and slagging have been improved. It has been developed to high practical applicability and fuel adaptability, burning features, and pollutant control of fluidized technology of biomass.

3.3.4.2 Applications of biomass-fired power generation

As one of the three main machines of a biomass-fired power plant, the biomass boiler is the most important section of the whole plant and it is the core technology of any power plant. The obvious differences between straw biomass burning and the common fossil fuel burning are the following: the difference between volatile matter precipitation and combustion and semi-coke combustion kinetics is large and different types of biomass have different energy densities and physical properties, and flowing regulations. More specifically, straw biomass often contains a large amount of potassium, chlorine, and other inorganic impurities, which easily leads to slagging, deposition, and high-temperature corrosion of heat surfaces as well as other alkali-related problems. To ensure the efficient and stable operation of a power plant, the biomass boiler should be adapted to the above characteristics of biomass combustion, which has comparatively high technical requirements for the design and manufacturing process [59].

Biomass power generation technology has gained increasing attention in America and Europe. Biomass provides a certain scale in total energy consumption. For example, the GREC power plant in Florida in America is a biomass-fired power plant, which was founded in 2013 and operates since then. The power plant loading capacity is 100 MW and it utilizes wood and other waste as fuel. It adopts the fluidized-bed combustion technology, including biomass burning boiler, condensing turbine, residue heat practice, and the fuel collection process.

In recent years, under the incentive of the Renewable Energy Law and the electricity subsidies policy of relevant renewable energy sources, the biomass power generation industry in China has also entered a phase of rapid development. The Twelfth Five-Year Plan for Renewable Energy Sources aims at reaching a loading capacity of all types of biomass power generation in China of approximately 5.5 million kW by the end of 2010. The amount of biomass energy reached the equivalent of approximately 20 million tons of standard coal, of which the biomass-fired power generation plays a central role. The Chongyang biomass power generation project is the biomass-fired power plant established by the Sunshine Kaidi New Energy Group Co., Ltd. The construction scale is one 120 t/h high-temperature and ultra-high tension circulating fluidized-bed biomass boiler with a 30 MW condensing turbine power generator unit. Its structural schematic diagram is shown in Fig. 3.20. The annual emission reduction of a biomass power plant is estimated to exceed 120,000 CO_2 equivalents. The project adopts the high-temperature and ultra-high pressure biomass circulating fluidized-bed biomass combustion boiler technology. In 2013, China CSEI conducted energy efficiency tests for this project. The results revealed that under full loading operation condition, the combustion efficiency of the biomass circulating fluidized-bed boiler can reach 99 % and the boiler efficiency is above 92 %. To ensure efficient combustion of straw, while avoiding the danger of alkalis, the boiler adopts a biomass crash conveying feeding system, which can better adapt to low energy density, loose volume, and low temperature of volatile matter of biomass fuels.

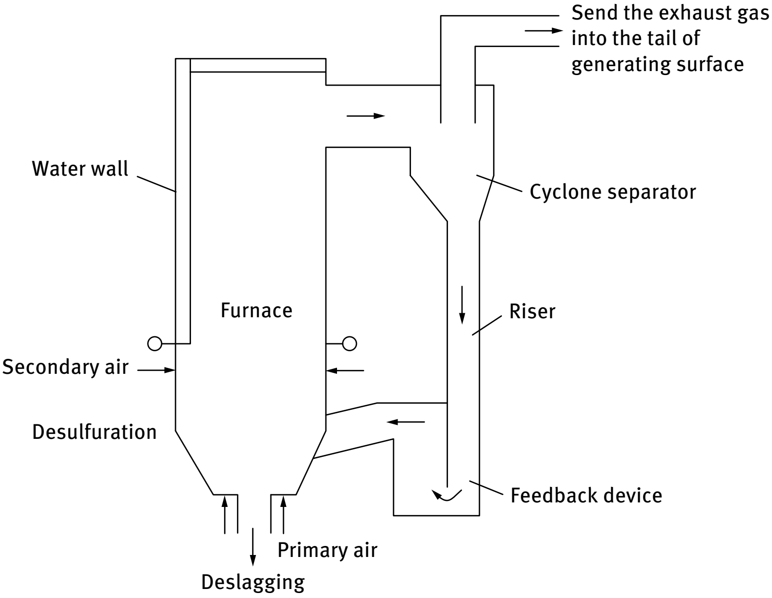


Fig. 3.20: Structural diagram of circulating fluidized bed.

3.3.5 Co-firing boiler

The co-firing of biomass and coal dust adds a certain amount of biomass into the traditional coal-burning boiler to burn with coal for steam, which facilitates the power generation of a turbine power generator unit. The mixing of biomass and coal does not require great transformation of facilities for current coal-fired power plants. It also benefits from lessening the reliance on traditional fossil energy of coal-fired power plants and lowers the emission of numerous pollutants.

3.3.5.1 Classification of co-firing boilers

The modes of co-firing boilers burning biomass and coal can be divided into three types: direct co-firing, indirect co-firing, and parallel co-firing. The structural diagrams are shown in Figs. 3.21, 3.22, and 3.23, respectively and are described in the following.

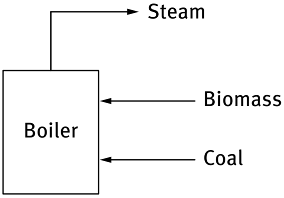


Fig. 3.21: Direct co-firing [59].

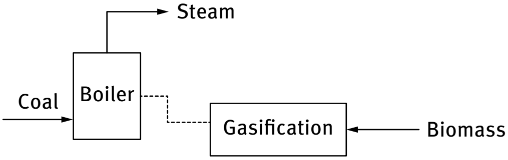


Fig. 3.22: Indirect co-firing [59].

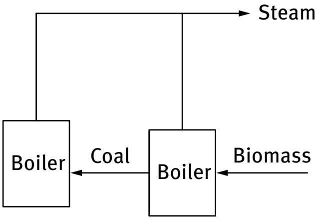


Fig. 3.23: Parallel co-firing [59].

3.3.5.1.1 Direct co-firing

In direct co-firing, both coal and biomass receive a simple treatment before they are transported to the hearth for burning. This is a common co-firing mode with simple operation and low cost.

The coal dust and biomass are mixed before going through the feeder and are then transmitted into a coal mill, which grinds them into particles before distributing them to a coal dust burner. The transformation of this solution costs low initial investment. However, this suffers from the risk of lowering the generation of the coal boiler. Thus, it is only limited to certain types of biomass and low co-firing proportion [60]. If the production of pulverized coal and biomass fuel are separated, the biomass is individually sent to the pipeline or burner after grinding. Two types of fuels will mix in the burner. The solution requires addition of a biomass conveying system, which implies a substantial investment [61]. Although a special production system and a burner for biomass fuel requires high investment cost, the co-firing proportion is very high and it has litte influence on the operation of the boiler. Using biomass fuel as returning fuel, which is burnt in the burner with a special design above the burning hearth, lowers the emission of NO_x. This however, is currently limited to the laboratory [60].

3.3.5.1.2 Indirect co-firing

According to different mixing burning forms of raw biomass materials, indirect co-firing can be divided into two types, which include co-firing between biomass gas and coal, and co-firing between biomass coke and coal. Co-firing between biomass gas and coal refers to the biomass being gasified before being sent to the boiler system for burning. Co-firing between biomass coke and coal refers to the biomass being thermally decomposed at low temperature (300–400 °C), which generates 60–80 % biomass coke to mix with coal. The indirect burning process works well for biomass fuel. It is able to process various types of biomass fuels. However, it requires an additional pretreatment system with high investment cost [62].

3.3.5.1.3 Parallel co-firing

Parallel co-firing refers to burning biomass and coal respectively in an independent biomass boiler and an independent coal boiler and conveying the mixing steam after burning biomass and coal to propel a steam turbine for power generation. Similar to indirect co-firing, parallel co-firing can utilize various type of biomass fuels, including biomass with high alkalis and chloride. The biomass ash and coal ash after burning are separated from each other and benefit the subsequent process [60].

3.3.5.2 State-of-the-art of co-firing boilers

More than 200 biomass co-firing projects around the world have successfully achieved business operation. The machine unit capacity varies from 50 MW to 800 MW, including many low-capacity machine units. Europe has the largest number of such biomass co-firing projects and over 100 projects are currently under operation. Over 40 projects are situated in North America. Most of the remaining projects are distributed throughout Australia. For example, a power plant in the Netherlands uses an ultra-supercritical boiler, which is supplied by the Alstom Company. The fuels are anthracite coal and biomass, and up to 10 % of biomass can be blended. The designed thermal efficiency is 46 %. The unit capacity is 2 × 800 MW. It is expected to be completed and ready for operation in 2015.

The development of biomass co-firing in China is still comparatively slow. A good example is a straw co-firing power plant in the Shandong Province, The plant adopted Denmark's BWE Company's technology, which utilizes an independent spray burning system for co-firing of wheat straw. The mass of designed burnt biomass is 3 × 5 t/h, which equals 60 MW according to the heat value conversion of biomass. Since commissioning, the system has operated well. The power plant enjoys electricity subsidies from the Shandong Power Grid and achieves excellent economic benefits.

Lianhua Li, Changda Cai, and Yongming Sun*

4 Anaerobic processes and biogas technology

With the rapid growth of China's economy, the overuse of fossil fuel has caused severe problems such as fossil resources deficiency, environmental pollution, and ecological destruction. Therefore, the development of clean and renewable energy has become the new consensus.

Biofuel is the fourth largest energy resource after oil, coal, and natural gas; it is also the earliest utilized renewable energy. Biogas is an important type of biofuel and has been used in China for centuries. Along with the rapid development of rural household biogas, large-scale biogas projects also ushered in the golden development period. According to statistics, at the end of 2013, the number of national household biogas digesters was ~43.3 million, and the number of large-scale biogas projects was ~100,000. The annual biogas yield was ~18 billion cubic meters, equivalent to 12 % of the country's annual natural gas consumption. The annual CO_2 emission was 6,100 tons, and the amount of organic fertilizer produced was 410 million tons, thus providing significant economic and social benefits. This chapter describes the principles of the anaerobic digestion process, including microbial species, process equipment, and applications.

4.1 Concepts and principles

Anaerobic digestion is a series of complex biochemical reactions under oxygen (O_2)-free conditions. In general, organic substances are decomposed by particular microorganisms, producing biogas. In this process, most of the energy in organic substances is stored in the form of CH_4, and a small part of CH_4 is oxidized to carbon dioxide (CO_2).

4.1.1 Basic concept

Biogas is a mixture of many components. The main composition of biogas is CH_4 (50–70 % by volume) and CO_2 (25–45 % by volume). Moreover, biogas also contains small amounts of nitrogen (N_2), hydrogen (H_2), O_2, ammonia (NH_3), carbon monoxide (CO),

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Lianhua Li: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China

Changda Cai: Hangzhou Energy & Environmental Engineering Co., Ltd. Hangzhou, 310020, China

***Corresponding Author: Yongming Sun:** Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China; E-mail: sunym@ms.giec.ac.cn , Tel. +86-20-37029835

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Tab. 4.1: Physicochemical properties of CH_4 and biogas.

Characteristics	CH_4	Standard biogas (CH_4 = 60 %, CO_2 < 40 %)
Volume percentage (%)	54–80	100
Calorific value (kJ/L)	35.82	21.52
Explosive range (%)	5–15	8.33–25
Density (g/L)	0.72	1.22
Relative density (g/L)	0.55	0.94
Critical temperature (°C)	−82.5	−25.7 to 48.42
Critical pressure (× 10^5 Pa)	46.4	53.93–59.35
Odor	Odorless	Slight odor

Notes: (1) Explosive range: the concentration range of flammable gas for establishing a detonation wave in the air or oxidation. (2) Critical temperature and critical pressure: the temperature and pressure of the gas beginning where it becomes a liquid, respectively.

hydrogen sulfide (H_2S), and other gases. The main physical and chemical properties of CH_4 and biogas are shown in Tab. 4.1 [2].

4.1.2 Fermentation principle

Anaerobic digestion is mainly divided into four steps: hydrolysis, acidification, acetogenesis, and methanation, as shown in Fig. 4.1 [63].

Hydrolysis: Organic wastes are macromolecules; microorganisms cannot directly use them. Therefore, these macromolecules are first degraded into small water-soluble molecules by the exoenzymes of facultative and obligatory anaerobic bacteria. Carbohydrates are hydrolyzed into simple sugars, proteins are degraded into amino acids, and lipids are cracked into glycerol and fatty acids. These small molecules can pass through microbial cells and are therefore used by microorganisms.

Acidification: The hydrolysis products from the hydrolysis phase are degraded by anaerobic bacteria to short-chain organic acids, alcohols, CO_2, and NH_3. Because volatile organic acids are the main products, this phase is called acidification.

Acetogenesis: Bacteria degrade the volatile organic acids, alcohols, and other products of the acidification phase into acetic acid and H_2.

Methanation: Methanogenic bacteria use acetic acid, CO_2, H_2, and another matrix to form CH_4.

4.1.3 Methanogenic pathway

4.1.3.1 Methanogenic pathway from CO_2 and H_2

Most methanogens can use H_2 and CO_2 as the substrates. The oxidation of H_2 is accompanied by the reduction of CO_2, forming CH_4, which is a unique reaction of

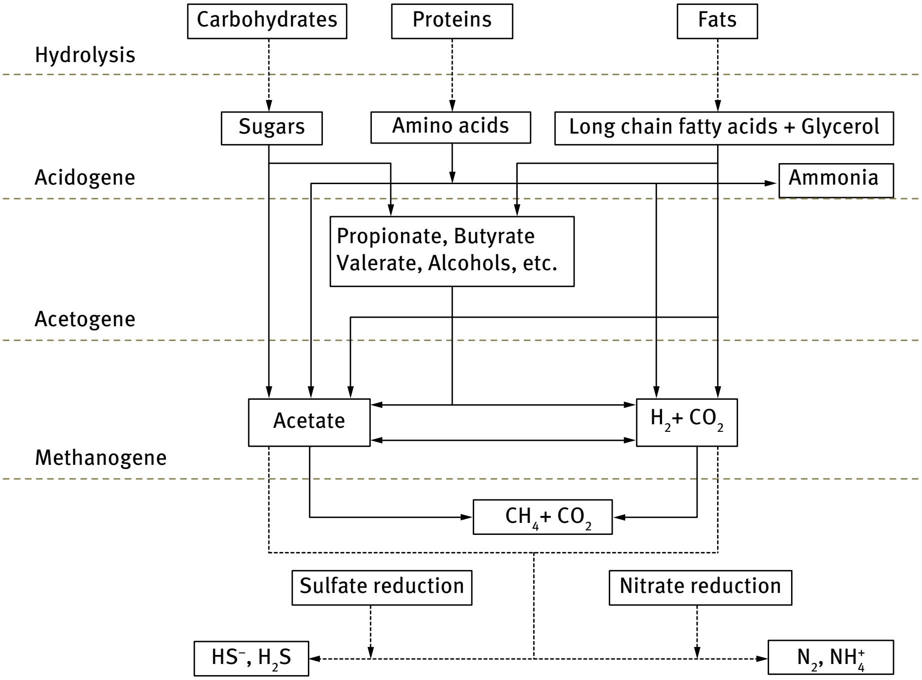


Fig. 4.1: Biochemical process of biogas fermentation.

methanogens in pure cultures. Methanogens obtain energy and synthesize cellular material through this process. The main reaction involved in this process is shown Tab. 4.2. First, the formylmethyl furan dehydrogenase catalyzes the reaction of CO_2 and formylmethyl furan, forming methane formyl furan (formyl-MF); second, the formyl-MF group is transferred to methotrexate (H_4MPT), forming methine-H_4MPT. This process is catalyzed by formyl transferase (formylmethanofuran: H_4MPT formyl-transferase, Ftr); then, N^5,N^5-formyl-H_4MPT reversibly hydrolyzes to N^5,N^{10}-methine-H_4MPT by N^5,N^{10}-methine-H_4MPT ring enzymatically. Under alkaline conditions, N^5,N^{10}-methine-H_4MPT autohydrolyzes to N^{10}-formyl-H_4MPT. In the third stage, methylene-H_4MPT dehydrogenase catalyzes the reaction of methine-H_4MPT and reduces coenzyme F_{420} to generate methylene-H_4MPT, which then further reduces to methyl-H_4MPT. In the fourth stage, the methyl group of methyl-H_4MPT is transferred into coenzyme M, generating methyl coenzyme M. This is very important, because this process is the only energy conversion process in the CO_2 reduction pathway. In the fifth stage, methyl coenzyme M generates CH_4 catalyzed by methyl coenzyme M reductase. In the sixth stage, $F_{420}H_2$ is formed by the reaction of H_2 and F_{420}. In the seventh stage, the reduction of CoM–S–S–HTP generates HS-CoM and HS-HTP catalyzed by an H_2-dependent hybrid disulfide reductase system. The H_2-dependent hybrid disulfide reductase system can be divided into several reactions: First, H_2

Tab. 4.2: Primary stages of the redox reaction of H_2 and CO_2 forming CH_4.

Stage	Reaction	Free Energy (kJ/mol)
First stage	$CO_2 + H_2 + MF \rightarrow HCO{-}MF + H_2O$	16
Second stage	$HCO{-}MF + H_4MPT \rightarrow HCO{-}H_4MPT + MF$	−5
	$HCO{-}H_4MPT + H^+ \rightarrow CH \equiv H_4MPT^+ + H_2O$	−2
Third stage	$CH \equiv H_4MPT^+ + F_{420}H_2 \rightarrow CH_2 = H_4MPT + F_{420} + H^+$	6.5
	$CH_2 = H_4MPT + F_{420}H_2 \rightarrow CH_3{-}H_4MPT + F_{420}$	−5
Fourth stage	$CH_3{-}H_4MPT + HS{-}CoM \rightarrow CH_3{-}S{-}CoM + H_4MPT$	−29
Fifth stage	$CH_3{-}S{-}CoM + HS{-}HTP \rightarrow CH_4 + CoM{-}S{-}S{-}HTP$	−43
Sixth stage	$H_2 + F_{420} \rightarrow F_{420}H_2$	−13.5
Seventh stage	$CoM{-}S{-}S{-}HTP + H_2 \rightarrow HS{-}CoM + HS{-}HTP$	−42
Overall reaction	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	−131

is activated by an F_{420} nonreactive hydrogenase, and the electron is transported to the electron transport chain. Then, CoM–S–S–HTP accepts the electron. Finally, heteroaryl disulfide reductase catalyzes the reduction of CoM–S–S–HTP [64].

4.1.3.2 Methanogenic pathway from acetic acid

Acetic acid is an important intermediate in anaerobic digestion. Although acetic acid is an important precursor of CH_4, only a small number of CH_4-producing bacteria can use acetic acid as the methanogenic substrate. The first stage of conversion of acetic acid to CH_4 involves the activation of acetic acid and synthesis of methylenetetrahydrofolate. Methanogens activate acetic acid using different methods: *Methanosarcina* uses acetate kinase and phosphotransacetylase to activate acetic acid, whereas *Methanothrix* uses acetyl coenzyme A (CoA) (acetic acid + CoA → acetyl CoA + H_2O). The second stage involves the breakdown of acetyl CoA. The C–O and C–C bonds of acetyl CoA are broken, generating a methyl group, carboxyl group, and CoA. This is catalyzed by CO dehydrogenase/acetyl CoA. The carboxyl group is oxidized to CO_2, and the methyl group is transferred to H_4SPT group, eventually forming CH_4 (acetyl CoA + $H_4SPT \rightarrow CH_3\text{-}H_4SPT + CO_2$ + CoA + 2 [H]). The third stage involves electron transfer and energy conversion during this process. When CH_4-producing bacteria use acetic acid and a mixture of $H_2 + CO_2$ as the matrix, the carbon flows from methyl-H_4MPT to CH_4 path are the same, but not the electron flow. When a mixture of $H_2 + CO_2$ is used as the matrix, H_2 is activated by membrane-bound hydrogenase, and electrons are transferred through dissimilation by disulfide reductase. In contrast, when acetic acid is used as the matrix, the electron carrier in methanogens is unclear [65].

4.1.4 Microbial fermentation

Biogas fermentation results from the interaction of complex microorganism, which can be divided into two categories: nonmethanogens and methanogens. Nonmethanogens are mainly facultative anaerobe, including fermentation bacteria, H_2-producing acetogens, and homoacetogenic bacteria.

4.1.4.1 Nonmethanogens

4.1.4.1.1 Fermentation bacteria

Fermentation bacteria hydrolyze cellulose, proteins, lipids, and other complex organic compounds into sugars, peptides, amino acids, fatty acids, and other dissolved organic matter, which are then further converted into acetic acid, propionic acid, butyric acid, H_2, CO_2, etc. Acidogenic fermentation bacterial action: (1) The extracellular release of hydrolytic enzymes facilitates the hydrolysis of insoluble macromolecular organic compounds into small water-soluble organic compounds that are easily absorbed by the cells; (2) when passing through intracellular enzyme systems, small molecules not only provide energy, but also converted to metabolites, which are then released to the extracellular material as a substrate for the next stage of the reaction, mainly organic acids, alcohols, ketones, etc. [66].

At present, the known fermentation bacteria have hundreds of species, mostly obligate anaerobic and facultative anaerobic heterotrophic bacteria. Based on the use of different matrices, these bacteria can be divided into the categories shown in Tab. 4.3 [67].

Tab. 4.3: Representative strains of fermentation bacteria strains.

Species	Representative strains
Cellulolytic bacteria	*A. cellulolyticus*, *C. stercorarium*, *Bacteroides succinogenes*, *Butyrivibrio fibrisolvens*, *Ruminococcus flavefaciens*, *C. lochheadii*, *C. longisporum*, *C. cellobioparus*, *C. cellulovorans*, *C. populeii, C. papyrosolvens*, *B. cellulosolvens*, *C. stercorarium*, etc.
Xylan (hemicellulose) decomposing bacteria	*Bacteroides ruminicola*, *B. fibrisolvens*, *Butyrivibrio fibrisolvens*, *B. xylanolyticus*, etc.
Pectinolytic bacteria	*Lachnospira multiparous*, *B. fibrisolvens*, *B. succinogenes*, *Clostridium pentinovorum*, *C. felsineum*, *B. petinophilus*, *B. galacturonicus*, etc.
Amylolytic bacteria	*B. amylophilus*, *Streptococcus bovis*, *Selenomonas ruminantium*, *Succinomonas amylolytica*, *B. ruminicola*, etc.
Proteolytic bacteria	*C. putrificum*, *C. thermoputrificum*, *C. paraputificum*, etc.
Lipolysis bacteria	*Anaerovibrio lipolytic*, etc.

4.1.4.1.2 H_2-producing acetogens

H_2-producing acetogens are strictly anaerobic bacteria with a long growth cycle, and most of them are mutually symbiotic bacteria. The H_2-producing acetogens are located in the trophic niche between acidogenic and methanogenic bacteria. They play an important role in connecting the functional niche, they further degrade propionic acid, butyric acid, and other volatile organic acids and ethanol into acetic acid and a mixture of CO_2 and H_2, and provide direct access to the substrate for the subsequent methanogenic bacteria. The metabolic characteristics of H_2-producing acetogens are as follows: The sole electron acceptor is a proton; most of the oxidation involves thermodynamic energy absorption in the standard state; growth and metabolism depend on the metabolite elimination of H_2 or formic acid. Thus, the bacteria must be cocultured with the H_2-consuming bacteria such as methanogens and sulfate-reducing bacteria to maintain their growth.

4.1.4.1.3 Homoacetogenic bacteria

Homoacetogenic bacteria, also known as H_2-consuming acetogenic bacteria, not only utilize organic matter to produce acetic acid, but also utilize H_2 and CO_2 to produce acetic acid. Homoacetogenic bacteria provide a direct substrate for CH_4 production. Homoacetogenic bacteria can directly use H_2, which can effectively reduce the H_2 partial pressure of the anaerobic digestion system in favor of biogas production. The mainly studied homoacetogenic acid bacteria are *Acetobacterium woodii*, *Acetobacterium wieringa*, *Clostridium aceticum*, *Clostridium thermoautotrophicum*, *Butyribacterium methylotrophicum*.

4.1.4.2 Methanogens

Methanogenic bacteria exist in different forms such as short rod, long rod-shaped or curved rod-shaped, filamentous, spherical, irregular quasi-spherical monomers, and assembled into irregular shape. The common methanogens have four forms: eight overlapping spherical, rod-shaped, spherical, and spiral. Methanogens have many common features:

(1) slow growth, for example, when growing on acetic acid, *Methanosarcina* doubling time is 1–2 d, whereas *Methanothrix* doubling time is 4–9 d;
(2) strictly anaerobic, sensitive to O_2 and cannot survive in air;
(3) use only a small number of simple compounds as the nutrient;
(4) live in a neutral or slightly alkaline environment under suitable temperature conditions;
(5) the main end-product of metabolic activity is biogas (CH_4 and CO_2 are the main) [68].

4.1.4.2.1 Isolation and cultivation of methanogens

Methanogens are strictly anaerobes and extremely sensitive to O_2, widely distributing in the sediments and animal digestive sludge. Their separation is usually carried out by two methods:

(1) Enrichment culture screening. Because only a small number of methanogenic microorganisms can take advantage of the growth matrix under anaerobic conditions, others such as sulfate and sulfur-reducing bacteria, denitrifying bacteria, and photosynthetic bacteria can be removed in a bacteria enrichment medium by removing sulfate, sulfur, nitrates, and cultivation methods in the dark. Therefore, it is a very effective separation method.

(2) As methanogens are archaea, antibiotics have no effect on these enzyme systems. Therefore, this is a method of separation.

4.1.4.2.2 Nutritional characteristics of methanogens

Carbon source: The main characteristics of methanogenic bacteria are their catabolic characteristics. Different types of methanogenic bacteria differ significantly, but as one group, they can use several simple compounds, most containing only one C. Therefore, methanogenic bacteria depend on other microorganisms to provide matrix. Therefore, most of the organic matter can be eventually converted to CH_4 with the interaction of different groups of microorganisms [69].

The most common reaction of methanogenic bacteria is the metabolism of CO_2 to generate CH_4 using H_2 as the reducing agent. Most of the methanogenic bacteria using H_2/CO_2 to generate CH_4 (H_2 nutrition) also use formic acid as an electron donor to reduce CO_2 using formate dehydrogenase.

Acetic acid is an important end-product of diverse fermentation pathways, and about two-thirds of CH_4 in the anaerobic digester is produced by acetic acid cleavage. *Methanosarcina* and *Methanothrix* can use acetic acid as the substrate. *Methanosarcina* bacteria grow faster and have higher cell yields, and they can use several different substrates, including aromatic groups, and sometimes a mixture of H_2 and CO_2.

Methanothermobacter thermautotrophicus and *Methanosarcina barkeri* can receive electrons from CO using CO dehydrogenase for growth, but their growth is relatively slow. Furthermore, some of the hydrogenotrophic methanogens can utilize a short-chain alcohol as the electron donor, resulting in the oxidation of secondary alcohols to ketones and further to carboxylic acids.

Methanol is not the main precursor of CH_4 in anaerobic habitats; a small amount of methanol is usually generated by pectin or some methyl-compounds. *Methanosphaera stadtmanae* can only grow with methanol and H_2.

Methylamines, particularly trimethylamine, are the anaerobic degradation products of methylated amino compounds and CH_4 precursors, but not all the methylotrophic methanogenic bacteria can utilize methyl sulfide.

Nitrogen source: Methanogens have poor ability to use amino acids. *Methanobacterium ruminantium* grows using amino acids. Trypticase can stimulate the growth of some methanogens. *Methanobacterium thermoautotrophicum* containing glutamate synthase can make glutamate available as the sole source of nitrogen, and some methanogens can utilize urea, purine, and molecular N_2. In general, in the presence of amino acids in the growth medium, the generation time can be shortened, and the cell yields can be increased, but *Methanothermobacter thermautotrophicus* is not affected.

Sulfur source: Sulfide is commonly used as the sulfur reductant and sulfur source in methanogenic culture. Some methanogenic bacteria can also use other inorganic sulfur sources such as elemental sulfur, sulfate, sulfite, and thiosulfate. Methanogens reduce the assimilation of sulfate and sulfite; therefore, these compounds cannot be used as an alternative electron donor. Organic sulfur sources include methionine and cysteine.

Growth Factors: Some methanogens must also have certain vitamins, and some need rumen fluid to thrive.

4.1.4.2.3 Classification of methanogens

To describe new methanogens, Boone and Whitman presented a standard classification method of methanogen, including pure culture, morphology, gram stain, solubility, mobility, nutrition-type feature, antigen fingerprint, final product, growth rate, growth conditions, the G+C content of DNA, lipid analysis, distribution of polyamine, nucleic acid hybridization, and 16S rRNA sequence analysis. The most effective method of classification is polyphasic taxonomy, which can more objectively and comprehensively show the status of each taxon methanogen evolution in natural systems. The data include phenotypic classes and genotypes of phylogenetic marker classes. The use of a comprehensive system of classification and identification technology can help to find more new CH_4-producing microorganism in nature.

"Berger's Manual of Systematic Bacteriology (9th edition)" summarizes and establishes a phylogeny-based classification system for methanogens. The system divides methanogens into five orders, namely, *Methanobacteriales, Methanococcales, Methanomicrobiales, Methanosarcinales*, and *Methanopyrales* [70]. They can be further divided into 10 families and 31 genera, as shown in Tab. 4.4.

(1) Methanobacteriales

The distinctive feature of Methanobacteriales is the limited availability of metabolic substrates; morphologies, lipid compositions, and rDNA sequences are also significantly different. Generally, the bacteria in Methanobacteriales use H_2 and CO_2 to produce CH_4. Some also use formic acid, CO, or dihydric alcohol as the electron donor in the reduction of CO_2. *Methanosphaera* can use H_2 and methanol to produce CH_4. The polymer of cell wall of Methanobacteriales is false murein, which distinguished them from *Methanomicrobiales*. The cells are gram-

Tab. 4.4: Methanogenic species.

Order	Family	Genus
Methanobacteriales	Methanobacteriaceae	Methanobacterium
		Methanobrevibacter
		Methanosphaera
		Methanothermobacter
	Methanothermaceae	Methanothermus
Methanococcales	Methanococcaceae	Methanococcus
		Methanothermococcus
	Methanocaldococcaceae	Methanocaldococcus
		Methanotorris
Methanomicrobiales	Methanomicrobiales	Methanomicrobium
		Methanolacinia
		Methanogenium
		Methanoculleus
		Methanoplanus
		Methanofollis
	Methanocorpusculaceae	Methanocorpusculaceae
	Methanospirillaceae	Methanospirillum
Methanosarcinales	Methanosarcinaceae	Methanosarcina
		Methanolobus
		Methanococcoides
		Methanohalophilus
		Methanosalsus
		Methanohalobium
	Methanosaetaceae	Methanosaeta
Methanopyrales	–	Methanopyrus

positive and rod-shaped, often existing in long chains or 40 μm long filaments. Methanobacteriales can be divided into *Methanobacteriaceae* and *Methanothermaceae*.

(2) Methanococcales

Methanococcales has two families and four species, all of them are irregular spherical, protein-containing cell walls, and can move with polar flagella. In the presence of a cleaning agent, the cells can be dissolved rapidly. Except for *Methanocaldococcus jannaschii*, other methanogenic bacteria lack C40 glycerides. Except Methanocaldococcus, other species can utilize H_2 and formic acid as the electron donor. Typically, selenium can stimulate the growth.

(3) Methanomicrobiales

According to 16S rRNA sequence similarity, Methanomicrobiales is divided into three families: Methanomicrobiaceae, Methanocorpusculaceae, and Methanospirillaceae. Because of its unique characteristics in morphology, *Methanospirillaceae* clearly differ from the other two subjects. All Methanomicrobiales can utilize H_2 and CO_2 to produce CH_4. Many of these species can use formic acid and two alcohols as the alternative electron donor, but cannot use acetic acid and compounds containing a methyl group. These species have different shapes, including spherical, rod-shaped, and rod with shell. Except two psychrotrophic strains (*Methanogenium marinum* and *M. frigidum*) and a thermophilic strain (*Methanoculleus thermophilicus*), many species are mesophilic. Except acidophilus bacteria (*Methanoregula boonei*) living in suitable pH of 5 or so, most species grow better in almost neutral pH.

(4) Methanosarcinales
Boone et al. reclassified acetotrophic and methylotrophic methanogens into two families. The methanogens are spherical or rod-shaped; most cell walls contain proteins; some have a shell enclosing or acidic heteropolysaccharide, but have no peptidoglycan and false murein. This type of bacteria can widely use matrix such as mixture of H_2 and CO_2 and acetic acid.

(5) Methanopyrales
Methanopyrales contain only one methanogen (*Methanopyrus kandleri*) and have no relationship with other known methanogens. It is the only known microorganism that can produce CH_4 above 110 °C. The bacteria can only use H_2 to convert CO_2 to CH_4; thus, it is an autotrophic methanogenic bacterium that can only use CO_2 as the sole carbon source. Amines and sulfur compounds can be used as the nitrogen and sulfur sources, respectively. The growth temperature is in the range 84–110 °C, and the optimum growth temperature is 98 °C. The growth pH ranges from 5.5 to 7, and suitable pH is 6.5. The NaCl concentration for growth ranges from 0.2 % to 4 %, and suitable NaCl concentration for the growth is 2 % (w/v). In the presence of S, it may be reformed to H_2S, and the cells tend to dissolve. The G+C content of DNA is 60 mol %. Based on 16S rRNA gene, phylogenetic analysis, and transcription elongation factor, *M. kandleri* has a significant correlation with other methanogenic bacteria, but based on the use of methyl coenzyme M reductase system, translation factors, and the development of entire genome sequence analysis, *M. kandleri* has close correlation with other methanogens. Thus, *M. kandleri* may belong to a separate branch of methanogens, instead of a branch of archaebacteria. The development of branch in 16S rRNA system tree is mainly because *M. kandleri* has a high GC content.

4.1.4.3 Microbial communities and their interactions during anaerobic digestion

Microorganisms in the anaerobic digestion process do not have a simple continuous relationship, but a complex balance of the ecosystem. The two groups, non-methanogenic and methanogenic bacteria, are interdependent on each other and create a good environment and conditions to sustain life. The relationships between groups of anaerobic microorganisms have the following aspects [71].

4.1.4.3.1 Non-methanogens provide a substrate for methanogens

Non-methanogen strains can ferment and hydrolyze complex organic compounds, such as carbohydrates, fats, proteins, producing H_2, CO_2, NH_3, volatile organic acids, ethanol, etc. Thus, non-methanogens provide carbon sources, electron donors, and nitrogen for methanogens.

4.1.4.3.2 Non-methanogens create redox conditions for methanogens

The air present in the reactor would inhibit the methanogenic bacteria, and even produce toxic effects. Microbial activity can consume the O_2 in air using aerobic and facultative anaerobic bacteria. Besides, diverse anaerobic microorganisms adapt to different redox potentials, and they grow and act alternatively, so that the redox potential of fermentation liquid gradually decrease, sequentially creating appropriate redox conditions for the growth of methanogens.

4.1.4.3.3 Non-methanogens create a suitable environment for methanogens

When wastewater is used as the raw material for anaerobic digestion, it may contain phenols, benzoic acid, cyanide, long-chain fatty acids, heavy metals, and other toxic compounds harmful to methanogens. Many types of non-methanogenic bacteria can cleave the benzene ring and degrade cyanide. These effects not only reduce the toxicity to methanogens, but also provide nutrients for methanogens. Moreover, the H_2S produced by non-methanogens can form insoluble metal sulfide precipitates with heavy metal ions, thus reducing some of the toxic effects of heavy metals.

4.1.4.3.4 Non-methanogenic and methanogenic bacteria together maintain a suitable pH

In the initial stage of anaerobic digestion, with the degradation of sugar, starch, and other materials, a large amount of organic acids is produced, and CO_2 is also partially soluble in water, thus decreasing the pH of the anaerobic digestion system. In this time, on one hand, the ammonifiers in non-methanogenic bacteria undergo rapid amination reaction, and the produced NH_3 neutralizes some of the acid produced; on the other hand, methanogenic bacteria use acetic acid, formic acid, H_2, and CO_2 to produce CH_4 and consume acid and CO_2. Because of the joint action of the two groups, the pH is stabilized at an appropriate range.

4.1.4.3.5 Methanogens release feedback inhibition for non-methanogens

The fermentation products of non-methanogens can suppress their own activities. In the normal operation of a digestion reactor, the methanogens can continuously use H_2, acetic acid, and CO_2 produced by non-methanogenic bacteria to generate CH_4. Without the feedback inhibition by the accumulation of H_2 and acids, non-methanogen metabolism occurs normally.

4.1.5 Microbial regulatory process

Biogas is produced from organic substances through anaerobic digestion by diverse bacterial populations. Only under the optimal growth conditions bacteria can grow rapidly to achieve efficient biogas production. Taken together, the basic conditions for producing biogas include a strict anaerobic environment, a suitable fermentation temperature, the optimum C/N ratio of raw materials, the optimum feed concentration, and a suitable pH. The process and conditions of the anaerobic digestion system significantly affect the biogas yield. It has been proved that careless control can cause the failure of the entire system. Therefore, good control of the process is the key to maintaining efficient biogas production [72].

4.1.5.1 Strict anaerobic environment

The core of anaerobic digestion is strictly anaerobic bacteria that are particularly sensitive to O_2. The presence of trace amounts of O_2 would inhibit their activity, and may even cause death. Therefore, the redox potential of the anaerobic digestion broth should be as low as possible (nonmethanogenic phase with +100 to −100 mV, methanogenic phase with −150 to −400 mV), and digestion occurs in the anaerobic environment state.

In early phase, some O_2 is present in the raw materials or reactor, but in a confined space; the metabolism of facultative anaerobic and aerobic bacteria rapidly consumes the residual O_2, creating strict anaerobic conditions for methanogens.

4.1.5.2 Fermentation temperature

Temperature is an important factor for biogas production. In general, a temperature of 8–65 °C can produce biogas. The higher the temperature, the higher the rate of gas production, but it is not a linear relationship. Biogas fermentation is divided into three zones: 8–26 °C for room-temperature fermentation, also known as low-temperature fermentation. Biogas production is usually in the range 0.15–0.3 $m^3/(m^3 \cdot d)$; 28–38 °C for mesophilic anaerobic digestion, the optimum temperature is about 35 °C, biogas production is 1.0–2.0 $m^3/(m^3 \cdot d)$; 46–65 °C for thermophilic anaerobic digestion, the optimum temperature is ~55 °C.

4.1.5.3 Raw materials for CH_4 fermentation

Raw materials are fed into the reactor to provide nutrition and energy for maintaining normal microbial activity; this is also the basis for the continuous production of biogas. Many wastes such as straw, manure, and sewage sludge can be used as the raw materials for biogas.

4.1.5.4 Suitable feed concentration

The feed concentrations of anaerobic digestion vary with the process. Generally, the feed concentration is in the range 2–30 %. When the fermented feed concentration is 10 % or less, the feed liquid is in the flowing liquid state, known as wet fermentation. When the feed concentration is more than 20 %, the solution is in the solid form, known as dry fermentation. Too low or too high fermented feed concentration is negative for biogas production. When the concentration is too low, the efficiency of reactor volume is reduced. When the concentration is too high, the water content is too low, and mass and heat transfer are also affected. These are not conducive to the metabolic activity of microbial, and the fermented liquid feed is not easy to break down. This causes massive accumulation of organic acids and damages CH_4 fermentation ecosystems, resulting in slight or no gas production. Therefore, depending on the water content, it is important to use different adaptation processes to ensure the normal production of biogas.

4.1.5.5 Suitable pH

The optimum pH of anaerobic digestion microbes is 6.8 to 7.5. Generally, when the pH is below 6 or above 8, anaerobic digestion process is suppressed, or even stops. This is mainly because pH affects the activity of microbial; by monitoring the volatile acid content to control the feed rate, precise management can be achieved. A high concentration of anaerobic digestion and inoculum with inadequate methanogenic bacteria at the start-up phase or a sudden increase load would imbalance the rate of acid production and CH_4 production, resulting in pH drop. When this occurs, feeding should be stopped; on the other hand, an alkaline substance should be added to adjust the pH or increase the quality of inoculum to make the fermentation process rapidly recover.

4.1.5.6 C/N ratio of raw materials

Carbon is not only an important component of the microbial cytoplasm, but also the material basis of the energy required for life activities. Nitrogen is the main element of microorganism such as proteins and nucleic acids. The C/N ratio of feedstock differs; the gas production also shows a significant difference. From the perspective of nutrition and metabolism, the carbon consumption speed of methanogenic microorganisms is 20 to 30 times faster than that of nitrogen. Therefore, during anaerobic digestion process, the raw material should not only be adequate, but also should be appropriately mixed to maintain a certain C/N ratio, thus not causing nitrogen deficiency or the absence of carbon nutrition affecting normal biogas production. For the other nutrients available under these conditions, the C/N ratio (20 to 30): 1 is normal for anaerobic digestion; in the case of imbalance, anaerobic digestion performance would be affected.

4.1.5.7 Inhibitors

Under normal circumstances, plants do not contain large amounts of toxic substances, but organic wastewater produced from livestock, poultry farms, and factories often contains disinfection and epidemic prevention drugs or toxic substances such as heavy metals. Toxic substances inhibit microbial growth, metabolism, and reproduction. For example, some organochlorines (CH_2Cl_2, $CHCl_3$, CCl_4, etc.) are highly toxic, for example, methylene chloride with concentration of 1 mg/L can cause poisoning of methanogens, leading to fermentation failure.

4.1.5.8 Stirring

Stirring is very important in the anaerobic digestion process; biochemical reactions depend on the metabolic activity of microorganisms. Stirring ensures that microbes are in constant contact with new substrate. Without stirring, the pool clearly undergoes stratification, forming a scum layer, a liquid layer, and sludge layers. Stratification leads to uneven fermentation feedstock, dead corners, and difficulty in releasing the biogas produced. Therefore, the fermentation of raw materials must be uniformly distributed by stirring to break the stratification, increasing opportunities for microorganisms to contact with raw materials, thus accelerating fermentation and increasing biogas production.

4.1.5.9 Inoculum

An artificial anaerobic digestion system must contain methanogenic microorganisms. If the microbial is not effective, biochemical CH_4 production cannot be completed. Therefore, it is very important in early phase to add inoculum containing a sufficient number of methanogenic microorganisms. When the conditions are ripe, it is better to use anaerobic sludge, consistent with ecological requirements, as the inoculum. In the absence of an appropriate inoculum, the enrichment and culture of bacteria is required to expand the number of bacteria.

In summary, biogas fermentation is microflora catabolic process of organics to produce biogas. Biogas microorganisms, similar to other living organisms, adapt to the environment. The necessary conditions to maintain a normal life for biogas microflora are mentioned above; CH_4 production can occur normally by satisfying these conditions.

4.2 Technology and equipment

Depending on the type, scale, local wastewater discharge standards, and the surrounding environmental capacity, types of biogas projects can be divided into eco-friendly and environment-friendly biogas projects. Eco-friendly biogas plants require land to treat the slurry residue, but environment-friendly biogas plants discharge the effluent into the waste pipe network after satisfying the appropriate emission standards. Both types of biogas plant have the relevant technology and equipment for pretreatment, anaerobic digestion, mixing, biogas storage, and utilization of residues. According to the utilization mode of biogas, the purification and upgrading technology and equipment include desulfurization, decarbonization, and dehydration equipment. The efficiency of biogas projects includes a suitable process route and equipment [73].

4.2.1 Pretreatment equipment and technology

Currently, the raw materials for biogas plant include manure, municipal solid waste, straw, agricultural processing residues, industrial waste, and energy herbs. To improve the efficiency of anaerobic fermentation, reduce the content of inhibitor, and accelerate hydrolysis, pretreatment is usually required.

4.2.1.1 Equipment used in manure biogas plant

Preventing solids from entering the downstream process, where they would influence the pipeline, equipment, and structures, and solid–liquid separation is indispensable in biogas engineering.

4.2.1.1.1 Solid–liquid separation

Because the separation process is different, the position and function of solid–liquid separation are not the same. Environmental protection first involves separation and then anaerobic digestion. This removes the suspended solids in wastewater and organic part by solid–liquid separation and reduces the liquid part of the pollutant load and the size of anaerobic reactor and required retention time. This also increases the removal efficiency of COD and improves the quality of effluent. Ecological energy systems first use anaerobic digestion and then the anaerobic residues for solid–liquid separation to enhance the biogas production. The separated residue is used as an organic fertilizer, and the biogas slurry is used for farmland irrigation or as a liquid organic fertilizer.

4.2.1.1.2 Fixed grid

In biogas projects for agriculture, livestock, and poultry manure, a fixed grid is usually set in the septic tank and pump set; the grid spacing is generally 15–30 mm, which is used to intercept bigger sundries.

4.2.1.1.3 Grid machine

Grid machines, the rotary grid of solid–liquid separator, are widely used in livestock and poultry fields. The device is driven by an electric speed reducer, and the stainless steel equipment includes multiple rows of engineering plastic gear plates and grids. It first sends the floating dirt above the platform, and then the tooth piece and grate rotary meshing process remove the dirt. This is a type of cleaning machine.

4.2.1.1.4 Hydraulic screen

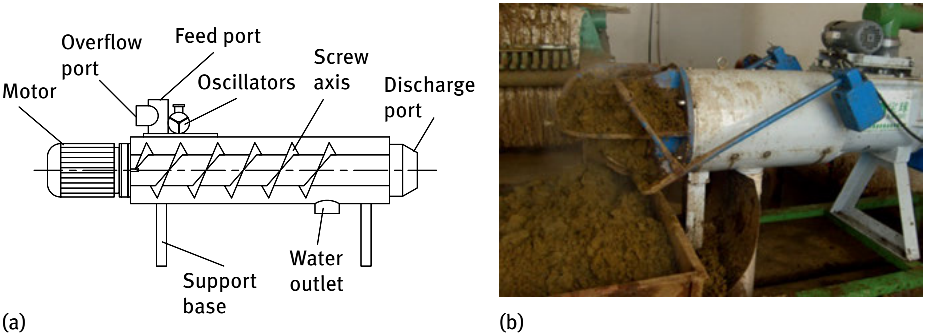
According to the size distribution of poultry and animal feces, solids larger than the size of mesh are left on the screen surface, and the liquid and solid mesh diameters are less than the outflow through the screen. The removal rate of solids depends on the size of mesh. If the mesh is larger, the removal rate is low, but not easy to jam and needs less cleaning. In contrast, if the sieve is smaller, the removal rate is higher, but easier to block, thus requiring more cleaning. Because of its high removal rate the most common sieve is a stainless-steel wedge fixed screen that is not easily blocked and has the advantages of a simple structure and stable and reliable operation. It is commonly used in the solid–liquid separation equipment of sewage treatment in biogas projects on livestock and poultry breeding farms.

4.2.1.1.5 Horizontal centrifugal separator

A horizontal centrifugal separator utilizes the centrifugal force produced by the high-speed rotation of the drum. Then, the solid particles are trapped in the basket, and the suspended liquid is automatically discharged under the action of centrifugal force. Meanwhile, the suspended liquid is passed through the filter medium, and the drum hole is thrown out, thus achieving liquid–solid separation and filtration. It is mainly used for separating small, lightweight, and extremely fine suspended solids. The speed of a horizontal centrifuge is often thousands of rpm, thus requiring a lot of power, resistance, and mechanical strength. Therefore, the power consumption of a horizontal centrifugal separator is very high. Moreover, the operating cost is high, and professional repair and maintenance are required.

4.2.1.1.6 Extrusion-type spiral separator

An extrusion-type spiral separator is a comparatively new solid–liquid separation equipment setup; its structure is shown in Fig. 4.2. A fecal solid–liquid mixture is pumped into the extrusion-type spiral separator from the feed port of the spiral separator. An extrusion screw installed on the screen with 30 rpm speed transfers dehydrated raw manure into the dry matter, and the solid matter formed is separated in the cylindrical machine mouth by phase extrusion. The liquid passes through the screen. The body of the machine is cast, and the surface is coated with a protective paint. The screen has different mesh sizes such as 0.5 mm, 0.75 mm, and 1 mm. Ac-



(a) (b)

Fig. 4.2: Structure of extrusion-type spiral separator.

cording to different requirements of solid substances, humidity can be regulated by adjusting the head of the machine.

The efficiency of an extrusion-type spiral separator depends on the storage time, dry matter content, water viscosity, and average efficiency. The capacity of processing pig manure water is ~20 m^3 per h; the capacity of processing cow dung water is approximately 10–15 m^3 per h, the capacity of processing chicken manure water is approximately 7–12 m^3 per h.

The advantage of an extrusion-type spiral separator is high efficiency. The main components are stainless-steel objects with firm structure, convenient repair and maintenance. The water content of separated dry matter is low, easy to transport, and can be directly used as a fertilizer. The extrusion-type spiral separator is suitable for the energy-efficient engineering of the anaerobic digestion, and it can also be used prior to the separation and anaerobic digestion of solid/liquid mixtures in energy and environmental protection.

4.2.1.1.7 Belt filter

Belt filters are divided into roll-type and extrusion-type filters. The characteristics of a belt filter are as follows: (1) The moisture content of filter cake is low, (2) the capacity to treat sludge is high, (3) convenient operation, (4) no vibration, (5) no noise, and (6) low energy consumption.

4.2.1.2 Pretreatment methods for lignocellulose

Lignocellulosic materials are widely available from many sources with diverse species, including the processing products of agricultural residue, crop straw, and energy plants. It has become one of the main raw materials of biogas projects. The pretreatment of crop straw includes collection, storage, transport, drying, crushing, and other steps.

4.2.1.2.1 Mode of storage and transportation

The storage and transportation of lignocellulosic raw materials include their bundling, loading, transportation, and stacking. The storage and transportation of straw include dispersed storage and centralized storage and transportation in China.

The dispersed collection and storage modes mainly involve farmers, households, and straw brokers as the main bodies who collect the straw and provide it to enterprises. There are specific “company + retail” and “company + broker” modes. The dispersed collection mode allows the vast rural areas and farmers to solve the problem of storage and transportation of straw, breaking the entire stock into parts, solving the problem of storage, and reducing the investment and management of raw materials, without increasing the cost of enterprises. However, this type of storage and transportation of raw materials can be used by farmers and brokers, and may also cause random increases in purchasing price due to the competition for raw materials.

The concentrated storage mode is the storage and transportation of raw material to the farm, which is responsible for raw material collection, drying, storage, safekeeping, and transportation, and according to the requirements of enterprises, selling the raw materials, for quality control and for combined storage. There are mainly two modes: “company + base” mode and “company + storage + transportation company” mode. The storage and transportation company needs to construct large raw material purchasing and storage stations, which occupy land, and also provide protection from rain, moisture, fire, lightning, and facility construction. It requires a lot of manpower and material resources to carry out routine maintenance and management. The one-time investment is large. The cost of depreciation and financial costs of fixed assets are higher, but the model can fundamentally solve the raw material supply randomness and risk, ensure the long-term stability and quality of raw material supply. Thus, it will become the main development direction.

4.2.1.2.2 Grinding

Grinding is the use of mechanical methods to overcome the internal cohesiveness and splitting of solid materials, i.e., the material is broken into small pieces using a large mechanical force. The material crushing and grinding methods can be divided into cutting comminution type, hammer mill, cutting and rubbing type, and combined crushing [5].

A cutting-type crusher is also called a grass-cutting machine or simply a cutting machine; its main function is to chop the stalks The working principle of a cutting crusher involves shear moving and stationary knife, cutting off the crop stalk and crushing them. A cutting-type crusher has the advantages of a simple structure and high productivity.

A hammer crusher is one of the most widely used crushers. A hammer crusher mainly uses a high-speed rotating hammer to produce a strong momentum and crushes the material. The main feature of this model is a simple structure, strong

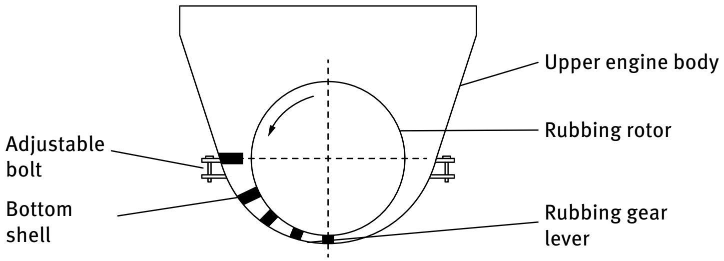


Fig. 4.3: Sketch of rubbing equipment.

adaptability, and convenient repair, good grinding quality, and strong production capacity. The structure of a hammer crusher can be divided into vertical and horizontal. According to the feeding mode, it can be divided into axial and radial type.

A rubbing and cutting crusher is mainly composed of two types of models: kneading machine and rubbing machine. The working principle of a rubbing machine is to change the installed height of the gear plate and fixed knife in the concave plate mill in a spiral direction when the feed material is at the high-speed rotating hammer, along the axial flow. When the crushing material is at a certain degree of pulverization, it will pass through the tooth plate gap into the delivery chamber by the conveying mechanism for collection (Fig. 4.3). Rubbing crushing is a new processing method developed by our national research and development group in recent years. The processing mode is a combination of cutting and crushing after processing the material through a rubbing machine, generally producing more soft and fluffy filaments. The main mechanism of a kneading machine is the rotor; the hammer mainly uses a spiral arrangement in the rotor mechanism. However, a rubbing machine still has the problems of a low production efficiency, high energy consumption, and is not very good with material of high humidity or toughness.

The combined grinding process combines the function of cutting, smashing, and rubbing, and it is a new crushing process. Li from the Northeast Forestry University combined the function of cutting, smashing, and rubbing into a device and designed a composite straw pulverizer, as shown in Fig. 4.4. The new design includes changing the feed port into an automatic feeding device, installing the fan equipment at the discharging port to improve the productivity, and ensuring the quality of grinding. The main power and energy consumption reduced. The composite straw pulverizer has a good adaptability; it can process material with a high humidity or toughness.

4.2.1.2.3 Feeding equipment

Depending on the concentrations of the total solid, the anaerobic feed pump is selected. At low concentrations, one can select the submersible sewage pump and submerged pump, and at high concentrations the screw pump, screw conveyor, and hydraulic pump solid. At present, the most widely used pump in biogas projects is

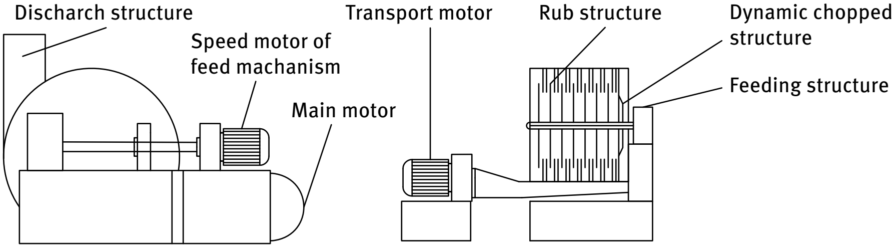


Fig. 4.4: Schematic of the combined grinding processing.

the screw pump, but it has the disadvantages of high cost of maintenance and high energy consumption. At present, the European charge pump mainly has a triple spiral feed, CAM rotor pump, and high-density solid hydraulic pump [74].

(1) Screw pump

The screw pump is a type of positive displacement rotor pump, mainly consisting of a stator and rotor. The mutually compatible stator and rotor form an annular sealed space that is unaccessible from both sides. When the rotor is running in the stator, the sealed cavity moves from the suction side of the pump to the discharge end, and the medium flows continuously inside the cavity from the suction side to the discharge end. The merits of the screw pump are that it does not form vortex transport in the medium and it is not sensitive to medium viscosity. Therefore, the screw pump can transport a high-viscosity medium, but the stator and rotor can be easily damaged. Therefore, they should be changed regularly.

(2) Screw conveyer

The working principle of a screw conveyer is that the rotating spiral blade will continually convey the material. The removal of material from the blades of a screw conveyor depends on the material weight and frictional drag caused by the material on the screw conveyor casing. In the delivery form, the screw conveyer can be divided into two types: shaft and shaftless. The former applies to dry powder materials without stickiness and small particles of material such as cement and fly ash. The latter applies to sticky materials, and the material wraps easily as a sludge, biomass, etc. (Fig. 4.5).

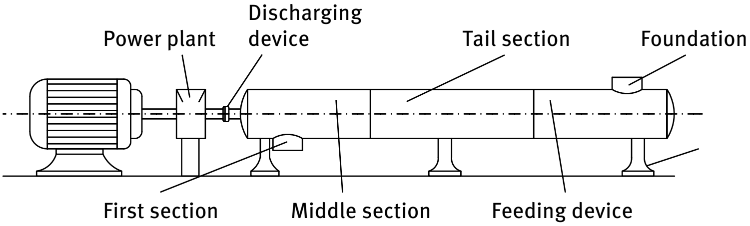


Fig. 4.5: Structure of a screw conveyer.

(3) Hydraulic solid pump

A hydraulic piston pump or solid pump driven by hydraulic power uses a hydraulic oil cylinder to promote the cylindrical transport of materials in the cylinder to the pipeline. Generally, the pump is divided into single plungers. The four types of pump are EKO single plunger pump, KOS, KOV, and HSP. A hydraulic solid pump not only transfers organic solid waste to the anaerobic fermentation reactor, but also separates sundries such as knives, spoons, bottle caps, and glasses. The advantage is very stable and reliable operation, but there are some disadvantages: loud noise, the delivery pressure reaches up to 130 bar, and the displacement reaches 0.5–500 m^3/h.

4.2.1.2.4 Churn-dasher

Pretreatment with a blender mainly involves the collecting tank and slurry pool, to stir the liquid dung and avoid sediment. There are mainly two types of mixer: QJB and vertical installation mixer.

(1) QJB mixer

A diving mixture stirrer has multiple motors with the direct coupling structure with the advantage of low energy consumption and high efficiency. The impeller is made by casting or stamping and has a high precision, thrust, and compact structure. A submersible mixer has propellers, a gear box, a motor, a rail, and lift hanger components.

(2) Vertical installation mixer

Depending on the process route, we can select different sizes of vertical agitator according to the different mixing requirements in the pretreatment. The traditional construction of a box stirrer is simple, but efficiency is low. The propeller agitator and efficient surface axial oars have a typical axial blade for stirring a mixture with a low viscosity fluid with a low shear, strong cycle, high speed, and low energy consumption. Therefore, it is suitable for environmental protection.

In the engineering of high-concentration biogas fermentation, the unit is needed to mix, for example, the slurry pool and the feeding pool. The TS of the slurry and viscosity is high, because particulate matter is present. It is not suitable for a conventional diving/vertical agitator. The 40 % open turbine agitator has cyclic shear capacity running in a low speed, which is suitable for stirring a mixture with a certain concentration and viscosity.

Irrespective of the type of blender, the material should not easily bind to the agitator, such as sundries and plastic bags.

4.2.2 Anaerobic reactor and process

According to differences hydraulic retention time (HRT), sludge retention time (SRT), and microbial retention time (MRT), reactors can be divided into three types (Tab. 4.5). The first type of reactor is a conventional reactor, characterized by the same MRT, SRT, and HRT, i.e., the liquid, solid, and microbial are mixed together and flushed out at the same time. It does not have enough microbes in the reactor, and the solid material cannot be completely digested with a shorter retention time. Therefore, efficiency is low. The second type is a sludge retention reactor, and its MRT, SRT, and HRT are separated by diverse solid–liquid separation methods, thus obtaining a longer MRT and SRT in a short HRT. The microorganisms and solid matter sludge are preserved during the discharging, increasing the microbial concentration in the reactor and prolonging the retention time of solid organic substances to completely digest them at the same time. The third type is the adhesive membrane reactor. This reactor is filled with an inert material for microbial attachment, which can bind microorganisms in the reactor and allow the liquid to flow through, thus enhancing the microbial concentration to effectively improve the efficiency of the reactor. Moreover, dry fermentation and two-phase anaerobic fermentation processes have also been developed to digest high-solid materials and easily acidify materials [75, 76].

Tab. 4.5: Types of anaerobic reactor (process).

Type	Characteristics	Examples
Conventional reactor	MRT = SRT = HRT	Normal reactor Plug flow reactor (PFR) Continuous stirred tank reactor (CSTR)
Sludge retention reactor	MRT and SRT > HRT	Anaerobic contact reactor (ACR) Upflow anaerobic sludge bed (UASB) Upflow solid reactor (USR) Expanded granular sludge bed (EGSB) Internal circulation (IC) anaerobic reactor Anaerobic baffled reactor (ABR)
Adhesive membrane reactor	MRT > SRT.+HRT	Anaerobic filter (AF) Fiber packed bed (FPB) Up-flow blanket filter (UBF) Fluidized anaerobic bed(FBR) Expanded bed reactor (EBR)
Dry fermentation	TS > 20 %	Dry fermentation reactor
Two-phase anaerobic fermentation	Acidification and methanogenesis are separated	Two-phase anaerobic fermentation reactor

4.2.2.1 High-concentration fermentation process and reactor

For high-concentration fermentation, CSTR, ACR, PFR, and USR are the general choice. CSTR and USR will be more suitable for high content of suspended substance with respect to economy and technology; especially CSTR is suitable for the coproduction of heat and power (CHP) without emissions [77].

4.2.2.1.1 CSTR

There is a stirring device in CSTR that completely mixes the substrate and microorganism, thus activating each corner of the reactor. This reactor is suitable for anaerobic fermentation with a high-solid substrate. CSTR can be designed as different structures according to the treatment scale. Horizontal tank, flat vertical tank, and high vertical tank have been designed (Fig. 4.6) [78].

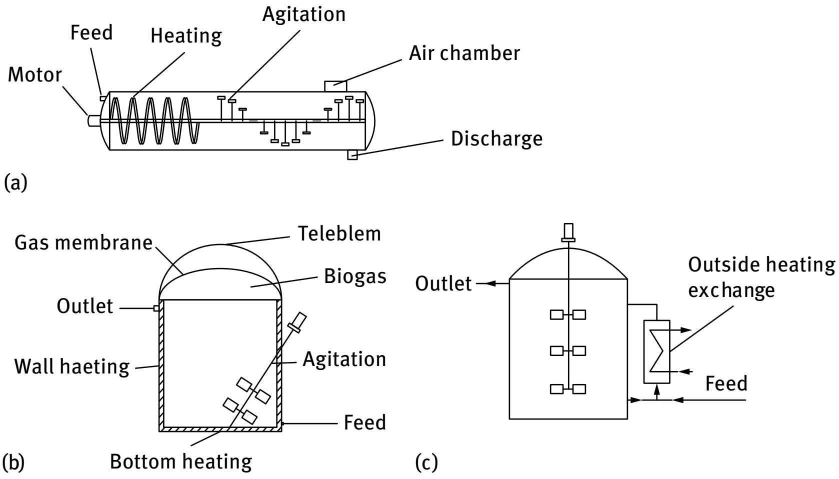


Fig. 4.6: Structure of CSTR.

CSTR is widely used in large- or medium-sized biogas projects in livestock and poultry farms. The outlet liquid of this reactor can be directly used as a liquid organic fertilizer. It can be used to handle the high-solid substrates, and the solid concentration of feeding substrates reaches up to 15 %. The stirring device stirs once every 2–4 h. Usually, stirring is stopped to discharge the digestive fluid and remove the supernatant until the solid and liquid are separated. To ensure the digestion efficiency and biogas production requirements, a long HRT of 10–20 d or longer is necessary. The organic loading rate of mesophilic and thermophilic fermentations are 3–4 kg COD/($m^3 \cdot d$) and 5–6 kg COD/($m^3 \cdot d$), respectively. Because some biological materials may be removed with the discharge at a high feed concentration in CSTR, a second-stage reactor is always needed to achieve a higher material utilization rate. The biogas generated in both the reactors is collected together for subsequent power or gas supply.

Advantages:
(1) The raw material adaptability and shock resistance are good.
(2) The substrate is completely mixed, has a homogeneous temperature distribution, the material and substrate are completely mixed, high fermentation rate, and volumetric gas production rate.
(3) Problems such as substrate precipitation, stratification and surface scum crust, and unfree gas overflow and short flow can be solved by the strong mechanical stirring.
(4) A simple structure, low energy consumption, convenient operation, and management.
(5) A large handling capacity, biogas production, and easy to start.

Disadvantages:
(1) Same HRT and SRT and cannot retain microorganisms.
(2) Needs a large volume digestion tank to satisfy the requirement of a longer HRT and SRT.

4.2.2.1.2 ACR

To overcome the sludge flush in CSTR, a sedimentation tank is added to the digestion tank to reclaim sludge, and this is the ACR process. This process not only decreases the loss of sludge and stablizes effluent quality, but also increases the concentration of sludge in the digestion tank, thus improving the organic load rate and processing efficiency.

The mixed liquid discharged from the digester is still difficult to separate in the sedimentation tank for many small biogas bubbles are attached to the surface of the sludge, making it easy to float; moreover, the sludge can still generate CH_4 during precipitation, preventing the settling and compression of granular sludge. Gas removal is a viable approach to improve separation efficiency. The widely used methods are as follows: (1) Vacuum degassing: Bubbles are removed from the surface of the sludge via the deaerator, improving the sedimentation performance of the activated sludge. (2) Quenching heat exchange: The mixture is discharged from the digester by rapid cooling, preventing sludge from producing gas. Thus, the anaerobic sludge is effectively precipitated. (3) Flocculating settling: The addition of flocculants to the mixture allows anaerobic sludge to easily coalesce into large particles, accelerating the subsidence. (4) An ultrafiltration device is used instead of a sedimentation tank to improve the solid–liquid separation effect. Moreover, to ensure the sedimentation tank separation effect, lower sedimentation tank surface load (less than 1 m/h) and longer residence time (4 h) are used (Fig. 4.7).

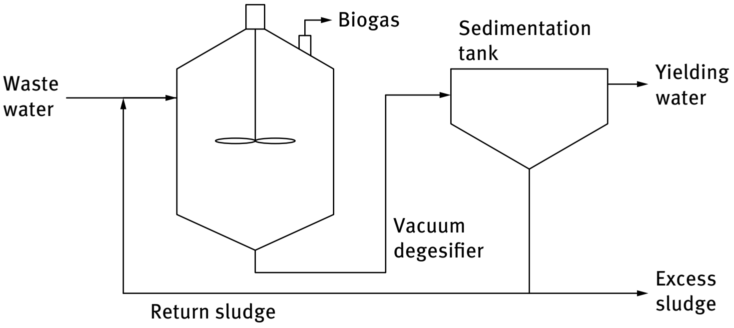


Fig. 4.7: Structure of ACR

Advantages:

(1) It improves the capacity of resisting impact load using sludge reflux. The concentration of sludge in the digester can reach 10–15 g/L.

(2) The volume load of digestive is improved to 4–8 kg COD/$m^3 \cdot d$ under mesophilic condition; the HRT is shortened to 10 d at room temperature.

(3) It can directly utilize the high concentration or large sized solid/liquid without any blocking problem.

(4) It produces high-quality outlet water obtained by precipitation.

Disadvantages:

(1) It requires a higher investment compared to CSTR for the use of additional equipment.

(2) The solid/liquid separation of mixture is difficult in the sedimentation tank.

4.2.2.1.3 PFR

PFR is a rectangular incompletely mixed reactor. A suspended solid substrate with a high concentration is fed into one side of the reactor and discharged on the other side. The reactor does not have a stirring device, but the biogas produced can stir the liquid along the perpendicular direction. The substrate naturally precipitates in the reactor and is generally divided into four layers, from the top to the bottom in the following order: scum layer, supernatant, active layer, and sediment layer. The anaerobic microbial activity occurs in the more exuberant area in the active layer. Therefore, the efficiency of anaerobic microbial activity is low, and it always operates under normal temperature. There is no vertical mixing along the machine direction, and the liquid material after fermentation is drained under the pressure of fresh feed liquid. The feed end has a strong hydrolysis and acidification effect, and CH_4 generation increases along the discharge direction. Solid is returned to the feeding end of the system lacking inoculum. To ensure the stability, a stable baffle should be designed to reduce microbial loss.

Advantages:
(1) No need for stirring, a simple structure, and low energy consumption.
(2) Can be applied to high SS wastewater, especially suitable for the anaerobic digestion of cow dung.
(3) Convenient operation, fewer faults, and high stability.

Disadvantages:
(1) The solids easily precipitate at the bottom of the pool, affecting the effective volume of the reactor, decreasing the HRT and SRT, and low efficiency.
(2) Sludge is returned as inoculum.
(3) It is difficult to maintain a consistent temperature for a reactor with a relatively large specific area.
(4) A thick crust forms easily.

Another form of PFR is an improved high-concentration plug flow process (HCF). HCF is a fermentation device combining plug flow, mixing, and high concentration. The anaerobic tank is stirred mechanically, and the plug flow moves to the back end. The feed end of the HCF anaerobic reactor is located at the top of the grille, and the digester gas chamber is isolated. The feed inlet is on the top of one side of the reactor, and the material liquid is discharged by overflow liquid and sediment form. The technology has the advantages of a high feed concentration, up to 8 % dry matter content, and a low energy consumption – not only a low heating energy consumption, but also a small installed capacity and low power consumption. It has a higher substrate utilization rate compared to PFR. The scum problem is solved. Other advantages are as follows: a simple process flow, less facilities and investment in the project management, simple operation, low operating cost, strong adaptability to raw materials, no preprocessing. The raw material can be directly fed into the pool. The volume of the horizontal single tank is small, making it easy to combine with other facilities (Fig. 4.8).

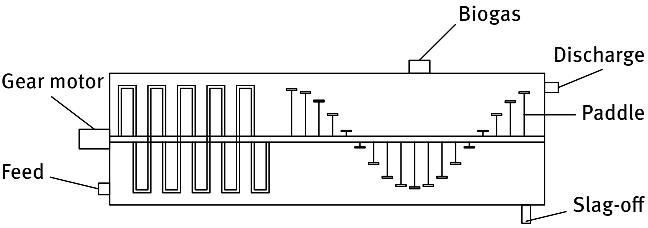


Fig. 4.8: Structure of HCF.

4.2.2.1.4 USR

USR has a simple structure, especially suitable for a highly suspended solid material (Fig. 4.9). The substrate is first fed into the bottom of the reactor and evenly distributed there, and then flows through the solid bed containing a high concentration of anaerobic microorganisms to the top bringing the organic solid completely into contact with anaerobic microorganisms for hydrolytic acidification and anaerobic decomposition. The rising CH_4 bubbles help to stir the mixture, promoting contact between organic solids and microorganisms. Microbial and undigested solid substances with a high special density stranded in the reactor rely on passive sedimentation; thus, the reactor maintains a high concentration of solids and organisms, improving MRT. Discharging the supernatant from the upper part of the reactor provides a much higher HRT and SRT than MRT. Both the three-phase separator and stirring device are absent, and the sludge is not returned. The SS loss can be reduced by arranging the slag blocking plate in front of the water outlet. A layer of scum is present in the reactor, and it reaches a dynamic balance after a certain thickness. The biogas passing through the scum layer into the top of the reactor breaks up the scum layer to a certain degree. The production reactor does not block the scum layer with a larger area. The excess sludge and inert substance can be periodically discharged from the mud pipe at the bottom of the reactor [79].

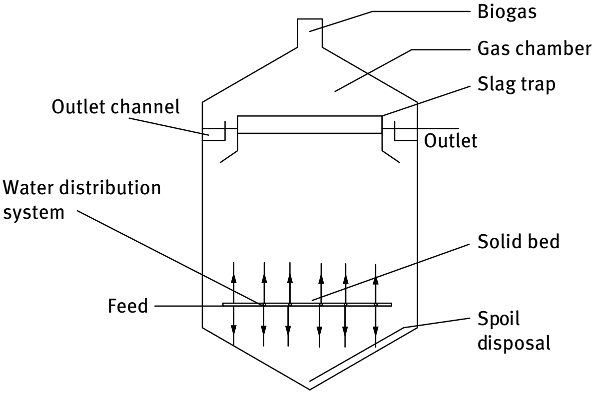


Fig. 4.9: Structure of USB.

According to studies in other countries, when USR was used for mesophilic fermentation with seaweed as the substrate, the TS concentration was 12 %, and the VS load was 1.6–9.6 $kg/(m^3 \cdot d)$. The yield of CH_4 yield was 0.6–3.2 $m^3/(m^3 \cdot d)$. It approaches the efficiency of UASB. However, UASB can only process dissolved organic wastewater, and the SS should be less than 3,500 mg/L.

Capital Normal University uses USR to study chicken manure mesophilic anaerobic fermentation. The feeding TS was 5–6 %, the SS was 45,000–55,000 mg/L, the

COD was 42,000–55,000 mg/L, the HRT was 5 d, the load of the USR was up to 10 kg COD/($m^3 \cdot d$), the gas yield was 4.88 m^3/($m^3 \cdot d$), the CH_4 content was 60 %, the SS the removal rate was 66.2 %, and the removal rate of COD was ~85 %. Such good results can be attributed to the longer SRT and MRT.

USR has a higher practical value in the treatment of a high SS waste according to national and international studies. USR can be utilized for treatment of many high SS wastewaters such as alcohol waste mash, pig manure, and starch wastewater.

Advantages:

(1) A longer SRT and MRT, the main reason for stable operation under high loading.
(2) A longer SRT, sludge is not refluxed, the removal rate of suspended solids is high, up to 60–70 %.
(3) In overload operation, the sludge sedimentation performance deteriorates, and the effluent COD increases, but is not prone to acidification.
(4) High gas production efficiency.

Disadvantages:

(1) Prone to problems such as pipe plugging or short flow for feed solids with a suspended matter content of > 6 %.
(2) The scum breaking facilities in the fermentation tank should be increased to prevent surface crust when dealing with substrates with a high cellulose concentration.
(3) The digestate has a very high COD and is therefore not suitable for emission standards; it is generally used as an agricultural fertilizer.

4.2.2.2 Low concentration fermentation process and reactor

In biogas engineering, a suitable anaerobic device should be selected for low-concentration SS waste, such as upflow sludge bed reactor (UASB), IC reactor, and EGSB [80].

4.2.2.2.1 UASB

UASB technology was developed by Holland G. Lettinga in 1974–1978. It is a suspended growth reactor without a carrier. It has become one of the main anaerobic technologies in the world, especially suitable for the anaerobic digestion of industrial wastewater and domestic sewage with a lower SS concentration. After the solid/liquid separation, swine manure wastewater can also be used in UASB for anaerobic digestion treatment. Its structure is shown in Fig. 4.10.

From the top to the bottom, the reactor is divided into three regions: sludge bed, suspended sludge layer, and gas/liquid/solid three-phase separator. The sludge bed is on the bottom of the reactor; it has good precipitability and cohesive granular sludge.

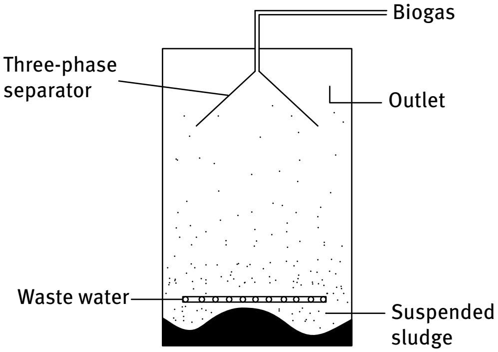


Fig. 4.10: Structure of UASB.

The wastewater is first fed into the sludge bed through the pipe, flows through the sludge bed, and mixes with the sludge, and then the microorganisms in the sludge decompose the organic matter present in the sewage and transform it into biogas. CH_4 is released continuously, and the smaller bubbles merge to become larger bubbles while rising. The upper reactor sludge forms a lower-concentration suspended sludge layer by the rising bubbles and water. The upper part of the reactor does not have a three-phase separator; the generated CH_4 bubbles enter a three-phase separator with the help of a baffle board and are then discharged from the pipeline through a water seal. The solid and liquid enter the settling zone through the narrow separator The precipitation zone is no longer affected by rising bubbles due to the impact of airflow motion with a laminar morphology. The liquid, sludge, and water are separated by the action of gravity, and the sludge along the inclined wall slides back into the sludge layer. Thus, the reactor accumulates a large amount of sludge. The separated liquid outflows from the overflow tank on the surface of the settling zone.

UASB can be divided into open UASB and closed UASB. The open UASB without a seal on top or only a layer of minimal sealing is used for low-concentration organic wastewater treatment. The closed UASB reactor is sealed, thus forming an air-tight chamber between the top surface and pool in the UASB reactor. This is mainly used for the treatment of high-concentration organic wastewater. The operation of a UASB is affected by the organic loading, pH, temperature, and trace elements. The organic loading of a UASB reactor is generally 10–30 $kg/(m^3 \cdot d)$. In general, a relatively low organic load is used in a UASB reactor in the start-up initial stage. The concentration of the influent or intermittent influent is gradually increased to increase the organic loading when the COD removal rate reaches a satisfactory value.

Such a good performance of UASB depends on the formation of a highly active granular sludge with good settling properties. The anaerobic granular sludge is a gray or brown-black special biofilm condensed by methanogens, acetogenic bacteria, and fermentation bacteria owing to biological flocculation and precipitation under a high hydraulic shear. The granular sludge is covered with many filamentous microbes, which intertwine to form an uneven surface. Thus, the specific surface area of the particles increases, favoring the contact of sludge and water to improve mass transfer effects. Granular sludge is generally divided into three types: (1) sludge with tight spherical particles (type A), mainly consisting of CH_4 Sarcina, whose particle size is small, generally 0.1–0.5 mm; (2) spherical particle sludge (type B), mainly consisting of rod-shaped bacteria, filamentous bacteria, and thus also known as rod-shaped bacteria granular sludge. The surface is surrounded by various forms of filamentous methanogenic bacteria. It has a high frequency of occurrence in a UASB reactor, a density of 1.033–1.054 g/cm^3, and the particle size is about 1–3 mm; (3) sludge with loose spherical particles (type C), mainly consisting of filamentous fungus with some inert particles attached to the surface, also known as filamentous fungus granular sludge. The sludge particles have a large particle diameter of generally 1–5 mm, a specific gravity of 1.01–1.05, and the sedimentation rate is usually 5–10 mm/s. When the acetic acid concentration in the reactor is high, granular sludge easily forms type A sludge. When the concentration of acetic acid is reduced, type A is gradually transformed into type B. When a suitable amount of suspended solids is present, C-type granular sludge is easily formed. A high concentration of highly active granular sludge in UASB should be passed through three stages including the start-up period, granular sludge formation, and maturity of sludge particles. It generally takes 1–3 months.

UASB is suitable for the treatment of low-concentration organic wastewater with a low SS. The SS of the inlet water should be less than 3,500 mg/L. If the content of suspended solid is very high, and the solid residues accumulate in the sludge bed, thus significantly decreasing the sludge activity and settling performance, this leads to sludge washout and destroys the sludge bed.

Advantages:

1. The reactor contains a gas/liquid/solid three-phase separator, producing gas and uniform water and achieving good natural mixing. The granular sludge formed in the reactor increases the stability of the process.
2. Sludge concentration up to 20–40 VSS/L. The COD removal efficiency can reach up to 80–95 %.
3. A longer SRT and MRT increase the organic load, shortening the HRT.
4. It usually contains a sedimentation tank and sludge reflux device.
5. It has a simple structure without stirring device and filling, thus saving costs and avoiding blockage problems of packing.
6. The concentration of the suspended solid and organics in the discharged water is low.
7. As the granular sludge formed by the first start-up process can be stored at room temperature for a long time without affecting its activity, the second starting time is shortened, making it possible for intermittent or seasonal operation and simple management.

Disadvantages:
(1) The feed suspension solid content should be low, or it will destroy the sludge bed.
(2) An effective water distribution device is needed to promote the even distribution of substrate on the bottom of the reactor.
(3) It is sensitive to sudden changes in water quality and organic load; thus, the impact resistant ability is very poor.
(4) A short flow may occur within the sludge bed, affecting the processing ability.
(5) When the impact load or the content of suspended solid feed increases, the sludge is easily lost.

4.2.2.2.2 EGSB

EGSB is the third generation of a high-rate anaerobic reactor developed in the Environmental Engineering Department of Kasetsart University in the Netherlands for granular sludge formed in a UASB in the late 1980s (Fig. 4.11). Compared to a UASB, an EGSB reactor adds effluent recycling. Therefore, the surface of the liquid upflow velocity is higher ($> 2.5 - 12\,\mathrm{m} \cdot \mathrm{h}^{-1}$), and the GSB in the expansion state improves the mass transfer of granular sludge.

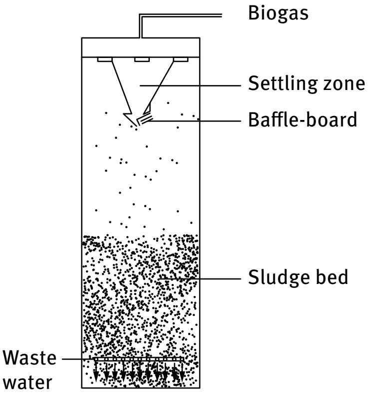


Fig. 4.11: Structure of EGSB.

The main parts of the EGSB reactor includes the following: the main body of the reactor, gas/liquid/solid three-phase separator, and water circulation part. The main functions of the water distribution system are to distribute the water evenly in the bottom of the reactor and produce a uniform upward velocity. Compared to a UASB reactor, an EGSB reactor has a large height (usually 20–30 m), large diameter ratio, and high reflux ratio. It reduces the required water distribution area, increases the speed, and maintains the granular sludge in the suspended state, i.e., the GSB remains in the “expansion” state partly or completely, promoting the complete contact of water and granular sludge. Therefore, the wastewater in the reactor has a short HRT and high volume load of up to 20–30 kg COD/($\mathrm{m}^3 \cdot \mathrm{d}$). Thus, the EGSB can process low-concentration organic wastewater. Water circulation improves the liquid upflow velocity, completely expands the GSB, facilitates complete contact between sewage and microorganism, strengthens the mass transfer effect in the reactor, and avoids dead angles and short flow.

It is generally believed that a UASB reactor is more suitable for the treatment of wastewater of up to 1,500 mg COD/L, and an EGSB reactor for the treatment of wastewater with less than 1,500 mg COD/L still has a very high loading rate and removal efficiency. For example, in the treatment of ethanol fermentation wastewater with 100–700 mg COD/L, the upflow velocity is 2.5–5.5 m/L with a load of 12 kg COD/($m^3 \cdot d$), and the removal rate of COD is between 80–96 %. In biological sewage treatment at room temperature with an HRT of 1.5–2 h, the COD removal rate can reach up to 90 %. EGSB provides better results than other processes in the treatment of low-concentration wastewater at a low temperature. For example, at 8 °C, and an influent COD concentration of 550–1,100 mg/L, the upflow velocity is 10 m/h, the organic load reaches up to 1.5–6.7 kg COD/($m^3 \cdot d$), and the removal rate of COD is 97 %.

An EGSB reactor can be considered a modified fluidized-bed (FB) reactor. The difference is that EGSB does not use any inert filler as the bacterial carrier, and the retention time of the bacteria in EGSB depends on the granular sludge formed, whereas the upflow speed of an EGSB reactor is less than that of an FB reactor, and the granular sludge does not reach fluidization, but expands the state.

The advantages of EGSB are as follows: (1) Structure: a high aspect ratio, a small occupation area, a uniform water distribution, the sludge is in the expansion state, and it is not easy to generate channeling and dead corners. (2) Operation: The COD organic loading rate can reach up to $40\,kg \cdot m^{-3} \cdot d^{-1}$. The sludge retention capability is strong. The liquid upflow velocity is high. The solid/liquid mixture is completely mixed. The reactor has a water outlet reflux system, more suitable for the treatment of wastewater containing suspended solid and toxic substances. The sludge and wastewater are completely mixed; therefore, it has obvious advantages in low temperature and low-concentration organic wastewater treatment. The granular sludge has a high activity, good settling performance, large particles, and good strength. (3) Scope of application: suitable for low-concentration organic wastewater; good adaptability to refractory organic wastewater, high molecular weight fatty acid, low temperature, low substrate concentration, high salinity, and high suspended solids in wastewater.

The disadvantages of EGSB are as follows: (1) Not suitable for wastewater with a high content of solids because the suspended solids may be washed out rapidly with the water, difficult to decompose. (2) The operating conditions and control technology requirements are higher because of the high velocity.

4.2.2.2.3 IC

An IC anaerobic reactor is the most efficient reactor in the third generation of super-efficient anaerobic reactors in the world developed by the Dutch company Paques in

1986. It has the combined advantages of a UASB reactor and an FB reactor, achieves substrate liquid internal circulation by using the lifting force of biogas produced in the reactor.

The basic structure of an IC reactor is shown in Fig. 4.12. It is just like two UASB reactors connected in series. The height of the reactor is 16–25 m, the ratio of height-to-diameter is 4–8. It has a mixing zone, a first reaction zone, a second reaction zone, an internal circulatory system, and water outlet area, a total of five parts. The IC system is the core part of the IC reactor, consisting of a three-phase separator, the CH_4 riser, a gas/liquid separator, and a sludge return pipe.

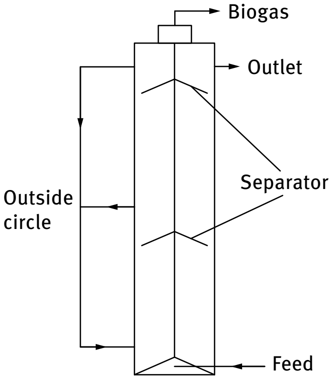


Fig. 4.12: Structure of an IC reactor

The working process of an IC anaerobic reactor mainly depends on the IC system. When starting the reaction, after the pre-acidification and regulation of pH and temperature, the wastewater enters the mixing zone in the bottom of the reactor and completely mixes with the inoculated sludge, gradually forming the GSB. Biochemical degradation occurs in the first reaction zone, where the volume load is very high, and most of the COD is degraded in this location. The biogas separated by the three-phase separator moves along the ascending pipe. Biogas stripping accelerates the mixing process of sludge and sewage, and makes the biogas, sludge, and sewage ascend along the gas/liquid separator tube and rise to the top of the reactor. Then, CH_4 is generated from this system, and the water sludge mixture settles down along the pipe to return to the EGSB zone, which is known as the IC. The flow rate can be 2–3 and 10–20 times that of an IC when treating low-concentration and high-concentration wastewater, respectively. The results of the circulation mean that the first reaction chamber cycle achieves not only a high biomass, long SRT, and high rising velocity, but also complete mixing of the sludge and liquid material, thus significantly improving the removal ability of the first reaction chamber. The treated wastewater is transferred into the second reaction chamber automatically. The residual organic matter in wastewater can be further degraded in the second reaction chamber granular sludge, thus better purifying the wastewater. After the two-stage treatment, the mixed liquid is separated at the precipitation zone. The liquid is discharged from the water outlet pipe, and the granular sludge precipitate automatically returns to the second reaction chamber, thus completing the wastewater treatment process.

The advantages of an IC reactor are as follows:

(1) High volumetric loading rate: Because of IC in an IC reactor, good mass transfer effect, high biomass, and longer sludge age are achieved. The organic loading rate of an IC reactor can be three times higher than that of a UASB reactor. In the treatment of high-concentration organic wastewater such as potato-processing wastewater, the volumetric loading can reach up to 30–40 kg COD/($m^3 \cdot d$) if the COD is 10,000–15,000 mg/L. For a low-concentration organic wastewater such as beer wastewater, the volumetric loading can reach up to 40 kg COD/($m^3 \cdot d$), and the removal rate of COD can reach up to 75–80 %.
(2) Investment and space saving: The reactor volume is only 25–35 % that of an ordinary UASB reactor, three times higher volume load than UASB, thus reducing the investment. Moreover, an IC reactor has the advantage of a large height-to-diameter ratio, thus requiring less space.
(3) Power saving: An IC reactor uses the biogas generated for compulsory recycling, thus saving energy.
(4) Strong shock-resistant capacity: Because an IC reactor has IC, the circulating liquid and water are completely mixed in the first reaction chamber. Thus, the harmful substances in raw wastewater are completely diluted, thus improving the reactor's resistance to shock load.
(5) pH buffer: The IC can be viewed as the interflow of the first anaerobic stage. The alkalinity produced during the organic degradation maintains a stable pH.
(6) High-quality effluent water and good stability: An IC reactor is equivalent to two UASB reactors in series. Two-stage treatments provide better effluent quality than single-level processing.

The disadvantages of an IC reactor are as follows:

(1) This reactor has a complex structure because of IC, and three-phase separator technology is used. An extensive internal piping system occupies the effective space of the reactor. Thus, the reaction efficiency is limited, and the total volume of the reactor increases.
(2) It is difficult to precisely control the circulation of CH_4 in the lifting pipe, and the return sludge pipe is too complex.
(3) The sludge from the return pipe increases the mixing of slurry, affecting the separation of sludge, water quality, and gas/liquid/solid separation.

A multiphase IC anaerobic reactor was proposed by Lin Changqing. It is an anaerobic digester with at least a reaction zone that connects in series with the corresponding gas-lift pipe, collecting pipe, reflux pipe, gas/liquid separator, three-phase separator, and gas seal of the IC anaerobic reactor chamber, as shown in Fig. 4.13. The reactor has

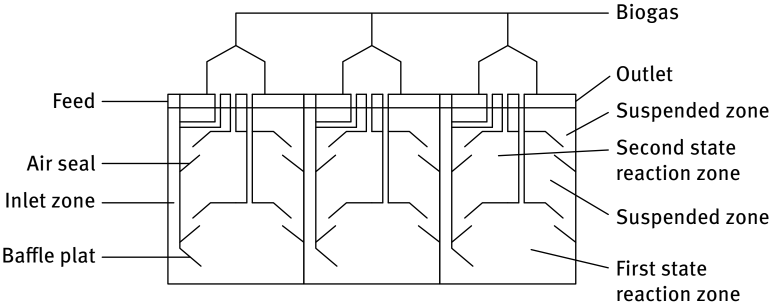


Fig. 4.13: Structure of multiphase IC anaerobic reactor.

the advantages of both IC and ABR. It uses the cycle effects of IC to mix the sludge and wastewater completely and achieve the concept of multistate and phase proposed by Prof. Lettinga, thus providing good design ideas for the development of an anaerobic reactor.

A composite IC anaerobic reactor is an improved IC anaerobic reactor, designed to mainly solve the problem of uneven mixing of circulation liquid and feed substrate and low efficiency of the second reaction zone when treating low-concentration organic wastewater. The reactor consists of an upflow pipe, a downflow pipe and the gas/liquid separation zone, a filter in the place of settling zone, an equidistant distribution of 2–4 tubes in place of a single downflow tube, and only one reaction zone. The second reaction zone is removed.

4.2.2.3 Dry anaerobic digestion

Dry anaerobic digestion is also called solid-state fermentation; solid organic wastes are used as the raw substrate. The TS content in the system is generally 20–40 %. Compared to wet fermentation, solid-state fermentation has a broad substrate scope, higher organic load, less sewage treatment capacity, lower energy consumption, less investment, and lower cost. Single-phase, dry-type, continuous processes include Belgium's DRANCO vertical plug flow fermentation, France's Valorga vertical gas mixing, and Switzerland's Kompogas horizontal push-flow fermentation processes. Germany's BIOPERCOLAT process is a two-phase, dry, continuous process; the Dutch Biocel and German BEKON processes are mono-phase, dry, batch processes [81].

4.2.2.3.1 DRANCO vertical plug flow process

The DRANCO (DRy ANaerobic COmposting) vertical plug flow fermentation process was developed by Belgian Organic Waste Systems in 1988. It is a continuous dry fermentation digestive system with a vertical mixer, a high solid content, single-phase, high temperature, no internal stirring, and 15–40 % feed solid concentration. Currently, 24 factories in Europe use the DRANCO process. The substrates for the DRANCO process include kitchen garbage, city garbage, sludge, and energy crops. The key technique is the feeding, distribution, and discharging system.

DRANCO vertical plug flow is shown in Fig. 4.14. The main body is a cylindrical tank, the diameter-to-height ratio is generally above 1:2, and no mechanical stirring. After screening and pretreatment, organic solid wastes are mixed with inoculum according to a certain proportion (usually 1:6 to 1:8). After steam heating, the substrates are fed into the tank from the top. The biogas generated in the tank is released from the top of the tank to the CH_4 storage system. The bottom of the tank has an inverted cone shape, containing a valve and spiral conveyer device used for discharging. After the solid–liquid separation, the biogas slurry is fed to the mixing feeding device and mixed with fresh material, thus achieving cyclic utilization. The biogas production of the DRANCO process is in the range 0.103–0.147 m^3/(kg wet weight), a power generation capacity of 0.15–0.32 MW h/(t material).

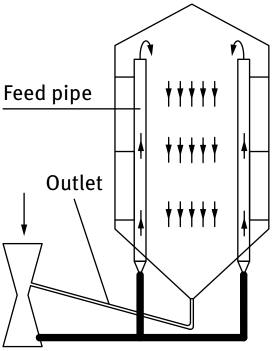


Fig. 4.14: Structure of the DRANCO process.

4.2.2.3.2 Valorga vertical gas stirring process

The Valorga process is a semi-continuous, single-phase, modified plug flow type single-stage dry fermentation technology developed by the French Valorga Company in 1981. The Valorga fermentation tank is a silo-type fermentation tank without mechanical agitation. A vertical cement board is set at 1/3 diameter. The TS concentration is 25–30 %; using steam heating, both mesophilic and thermophilic fermentation are suitable. The residence time is 18–23 d, and pressurized biogas is used for stirring. After dehydration, the digestate can be used as a fertilizer. The specific gas yield is in the range 0.22–0.27 m^3/kgVS.

Valorga technology is widely used in Spain, Germany, Italy, and Switzerland. Twelve biogas projects have been built and are under constant operation; the annual treatment capacity is 1,047,000 t. Barcelona's garbage disposal plant uses Valorga dry fermentation technology. After screening and sorting, the garbage is fed into the digestion tank for mesophilic (37 °C) fermentation. This project includes three seat digesters with a diameter of 16 m and height of 22 m, feeding once a day; the residence time is 20–30 d. Biogas at 5 atm is injected from the bottom of the anaerobic tank to mix with the substrate. There are 200 air injectors at the bottom of the tank.

4.2.2.3.3 Kompogas horizontal plug flow process

After passing through a ~20 m long, sleeve-type heat exchanger for pre-heating treatment, the substrate can be fed into the tank. The mixing depends on the mixer and high pressure delivery pump. The small rotating stirrer located in the center of the reactor also moves the substrate forward. Moreover, the stirring rotation also helps in releasing biogas and promotes the fermentation of the substrate mixture. After fermentation, the residues are transferred to the dehydration system using reciprocating pumps and then dehydrated using the screw extrusion machine.

The Kompogas process is a typical process for organic waste treatment, including waste reception, screening, intermediate storage, and humidity control. The basic requirements for the raw material are as follows: The raw materials have an average particle size of ~40 mm, the length of the raw materials is < 200 mm, the content of TS is > 30 % when treating cellulosic waste, but < 30 % for food waste. The fermentation temperature is ~55 °C, and the retention time is 15–22 d. Fermentation involves complete isolation and heating to destroy plant seeds, roots, and pathogens (Fig. 4.15).

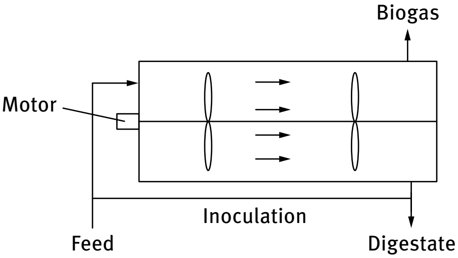


Fig. 4.15: Kompogas Process

4.2.2.3.4 The BIOPERCOLAT two-phase process

The BIOPERCOLAT process is a two-phase process developed by the WEHRLE Company. It can be divided into (1) primary acidic hydrolysis stage and (2) fermentation stage. The hydrolytic acidification stage involves the hydrolytic acidification of a high concentration of organic solids under the action of aerobic microbes. The microaerobic conditions can improve the decomposition rate of organic matter, and the residence time is 2–3 d. After acidification and solid–liquid separation, the solid phase is fed into the composting system, and the liquid phase is mixed using a leachate to enter the second-stage fermentation system. The two-stage fermentation system has a piston with filler stream temperature anaerobic fermentation tank. The biogas slurry is transferred into the filtration system after partial reuse, and the rest is used for post-processing. The difficulty of this process lies in the anti-clogging technology in the acidic hydrolysis tank filtration system.

4.2.2.3.5 Carport batch dry fermentation

The carport dry fermentation project consists of a reactor built with concrete materiel, high-precision driving sealing doors, and a highly sensitive automatic monitoring device to ensure safe and stable operation. The bottom can be heated using pipe heating, thus ensuring that the temperature of anaerobic fermentation materials remains at ~38 °C. The fermentation warehouse has a modular structure, no blender, easy to achieve expansion, and large-scale application, suitable for an annual output of above 1,000,000 m^3 biogas engineering. The technology can directly utilize a high solid content of organic matter such as municipal garbage or crop straw. It is the most mature single-phase intermittent dry fermentation biogas technology in Europe.

The carport dry fermentation system mainly includes a material transport and storage management system, a modular dry fermentation workshop, a heat preservation and heating system for biogas fermentation, a soft capsule collection and storage system, biogas power generation, a transmission and distribution system for the purification of biogas residue, and a fertilizer manufacturing system. Organic solid waste and fermented substrate are transferred to the fermentation chamber using a loader forklift. It is continuously inoculated through leachate recirculation. The heating of material and leachate is provided by the sidewall and leachate storage tank heat exchanger. The modular dry fermentation workshop includes a fermentation warehouse, a concrete structure for the hydraulic seal door, a CH_4 collection and transfer system, a spray system, a spraying liquid collection system, a heating system, and protective devices. The central shaft of the sealing door is installed on the top of the feed end. Under the push or pull of an air cylinder, the upper and lower rotary is closed, and the carport is opened. A biogas outlet and sprinkler head are installed on the top of the warehouse. A spray liquid collection system is installed on the bottom of the fermentation tank. Feeding or discharging can be carried out by the loading vehicle or forklift. The carport dry fermentation device is widely used in Europe, but is still in the demonstration state in China.

Compared to other dry fermentation technologies, the carport dry fermentation technology has many unique advantages. First, a carport dry fermentation system does not have a stirrer and pipeline, and the operation is not affected by inorganic materials such as plastic and sand. A relatively wide range of materials can be used directly, simplifying the material screening and pretreatment process and reducing the cost of the project. Second, this system has no moving parts such as a stirrer, thus it has high reliability and low energy consumption. Third, it can use discharge loaders and other engineering machinery feeding equipment, thus has a high equipment efficiency and strong versatility. Fourth, no liquid biogas slurry is produced after fermentation, and after simple treatment, the obtained solid residues can be used as a garden manure or crop fertilizer. Thus, it has a low cost of post-treatment and high efficiency. The carport dry fermentation technology also has inherent limitations: Because there is no mechanical stirring, the raw materials should be inoculated before entering the fermentation chamber and fully mixed. The anaerobic retention time is relatively long. The door should be opened during the intermittent discharge and there are high requirements for safe operation. Because it cannot run continuously, multiple carport reaction devices that occupy a large space are usually required (Fig. 4.16).

Fig. 4.16: External and internal structures of carport dry fermentation digester.

With the development of biogas technology in China, large dry fermentation systems will become the preferred technology for the treatment of organic solid wastes. At present, the Guangzhou Institute of Energy Conversion, Chinese Academy of Science, Tsinghua University, and other research institutions have launched studies on dry anaerobic fermentation (Fig. 4.17).

Fig. 4.17: Feeding process of carport dry fermentation.

4.2.2.3.6 Film-covered dry anaerobic fermentation tank reactor

Solid materials in the reactor produce biogas and organic fertilizer after the completion of three stages: (1) aerobic heating-up, (2) anaerobic digestion, (3) aerobic composting. No slurry and other wastes are produced. Its outstanding characteristics are as follows: The use of aerobic biological fermentation heats the solid material supplemented with efficient heat preservation measures without using any external heat source. This maintains a moderate temperature (35–42 °C), and the temperature drop is less than 0.15 °C · d, efficiently improving the biogas production rate and reducing the energy consumption of the system and operating cost [82].

The design of a film-covered fermentation tank generally requires the coating of a dry anaerobic fermentation tank reactor. Take the eight-fermentation tank as an example (Fig. 4.18): four of them are in the anaerobic gas production stage, one in the aerobic pretreatment temperature increase stage, and three in the dehydration stage.

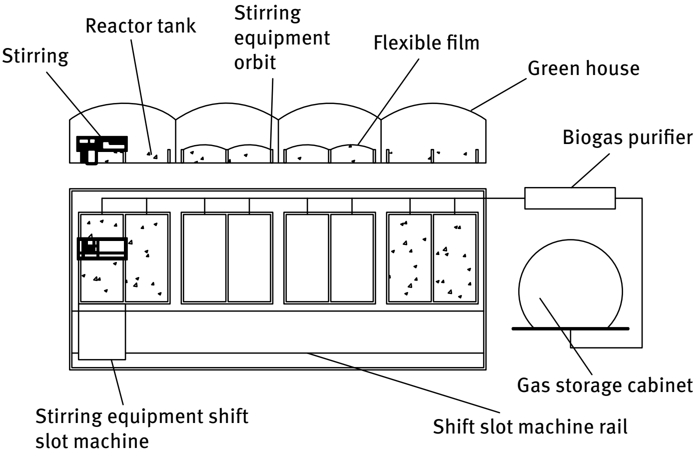


Fig. 4.18: Structure of film-covered dry fermentation system.

4.2.2.3.7 Integrated two-phase (circular inoculation-type) anaerobic digestion technology

The two-phase (circular inoculation-type) anaerobic digestion technology is a mesophilic fermentation technology. Crop straw is used as the substrate, feeding from the top of the digester. The solid–liquid separation depends on the difference between the specific gravity of straw and fermentation liquid. At the same time, the feeding substrate is mixed with a circulating slurry for inoculation. This process is suitable for a mixture of dry straw, silage straw, and manure. The fermentation process does not require water or requires only a small amount of water. No biogas slurry is produced because it is circulated to inoculate the substrates, thus efficiently solving the problem of how to efficiently utilize the digestion products. Tianjin Jinghai Sidangkou Straw Biogas Engineering is a demonstration project of this technology.

4.2.2.4 Two-phase anaerobic fermentation process

The acidic hydrolysis and CH_4 generation stages of two-phase anaerobic fermentation process are carried out in two reactors. This process is commonly used to treat materials that can be easily acidified. To avoid the inhibiting effect of organic acid accumulation, the hydrolytic acidification and methanogenesis steps are completed separately in two reactors, and the operation of these two reactors and their conditions are optimized individually to improve the efficiency of the digestion reactor system.

4.2.2.4.1 Two-phase liquid–liquid anaerobic fermentation

This process (Fig. 4.19) is mainly used for the treatment of easily acidified high-concentration organic wastewater. Because acidic hydrolysis bacteria are reproduced rapidly, the acidification reactor has the advantage of small size. The pH of the fermentation broth rapidly drop to less than 5.5 because of the high rate of acidification, thus completely inhibiting the activity of methanogens and often making this process become the rate limiting step of anaerobic fermentation. To avoid inhibition by organic acids, a methanogenesis reactor should be larger than an acidification reactor. Because these two reactors have different amounts of suspended solid, the second reactor can use UASB, but the first reactor should be CSTR.

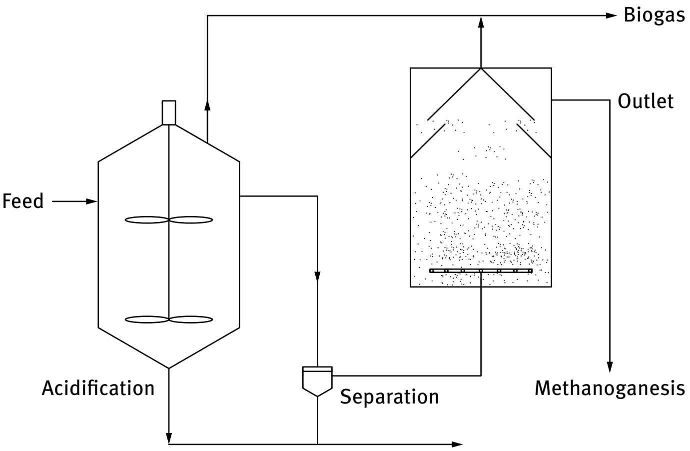


Fig. 4.19: CSTR-UASB two-phase anaerobic fermentation

Pacques and BTA processes belong to this technology. Pacques is a medium-temperature process, mainly for the treatment of fruit and vegetable wastes. The hydrolysis reactor has a TS of 10 % and is equipped with air agitation. After dehydration, the liquid is fed into the UASB reactor as the inoculum, a part of the solid is added to the hydrolysis reactor, and the remaining part is used for compost. The requirements of the BTA process are ~10 % TS content and mesophilic anaerobic digestion; a methanogenesis reactor equipped with an attached biofilm reactor is used to improve MRT. To maintain the pH of the hydrolysis reactor at between 6 and 7, the methanogenesis reactor digested liquid should be recycled back to the hydrolysis reactor.

4.2.2.4.2 Two-phase solid–liquid anaerobic fermentation

The two-phase solid–liquid anaerobic fermentation process is mainly used for the treatment of organic solid wastes. The solid materials such as straw and city organic waste are fed into the filter bed (also known as solid infiltration bed) for acidification. Then, the leachate is fed into a high-efficiency methanogenic reactor such as UASB or AF, and the effluent is recycled (Fig. 4.20). In the entire process, the system does not discharge any liquid, and the solid residue generated in the process can be used to produce organic fertilizers by subsequent processing. This improves the digestion rate and stability of the system by leachate collection and biogas slurry spraying and stirring, thus solving the traditional problems such as easy acidification, difficult to stir, and gas production instability.

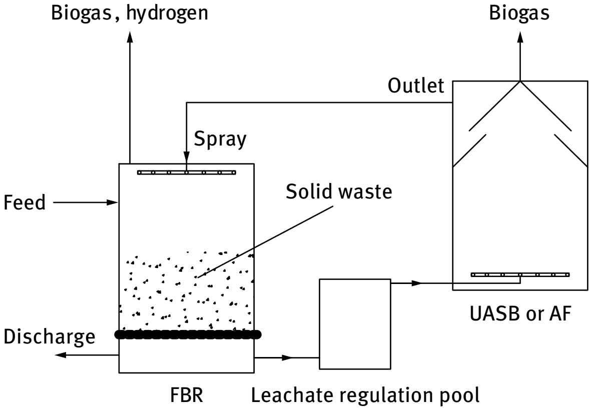


Fig. 4.20: Solid–liquid two-phase anaerobic digestion.

Moreover, the use of a two-phase fermentation process can spontaneously hydrolyze the refractory organics by heating or microaerobic method in acidification reactors. Similar to the BIOPERCOLAT technology in Germany, acidification is completed under a high TS content and microaerobic conditions; the microaerobic hydrolysis reactor and the attached biofilm CH_4 production reactor can shorten the digestion time to 7 d. However, it has been reported that the commercial application of the two-phase process accounts for only 10 % of the total amount of city garbage treatment because of their complex structure.

4.2.2.5 Other anaerobic digestion processes and reactors

4.2.2.5.1 ABR

ABR is a new type of highly efficient anaerobic reactor based on UASB and developed by Stanford University. ABR is a series of reactors divided into several series of reaction chambers. The substrate moves forward along the guide plates. Using the wastewater and CH_4 flows, the sludge moves up and down the reaction chamber. However, its velocity in the horizontal direction is very slow owing to the settling performance and guide plates; therefore, a lot of anaerobic sludge is entrapped in the reaction chamber. Thus, although ABR can be regarded as multiple simple UASB reactors in series, ABR is closer to the plug flow process.

To further improve its performance, many transformations have been made (Fig. 4.21). Fig. 4.21(b) shows the original form of ABR. To concentrate the microbes in the upflow zone (the main reaction zone), the width of the downflow zone was reduced, and angles were added to increase the hydraulic stirring action (Fig. 4.21(a)).

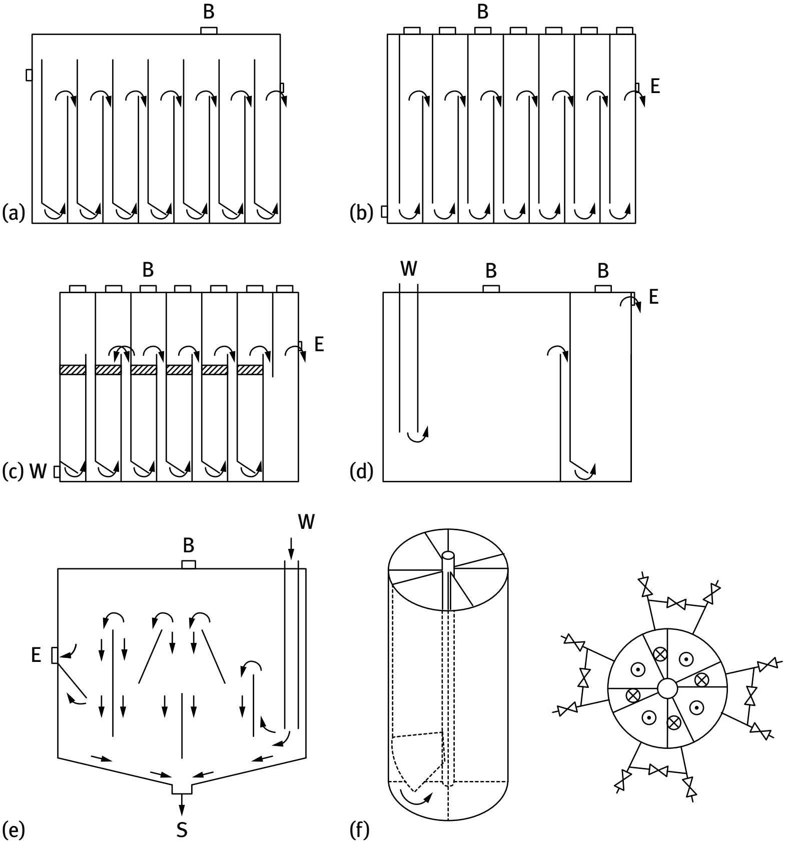


Fig. 4.21: Structure of ABR. B–biogas, W–water, E–exit

To improve the MRT when treating high-concentration wastewater, the following changes are carried out (Fig. 4.21(c)): A settling chamber was added behind the last reaction chamber to recycle the sludge; composite fillers in each lattice were placed on the top of the reaction chamber to prevent the loss of sludge. Gas is collected separately to study the performance of each grid and ensure that the H_2 generated in acidification does not affect the activity of methanogens. The horizontally baffled anaerobic reactor is a new type of ABR reactor proposed in 1985 (Fig. 4.21(e)). This reactor can achieve the two-phase solid–liquid separation efficiently, and it has the advantages of occupying a small area, easy operation, low cost, suitable for the treatment of high SS concentration organic wastewater. To reduce the rising velocity, a two-space ABR was designed (Fig. 4.21(d)). The volume of the first space is two times that of the second space. This reduces the rising speed, thus depositing most of the suspension in the water and increasing the SRT. The latest type of ABR is periodic ABR (PABR, Fig. 4.21(f)) developed in 1998. PABR consists of two coaxial cylinders. The region between these two cylinders is divided into several reaction zones using guide plates. Each reaction zone contains a liftflow and a downflow region; the adjacent region is connected through an external distribution pipe. The biggest advantage of this reactor is flexible operation and selection of different operation cycles according to the change in influent concentration and flow, thus making PABR work under the most suitable conditions and achieving the best treatment result.

4.2.2.5.2 Anaerobic filter (AF)

An AF is filled with an inert medium (also known as packing) including coke and synthetic fiber filler. Biogas fermentation bacteria, especially methanogens, attach onto a solid surface and form a biofilm; when sewage passes through the biofilm, the organic matter is utilized by the bacteria to generate biogas.

The main function of the filler is to provide an attachment area for anaerobic microorganisms. In general, the surface area of reactor carrier is larger per volume, and it can withstand a higher organic loading. Moreover, the filler should also have a considerable void ratio. It can achieve a longer HRT, and the removal rate of organic matter is higher under the same organic loading conditions if the void ratio is high enough. Moreover, it can prevent the clogging of the filter and produce a short flow.

The performance of a YDT-type elastic fiber filler developed in recent years is better than a soft fiber, because usually a soft fiber filler causes adhesion after a slightly longer running time, thus reducing the surface area and pore volume. Studies have shown that an elastic fiber filler has a larger practical specific surface area, is difficult to clog, rapidly forms a biofilm, and is easy to demold. The biofilm is produced rapidly, and the organic load rate is high.

An AF has the following advantages:
(1) No mixing operation;
(2) because of a high loading rate, the reactor volume is reduced;
(3) the microbial membranes fixed on the inert medium can tolerate the load changes;
(4) a long-term shutdown can be restarted immediately.

Disadvantages:
(1) The packing cost is higher, and the construction and installation are complex. The packing life is generally 1–5 years, and thus AFs should be regularly replaced.
(2) It is easy to clog packing and short circuit.
(3) It is only suitable for the treatment of wastewater with a low SS content.

4.2.2.5.3 Anaerobic membrane bioreactor (AnMBR)

Studies on AnMBR often involve the membrane technology as the terminal processing of biological water filtration systems. The addition of a filter in the end of an anaerobic reactor can effectively prevent the outflow of anaerobic sludge, improve water quality, and ensure that sludge concentration is maintained in the reactor at the same time [83].

AnMBR anaerobic systems mainly is UASB, EGSB, FB, AF, or ABR.

The membrane of AnMBR mainly consists of an ultrafiltration or microfiltration membrane, and it mainly has two forms, namely, external and built-in. The external-type AnMBR (Fig. 4.22(a)) has a membrane separate from the bioreactor and a pump is needed for liquid circulation to form a tangential flow on the surface of the film, preventing membrane pollution because of the lack of an air-bubbling reactor. For each 1 m^3 film in water, the liquid (sludge mixed liquor) feed is often 25–80 m^3. Therefore, the energy consumption is very higher. However, because this configuration can effectively prevent membrane pollution, it is currently the most common configuration in AnMBR. In the built-in type AnMBR, the membrane are immersed into a liquid tank; this configuration prevents the deposition on the surface of membrane by aerating. However, the reactor should maintain an anaerobic environment; therefore, often biogas is used for scouring the membrane surface. The built-in type can be further divided into two types as shown in Fig. 4.22(b) and 4.22(c).

A submerged anaerobic rotary membrane bioreactor (SDR AnMBR) has a double shaft rotary membrane in the reactor that can rotate in the same direction. It can produce a certain intensity of shear force on the membrane surface to reduce the surface membrane concentration polarization and prevent the formation of a gel layer, thus effectively preventing membrane pollution.

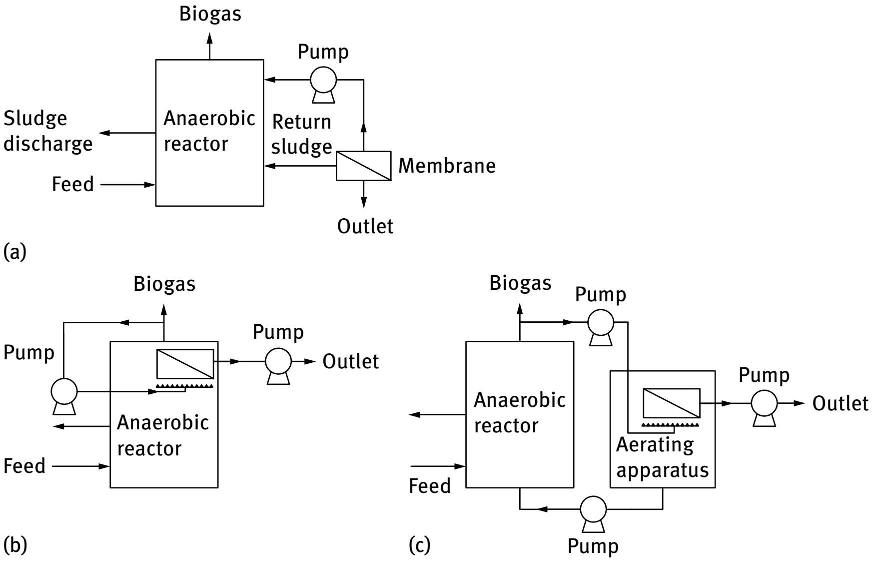


Fig. 4.22: Structure of AnMBR.

4.2.3 Biogas storage

As an effective way of balancing biogas production and utilization, a biogas reservoir is extremely important in large- and medium-sized biogas projects. The common forms of biogas storage cabinets are low-pressure wet-storage cabinets, low-pressure dry-type biogas storage cabinets, double-membrane dry-type biogas storage cabinets, and gas production and storage integrated-type gas storage cabinets.

4.2.3.1 Low-pressure wet-gas storage cabinet

A low-pressure wet biogas storage cabinet is a variable volume metal cabinet (Fig. 4.23) composed of a sink, a bell, a tower section, and an elevation guide device. When the biogas is imported into the biogas storage cabinet, the bell and tower section are placed sequentially in the sink (from small to large diameter) in increasing order. When exporting biogas from the biogas storage cabinet, the bell and tower section in turn (with decreasing diameter) descend to the sink. Between the bell and tower section, inside and outside the tower section, a water seal is used to isolate the biogas inside the cabinet from the atmosphere. Therefore, the volume and pressure of biogas storage change with the lifting of the tower section. A wet biogas cabinet has the advantages of a simple structure, easy construction and operation, and reliable sealing. However, in the cold season or region, the sink should install an insulation facility or add anti-freeze, and regular anti-corrosion treatment is also necessary for

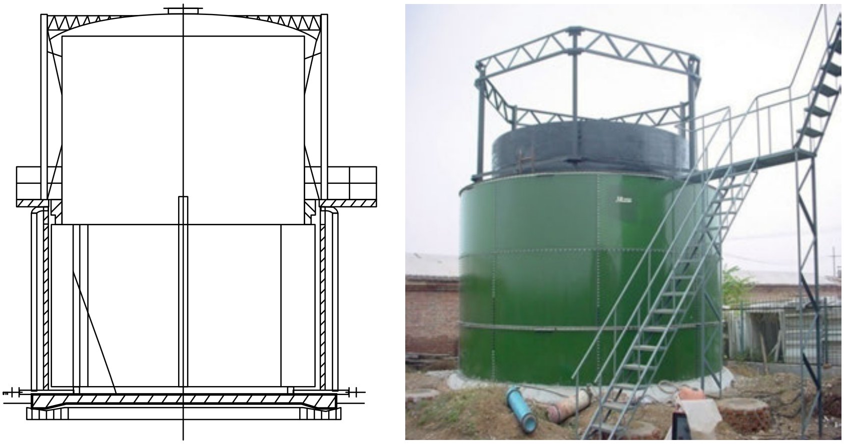


Fig. 4.23: Low-pressure wet biogas storage cabinet.

the points where the sink, bell, tower section, and guide are in long-term contact with water, reducing the effective volume of stored biogas.

4.2.3.2 Low-pressure dry-type biogas storage cabinets

Dry biogas storage cabinets can be divided into two types: a rigid structure and a flexible structure. The dry biogas storage cabinet with a rigid structure completely welded by a steel plate is generally applicable to a large biogas storage device. Its requirements of a high production process and a set of security devices require a larger project investment.

The Lipp biogas cabinet has been developed by the introduction and assimilation of German technology by Hangzhou Energy and Environment Engineering Co., Ltd. This mainly consists of a cylindrical air bag and steel protective shell. The top of the cabinet and body (shell) is made of 2 mm galvanized coil using the Lipp double-bending patent technology. Lipp biogas storage cabinets are economic, reasonable, and beautiful and can avoid the outside influence of mechanical damage, weather, and animals when used to protect airbags. Airbags used in the hot press forming technology are made of special fiber plastic films with a low permeability and high anti-corrosion and anti-wrinkle properties. The top of the airbag fastened in a fixed ring is connected with a balancing device using a rope mechanical device that can move up and down to ensure that the airbag can achieve the same storage and emission under any operating condition. The bottom of the airbag is provided with an air inlet and outlet to avoid interference. The balancing device is provided with a measuring rod to display the inflation height. The inflation height signal can also be obtained by arranging a limit switch on the balance block to control the balance or by positioning an ultrasonic range finder at the top of the tank. The biogas cabinet has the combined advantages of a rigid and flexible structure, ensuring good security, extending service life, reducing the unilateral investment, as well as shortening the construction period. The structure of a Lipp dry biogas storage cabinet is shown in Fig. 4.24.

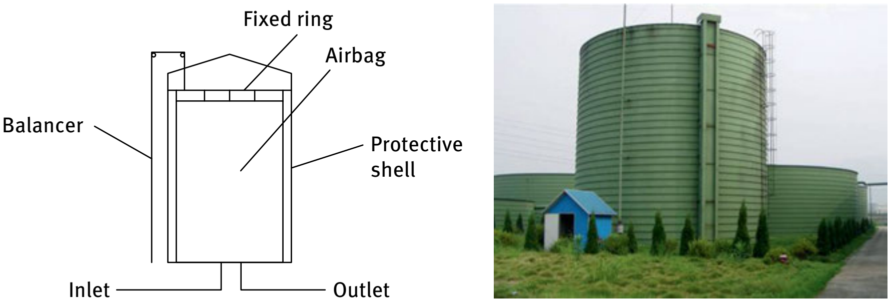


Fig. 4.24: Lipp dry biogas storage cabinet.

4.2.3.3 High-pressure dry biogas storage cabinet

The storage pressure of dry high-pressure gas storage cabinets is up to ~16 MPa. There are two types of cabinets: horizontal cylindrical and spherical. A high-pressure gas cabinet has no internal moving parts and has a simple structure. The storage volume changes according to the storage pressure. It is usually used for the storage of liquefied petroleum gas, olefins, liquefied natural gas, liquefied H_2. In the recent years, it has also been used for the storage of biogas. The storage cabinets with a capacity of > 120 m^3 are often spherical, and those < 120 m^3 are often horizontal cylindrical.

4.2.3.4 Double-membrane dry-type biogas storage cabinets

Double-membrane dry gas storage cabinets are usually composed of an outer membrane, intima, a bottom membrane, and a concrete foundation (Fig. 4.25). The inner cavity is surrounded by intima, and the bottom membrane is airtight. The outer membrane is inflated into a spherical shape. Gas storage cabinets are located inside explosion-proof blowers, which can automatically adjust the amount of gas input and output to maintain a stable air pressure inside. The internal and external membranes as well as the bottom membrane are welded using the HF welding process, and the material surface is specially treated with high-intensity polyester fiber and acrylic varnish. The gas storage cabinets can be UV resistant and leak-proof. The membrane does not react with biogas, and the tensile strength can be maintained at temperatures from −30 °C to 60 °C. It overcomes the shortcomings of the traditional flexible dry gas storage cabinet.

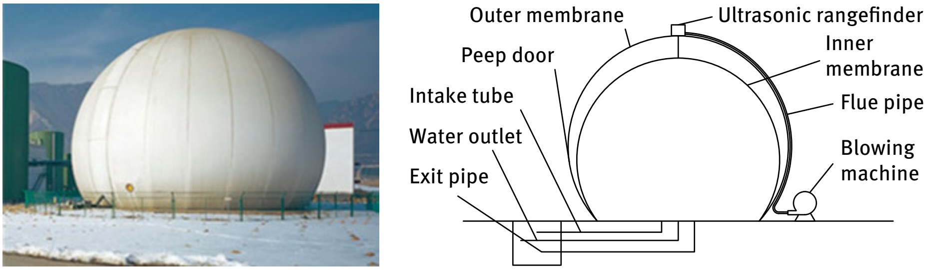


Fig. 4.25: Double-membrane dry gas storage cabinet structure.

A double-membrane dry gas storage cabinet is easy to install, less time-consuming, and usually requires only a few days. The biogas inlet, outlet pipe, and condensation drainpipe are embedded during the construction of the concrete foundation. The gas cabinet is first sealed with the bottom membrane using a special sealing technology during installation. The bottom membrane is fixed using concrete, followed by the installation of the intima, outer membrane, and sealing ring. The sealing ring is fixed in the concrete foundation using pre-buried bolts or chemical bolts. Then, the installation of cabinet is completed. Double-membrane dry-type gas storage cabinets are frequently used in European biogas projects; currently also used in domestic settings. They have different specifications and types. A dry double-membrane gas storage cabinet costs 30–60 % less than a wet-gas storage cabinet.

4.2.4 High-value utilization technology and equipment for biogas

The composition of raw biogas and requirements of the target product standard determine the required cleaning and purification technology. Desulfurization and dehydration are needed when the biogas is used for power generation. When biogas is used for vehicles, the natural gas standards for vehicles should be satisfied by following three steps: cleaning, purification, and modulation. Cleaning removes H_2S, water vapor, particles, and other harmful trace materials in biogas. Purification removes CO_2 from biogas, improving the applicability and calorific value. It is the core process for biogas purification and upgrading. Modulation achieves the vehicle fuel or gas network requirements. The purified biogas undergoes other subsequent processing. At present, the desulfurization methods include wet desulfurization, dry desulfurization, and biodesulfurization. Common water vapor removal methods include the condensation method and desiccant dehydration. The decarbonization methods include pressure swing adsorption (PSA), membrane method, and solvent physical absorption. Other components requiring purification are particulate matter, NH_3, and O_2, and their content is generally not high. Therefore, they can be removed together with other gas components during purification [84].

4.2.4.1 Desulfurization process and technology

H_2S is a colorless and highly toxic gas that smells like rotten eggs. It can cause a lot of harm to humans, equipment, and the environment. According to the requirements of the design of Biogas Engineering in China's current regulations, the H_2S present in biogas should be efficiently removed before use, and its content should be $< 20\,\mathrm{mg/m^3}$. The H_2S removal process can be divided into two types: in situ desulfurization and biogas desulfurization. In in situ desulfurization, the desulfurization agent is added to the fermentation tank, thus removing H_2S and performing fermentation simultaneously. This method can save investing in a desulfurization unit, but the H_2S concentration in the outlet biogas is still high. Biogas desulfurization removes the H_2S present in biogas.

There are two methods of biogas desulfurization: dry desulfurization and wet desulfurization. The new biological desulfurization process is micro-oxygen desulfurization, desulfurization of molten carbonate fuel cells, and other methods. Several types of biogas desulfurization methods are shown in Tab. 4.6.

4.2.4.1.1 Dry chemical desulfurization

Iron oxide is commonly used as a desulfurization agent in biogas dry desulfurization (Fig. 4.26). Iron oxide has a solid strip porous structure and rapid irreversible chemical adsorption of H_2S, and the outlet H_2S concentration can be less than $1 \times 10^{-6}\,\mathrm{mg \cdot m^{-3}}$. It also has a certain effect on the removal of organic sulfur and mercaptan, mostly nitrogen oxide. When biogas is passed through the desulfurizing agent bed layer, the H_2S present in biogas comes into contact with active iron oxide, generating iron sesquisulfide. When the outlet H_2S content is $> 20\,\mathrm{mg \cdot m^{-3}}$, it shows that the activity of desulfurization agent decreases, and the desulfurizing agent should be regenerated or replaced. When the sulfur content in desulfurizing agent is $< 30\,\%$, the desulfurization agent can be recycled. If the sulfur content in desulfurizing agent is $> 30\,\%$, the desulfurization agent should be replaced. The regeneration of desulfurization agent makes the iron sulfide react with O_2 in air, generating the sulfur monomer and Fe_2O_3. When the color of the observed desulfurization agent changes from black to red-brown, regeneration is completed. The regenerated Fe_2O_3 can be used further. The regeneration of desulfurization agent can be repeated until the desulfurization agent is inactivated when most of the pores are clogged.

Iron oxide dry desulfurization has many advantages: low investment, simple operation, etc. The disadvantages are (1) the discarded desulfurization agent can pollute the environment; (2) the operation is not continuous; (3) extra desulfurization towers are needed; (4) the replacement of large amounts of desulfurization agent is labor intensive; and (5) the device occupies a large area. Guangxi Wuming Anning Starch Co., Ltd. is an enterprise engaged in biogas preparation for gas-driven vehicles in China. It mainly utilizes cassava alcohol production waste liquid and cassava starch production waste as the raw materials. It uses the Fe_2O_3 dry desulfurization method at a

Tab. 4.6: Several H_2S removal methods.

Method	Advantages	Disadvantages
Fermentor in situ desulfurization ($FeCl_3/FeCl_2/FeSO_4$)	Low investment cost, low energy consumption, simple operation and maintenance, simple technology, H_2S does not enter the biogas pipeline	High outlet H_2S concentration (100–150 ppmv), high operating cost, pH, and temperature variation are harmful to the fermentation process, it is difficult to determine the appropriate amount of addition.
$Fe_2O_3/Fe(OH)_3$ bed	> 99 % desulfurization efficiency, low investment cost, and simple operation	Water-sensitive method, high operating cost, heat regeneration, bed combustion risks, reaction is hindered with the number of regenerations, release of toxic dust
Activated carbon adsorption	High desulfurization efficiency, outlet H_2S concentration < 3 ppmv, high purification rate, low operating temperature	High investment and operating cost, H_2S removal needs O_2, H_2O will occupy H_2S binding sites, 450 °C regeneration, elemental sulfur is easily deposited in holes
Pressurized water scrubbing	Outlet H_2S concentration < 15 ppmv, water does not need regeneration, low cost, and simultaneous removal of CO_2	High operating cost, technical difficulties, easy to plug the absorption tower
Chemical absorption method	Removal efficiency up to 95–100 %, low operating cost, small reactor size, renewable, less loss of CH_4	Technical difficulties, oxidized products are regenerated, CO_2 causes precipitation
Membrane separation	Desulfurization efficiency is > 98 %, removal of CO_2, the mass transfer rate is fast, simple equipment, low energy consumption, little environmental pollution	High membrane cost and high operating and maintenance cost
Biodesulfurization	Desulfurization efficiency is > 97 %, low investment cost, simple equipment, operational, simple process, low energy consumption	Long biological growth cycle, introduction of O_2/ N_2

temperature of 30 °C. The biogas flow rate is less than or equal to 40 m^3/min, and the desulfurization effect can satisfy the national standard.

4.2.4.1.2 Wet chemical desulfurization method

Wet desulfurization utilizes the contact of particular solvent countercurrent with gas in the absorbing tower to remove H_2S, and the solvent can be reused after regeneration. Wet desulfurization is mainly divided into two types: absorption and regen-

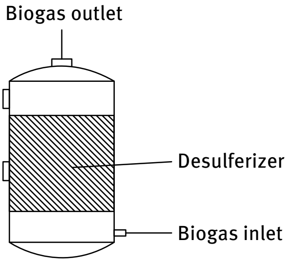


Fig. 4.26: Iron oxide desulfurizing agent and dry desulfurizing tower.

eration. The process is simple, and elemental sulfur can be recovered directly. It is suitable for large-scale biogas engineering of high biogas production with a high concentration of H_2S.

According to different absorption reaction mechanisms, wet desulfurization methods can be divided into physical absorption method, alkali absorption method, and redox method. Physical adsorption mainly utilizes the high-pressure water scrubbing method, taking advantage of the solubility of H_2S in water to separate H_2S from biogas. However, the desulfurization efficiency of this method is not high. The alkaline solution absorption method is stable and does not need much equipment. However, regeneration is difficult. This method is suitable for deep desulfurization. Redox method has the advantages of quick response and efficient sulfur recovery, but the oxidant cannot be regenerated or recycled, resulting in poor economy.

Alkali absorption method

The alkali absorption method mainly involves acid–base neutralization reactions to absorb acidic gases such as H_2S, mainly including sodium carbonate absorption method and NH_3 water absorption method. This method is simple and economical. However, CO_2 partially reacts with sodium carbonate or NH_3 to produce ammonium carbonate or sodium carbonate, thus reducing the absorption efficiency. The absorption liquid should be replenished in time, resulting in a lot of raw material waste and increasing the operating cost.

To solve the problem of absorption of liquid regeneration, Dutch Parker developed a combination of sodium absorption and bioregeneration Shell-Paques desulfurization technology. The Shell-Paques desulfurization technology is shown in Fig. 4.27. First, the raw biogas is fed into the gas washing tower, completely contacting the aqueous solution of soda including sulfur bacteria. H_2S is dissolved in alkali solution for transferring to bioreactor. Sulfide is oxidized to elemental sulfur by *Thiobacillus* in the bioreactor. Sulfur precipitated in the form of a slurry in the bioreactor can be further dried into a powder or sulfur commodity using the molten, resource utilization technology.

At present, the Schell-Paques technology is used in industry. The technology has the advantages of being a simple process, occupying a small area, high H_2S absorption

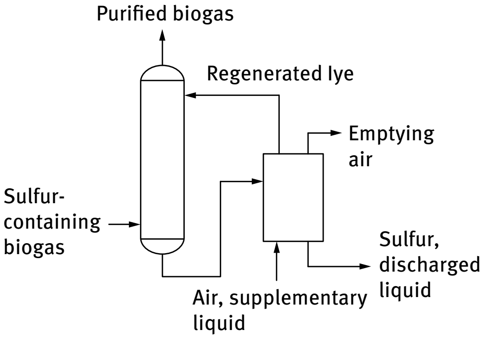


Fig. 4.27: Process of Shell-Paques desulfurization technology.

efficiency, alkaline solution internal circulation, automatic strain regeneration, low energy consumption, less use of chemical solvent, and low operating cost. However, there are still some difficult issues of biological regeneration. The section temperature should be maintained in the range 30–40 °C, and the biological reactor has a start-up problem.

Naphthoquinone oxidation desulfurization method

Naphthoquinone is made from naphthalene by the catalytic oxidation of vanadium pentoxide. It has the following characteristics: a high redox potential, water solubility, high stability, can be sublimed at room temperature, nonvolatile, slightly affected by CO_2, and other characteristics. The process is shown in Fig. 4.28.

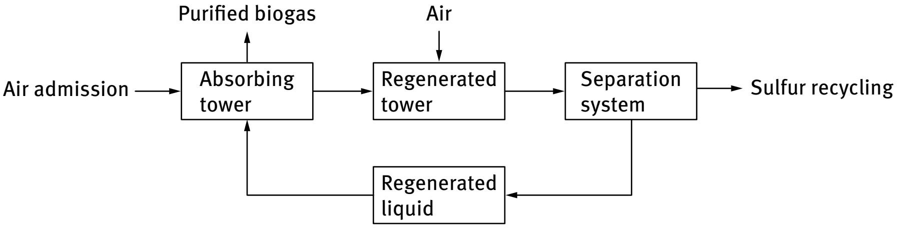


Fig. 4.28: Naphthoquinone oxidation desulfurization process method (3)

The naphthoquinone method utilizes a solution of sodium carbonate as the absorbent and 1,4-naphthoquinone-2-sulfonate as the catalyst. During desulfurization, H_2S is converted to elemental sulfur by quinine with a suitable redox potential. The reaction is shown as follows:

$$\text{Absorption process:} \quad \text{naphthoquinone} + H_2S = \text{naphthol} + S \downarrow$$

$$\text{Regeneration process:} \quad \text{naphthol} + O_2 = \text{naphthoquinone} + H_2O_2$$

Naphthoquinone has high desulfurization efficiency and is not affected by temperature. Desulfurization can reach 100 % at ambient temperature. The technology has been applied to the chemical and refinery off-gas desulfurization outside China, but the quantity is not high. The main reason is the high cost of the project. Moreover, a certain amount of naphthoquinone is lost during the separation, and the high cost of naphthoquinone leads to a high operating cost. Because of the high investment and operating costs, naphthoquinone desulfurization has not been widely applied.

Ferric chloride absorption-electrochemical regeneration desulfurization technology has been systematically investigated (Fig. 4.29). The process utilizes Fe^{3+}/Fe^{2+} as the oxidation absorber. At 65 °C, 18 g $FeCI_3$ solution, with a flow rate of 200 mL/min H_2S for 5 min, the sulfur yield is 95 %. Then, the electrolytic oxidation of Fe^{2+} regenerates Fe^{3+} and returns it to the absorption reactor. H_2 is recovered at the cathode. The ferric chloride absorption-electrochemical regeneration desulfurization process is shown as follows:

$$\begin{aligned} \text{Absorption process}: \quad & H_2S(g) \rightarrow H_2S(aq.) \\ & H_2S(aq.) + Fe^{3+}(aq.) \rightarrow Fe^{2+}(aq.) + S(s) \\ \text{Regeneration process}: \quad & Fe^{2+}(aq.) - 2e \rightarrow Fe^{3+}(aq.) \quad \text{(Cathodic reaction)} \end{aligned}$$

where aq. represents the aqueous phase, and g represents the vapor.

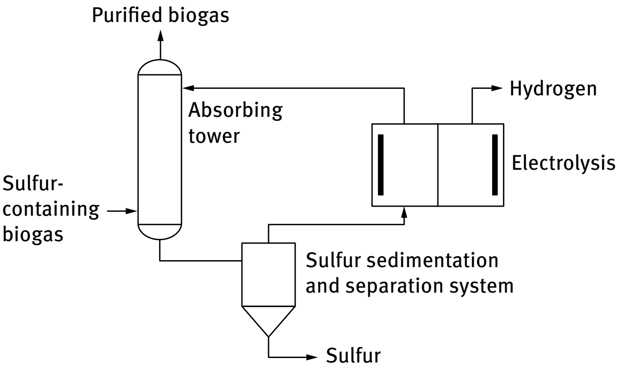


Fig. 4.29: Ferric chloride absorption-electrochemical regeneration desulfurization process.

The whole process involves the absorption of a liquid with no loss, and many sources are available. The technology has a low cost. The regeneration of absorption liquid is clean, convenient, and fast. Moreover, other chemical raw materials do not consume energy, and electrolysis involves low electric consumption. Each step of the whole process is easy to control and can be carried out at normal temperature. The process is not affected by CO_2 and NH_3.

4.2.4.1.3 Biological desulfurization technology

Biological desulfurization transforms sulfide into elemental sulfur or sulfate in three stages: (1) sulfide dissolution, (2) microbial absorption, and (3) microbial decomposition and transformation. According to their activity, the microorganisms that can transform sulfide are mainly photosynthetic bacteria, denitrifying bacteria, and colorless sulfur bacteria. The desulfurization of photosynthetic bacteria equire the valid introduction of :radiant energy. When H_2S is converted to elemental sulfur microparticles, the solution becomes turbid, and light transmittance decreases, thus affecting desulfurization efficiency. Therefore, it is difficult to achieve good economy and technique. Denitrifying bacteria require nitrate as the electron acceptor in the oxidation of sulfide, thus simultaneously achieving desulfurization and denitrification. However, the application of technology is limited by the properties of raw materials. The development of biogas desulfurization technology with colorless sulfur bacteria has been the main focus of study in the recent years; practical applications in laboratory research and engineering have made great progress.

Optical energy biological desulfurization

*Chlorobium limicol*a is a strictly anaerobic autotrophic microorganism. In the presence of light, CO_2, and inorganic nutrients, CO_2 can be used for the synthesis of new cell materials, whereas S can be converted to elemental sulfur and released to outside of the cells. Under certain conditions, elemental sulfur will be further oxidized to SO_4^{2-} by *Chlorobium limicola*. The above process can be expressed as follows:

$$2nH_2S + nCO_2p \xrightarrow{\text{light energy}} 2nS^0 + n(CH_2O) + nH_2O$$

$$nH_2S + 2nCO_2 + nH_2O \xrightarrow{\text{light energy}} nSO_4^{2-} + 2nH^+ + 2n(CH_2O)$$

When an autotrophs desulfurization reactor is used, CH_4 directly enters the reactor, and the purified gas is discharged directly from the reactor. The feed system provides microbial nutrients, and the product is discharged from the system during the discharging. Microorganisms in the reactor may be suspended in the growth-activated sludge, and the microorganisms may also be fixed on the packing film.

Many studies in recent years have focused on optimizing the light source, microbial suspension mode, and elemental sulfur separation modes. In the selection of the light source, monochromatic light is mainly used as the light source of the reactor. When a light-emitting diode (710 nm) is used and the desulfurization efficiency is 18.7 times of an incandescent lamp light source, the desulfurization efficiency of a flat plate type reactor can be increased by 31 times. In the growth pattern of microorganisms, the desired fixed growth light intensity is 30 % lower than the suspended growth, but with running time, the desulfurization efficiency of fixed growth clearly decreased. This is mainly because the transmission attenuation of light increases when a biological membrane reactor is used, and the central portion of the reactor has insufficient light.

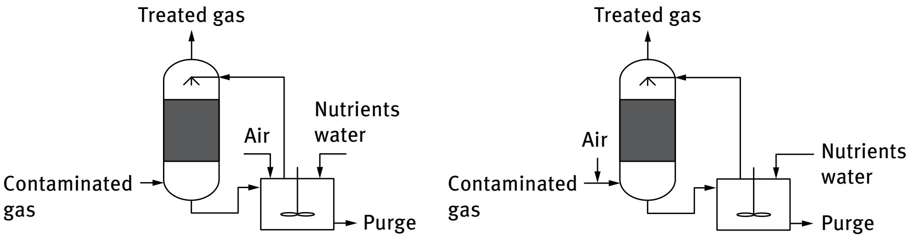
Chemotroph desulfurization

Colorless sulfur bacteria including strict chemoautotrophic bacteria and heterotrophic bacteria can oxidize H_2S, elemental sulfur, thiosulfate, and persulfate, generating elemental sulfur or sulfuric acid.

Chemoautotrophic microbes utilize CO_2 as the carbon source and can transform S^{2-} into elemental sulfur. Under aerobic conditions, O_2 is used as the electron acceptor, and in the absence of oxygen, nitro compounds are used as the electron acceptor. When O_2 is the rate limiting factor in the biochemical reaction, sulfur is the main product; when S^{2-} is the rate limiting factor in the biochemical reaction, the main product is SO_4^{2-} instead of elemental sulfur.

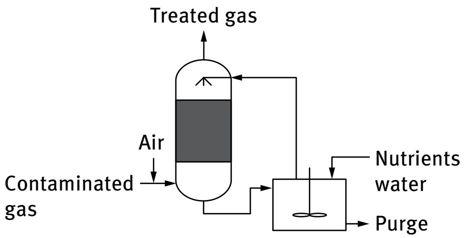
$$H_2S + CO_2 + \text{Nutrients} + O_2 \xrightarrow{\text{Chemoautotroph microbes}} \text{Biomass} + S^0\ \text{or}SO_4^{2-} + H_2O$$

Chemoautotrophic-type biological desulfurization can be divided into two categories: single-stage desulfurization and two-stage desulfurization. In single-stage desulfurization, H_2S is directly fed into the reactor, and absorption and oxidation processes are completed in the reactor. The main types of reactor include a biological scrubber, biofilter, and biological trickling filter (Fig. 4.30). The biological scrubber removal of H_2S consists of two phases: (1) H_2S liquid absorption and (2) H_2S biooxidation in the liquid phase. Biofilter is a three-phase bioreactor with a high porosity, high buffering capacity, high nutrient availability, and high water holding capacity filtration layer to ensure that the target microorganism can be grown. Gas continually enters the biofil-



Bio-washing

Bio-filter



Biological trickling filter

Fig. 4.30: Three types of bioreactor.

ter, and the nutrient solution should be added intermittently. A biological trickling filter has a similar principle to a biological filter. Moreover, a nutrient solution continuously trickles through the packed bed. In two-stage desulfurization, the H_2S present in the gas phase enters the desulfurization reactor after absorption to complete the oxidation of sulfide using autotrophic microorganisms. The process diagram is shown in Fig. 4.31. Many studies have shown that in biological desulfurization, while controlling the conditions of the gas/liquid ratio, pH, dissolved O_2, and temperature of absorption liquid, the efficiency of two-stage chemoautotroph-type biological desulfurization can reach 99 %.

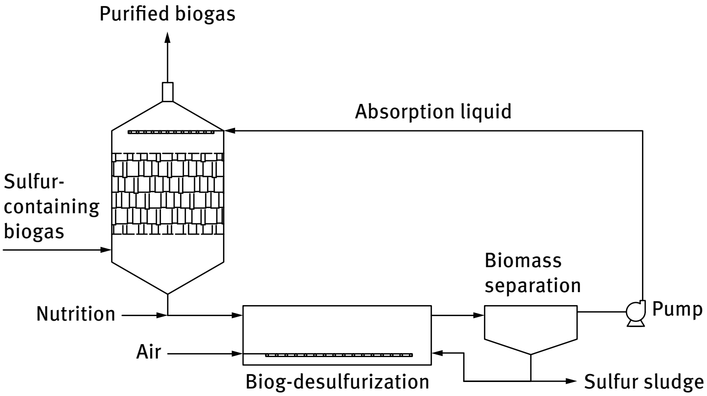


Fig. 4.31: Chemoautroph biological desuphurization unit (Hu Mingcheng 2006)

Biodesulfurization has the following advantages: no chemical catalyst, no secondary pollution, less biosolids, less energy consumption, low processing cost, high H_2S removal efficiency, and recyclable elemental sulfur.

4.2.4.2 Dehydration process and technology

Biogas usually contains a certain amount of water; the water will affect the use of biogas. For example, the water coordinated to H_2S in biogas will corrode the pipelines and equipment; moisture will condense on the diaphragm of check valve, safe valve, and other equipment in the gas delivery pipe, affecting its accuracy. Moreover, the moisture will increase the pipeline's flow resistance and reduce the heat of combustion of biogas. Therefore, biogas distribution systems are required to support the dehydration process. At present, the commonly used methods are gravity dehydration, dehydration condensation, and adsorption dehydration.

4.2.4.2.1 Gravity dehydration

The main principle of gravity dehydration is that biogas tangentially enters a gas–water separation device from the upper side with a certain pressure rotating under centrifugal force. Then, it passes through a horizontal and vertical mesh strainer to separate the water vapor from the biogas, and the water within the device flows downward under gravity along the inner wall and is collected in the bottom of the device periodically. Fig. 4.32 shows a schematic diagram of the gas–water separation device.

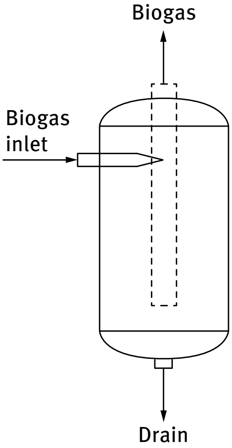


Fig. 4.32: Schematic diagram of the gas–water separation device.

4.2.4.2.2 Condensation dehydration

Condensation dehydration is the most commonly used method for dehydration in biogas engineering in China. By setting a cooler in the pipeline and reducing the temperature of biogas using a refrigerant, the water in the biogas is separated and discharged after condensation at a relatively low dew point. The cooled gas is conveyed by heating to avoid condensation. In large- and medium-sized biogas projects, the water condenser is set at the lowest point of the conveying pipeline to remove the condensed water in the pipeline [85]. Usually, the manual and automatic methods are used for drainage, as shown in Fig. 4.33.

4.2.4.2.3 Adsorption dehydration

Adsorption dehydration is carried out by passing the biogas through an adsorption bed; the moisture in the gas is absorbed by the desiccant inside the bed. Conventional desiccants include silica gel, molecular sieves, alumina, and magnesia.

Molecular sieves are widely used as the desiccant. A molecular sieve is a strong polar adsorbent for polar molecules such as H_2O and H_2S in biogas with a strong affinity for them; therefore, molecular sieves have also been widely used as an adsorbent to

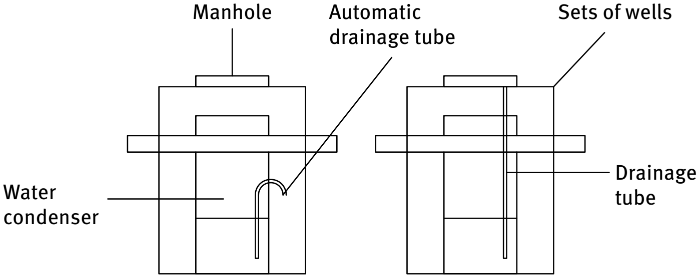


Fig. 4.33: Condensation.

remove H_2S in gas. The regeneration of a molecular sieve after the adsorption of gas is mainly carried out by pressure swing regeneration and variable-temperature regeneration. A part of the product gas is used for desorption by pressure swing regeneration, leading to a decrease in the recovery rate, whereas temperature regeneration does not consume the product gas.

Silica gel is a polar adsorbent with a specific surface area of up to $600\,m^2 \cdot g^{-1}$, and it can be used for biogas dehydration. Activated alumina is a polar adsorbent with a specific surface area of $350\,m^2 \cdot g^{-1}$ and a high mechanical strength, and it can be reused.

Triethylene glycol (TEG) or diethylene glycol dehydration is the most commonly used dehydration process in the natural gas industry. The raw gas is fed into the bottom of an absorption column and is subjected to countercurrent contact with the lean TEG from the overhead of the tower, where water is absorbed by TEG. The rich absorbent solution is concentrated and regenerated using a rectifying column and reboiler after the impurity is filtered. The dehydration processing amount of the TEG absorption method is large, and the technology is mature. However, after a period of operation, foaming appears in the solution, and the crystallized salt jams. The absorption liquid is lost, and other problems occur. Therefore, timely maintenance and management is necessary.

4.2.4.3 Decarburization process and technology

Biogas decarbonization methods can be divided into liquid absorption method and solid adsorption method (Tab. 4.7) [86]. The liquid absorption method is mainly divided into two types: physical absorption and chemical absorption. The physical absorption method mainly involves the solubilization of CO_2 in a liquid followed by separation from the mixture. The chemical absorption method is mainly based on the reaction of CO_2 with an alkaline sorbent. Solid adsorption is mainly divided into fixed-bed adsorption decarburization and selective membrane separation decarburization [87].

Tab. 4.7: Methods for CO_2 removal.

Method	Advantages	Disadvantages
Pressure scrubbing	High purification efficiency (> 97 % CH_4), less CH_4 loss (< 2 %), can simultaneously remove H_2S when H_2S < 300 ppm, easy to operate, simple solvent regeneration, tolerates certain impurities, adjustable processing capability by varying the pressure and temperature	High investment and operating cost, the growth of bacteria causes clogging, easy foaming
Propylene carbonate method	High purification efficiency (> 97 % CH_4), high absorption capability, energy efficiency compared to the water method, renewable solvent, can simultaneously remove H_2S, organic carbide, and water	High solvent evaporation, large loss
Polyethylene glycol method	High purification efficiency (> 97 % CH_4), less CH_4 loss, high absorption capability, energy efficiency compared to the water method, renewable solvent, can simultaneously remove H_2S, organic carbide, and water, low evaporation	High investment and operating cost, incomplete regeneration
Alcoholamine Method (MEA, DEA, MDEA)	High purification efficiency (> 97 % CH_4), less CH_4 loss (< 0.1 %), high absorption capability, renewable solvent, high operating cost,	High investment cost, high regeneration temperature, high energy consumption, easy to decompose in the presence of O_2 forming toxic substances, salt precipitation, corrosive, easy foaming
Membrane separation	Reliable, easy operation, can simultaneously remove H_2S and water, removal efficiency (< 92 % or > 96 %), can produce pure CO_2	Alternatively, membranes are limited, less CH_4 purity and processing capacity, multistep treatment needed to achieve a high purity, large CH_4 loss
Pressure swing adsorption (carbon molecular sieve, zeolite, silica gel aluminum)	High purification efficiency (> 95 % CH_4), less energy consumption, can simultaneously remove O_2 and N_2, high pressure but recyclable, tolerates certain impurities, also suitable for a low processing capacity	High investment and operating cost, many process controls, large CH_4 loss
Cryogenic separation	High purification efficiency (90–98 % CH_4), easy to obtain liquefied CH_4	High investment and operating cost, high energy consumption, low temperature, high pressure

4.2.4.3.1 Absorption Method

Biogas is purified by the absorption method because H_2S has a stronger solubility than CH_4 and CO_2. The absorption methods mainly include high-pressure water washing, physical absorption, and chemical absorption [88].

High-pressure water scrubbing method

The high-pressure water scrubbing method used for the removal of CO_2 is a physical absorption method, and gas is separated according to different water solubilities of CH_4, CO_2, and H_2S. When the temperature change is small, the CH_4 solubility in water slightly changes with pressure, whereas CO_2 and H_2S solubility increases under a higher pressure. When pressure decreases, CO_2 is released due to the lower solubility in water, thus separating the CO_2 and H_2S and completing biogas purification. The high-pressure water scrubbing method has microbial tower plugging problems in long-term use, thus affecting the decarburization efficiency. It can be solved by using UV radiation, high temperature provided by hot water, peracetic acid, citric acid, or a detergent washing tower.

In the high-pressure water scrubbing process, compressed biogas enters the absorption tower from the bottom, whereas water enters the absorption tower from the top to achieve a crossflow absorption (Fig. 4.34). The water absorbed by CO_2 and H_2S can be reused in the absorption column by decompression or air stripping regeneration. The washing method has a low requirement of sulfur content in biogas; generally, biogas with H_2S content of < 200 ppmv can be used. Low-sulfur biogas desulfurization devices without a separate design are available. The removal efficiency of CO_2 and H_2S is related to the size of the absorber, gas pressure, concentrations of gas components, water flow rate, and the fineness. It can theoretically reach 100 %. Because this method requires a lot of water, few domestic demonstration projects have used this technology.

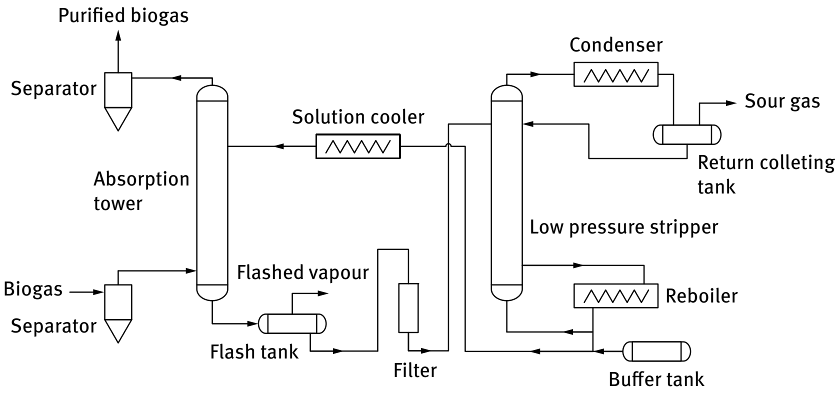


Fig. 4.34: Chemical absorption process flow diagram.

Chemical absorption method

The chemical absorption method involves the reaction of CO_2 in biogas with the solvent in the absorber to form a rich liquid; then, the rich liquid is transferred into the desorption tower for regeneration, absorption, and desorption alternately, thus separating CO_2 (Figs. 4.34 and 4.35).

Chemical absorption solvents are mainly alkanolamine solutions and alkali solutions such as monoethanolamine (MEA), diethanolamine (DEA), triethanolamine (TEA), diglycolamine (DGA), methyldiethanolamine (MDEA), diisopropylalcohol amine (DIPA), NaOH, KOH, $Ca(OH)_2$ and NH_3. The alcohol amine method for CO_2 absorption is widely used in industry, mainly based on the reversible reaction of an alkali with a weak acid. The reaction can be controlled by adjusting the temperature. The reaction is generally carried forward to form salts at 311 K to absorb CO_2; the reverse reaction is carried out at 383 K, releasing CO_2. This technique is not suitable for biogas containing O_2, because O_2 will induce the foaming of absorption solvent.

Fig. 4.35: Solvent absorption projects.

ME method

The absorption of CO_2 using an MEA aqueous solution is good. The reaction of MEA with CO_2 generates a carbonate. Heating decomposes the carbonate, releasing CO_2. The reaction device is simple, and the removal efficiency is high. However, the MEA technology has many shortcomings such as a high cost, slow absorption rate, small capacity, large absorbent dosage consumption, high equipment corrosion rate, and high absorbent regeneration energy consumption.

The reaction of CO_2 with MEA during absorption can be expressed as follows:

$$CO_2 + HOCH_2CH_2NH_2 \rightarrow HOCH_2CH_2HNCOO^- + H^+$$

$$H^+ + HOCH_2CH_2NH_2 \rightarrow HOCH_2CH_2 + NH_3^+$$

The complete reaction can be expressed as follows:

$$CO_2 + 2HOCH_2CH_2NH_2 \rightarrow HOCH_2CH_2HNCOO^- + HOCH_2CH_2 + NH_3^+$$

DEA method

The reaction of DEA (aqueous solution) with CO_2 is similar to that of MEA. Because the boiling point of DEA is high, it can absorb CO_2 at higher temperatures; therefore, this method has been widely used. The modified DEA (DEA-SNPA) method is used at pressures of 6.86–7.35 MPa. The concentration of DEA can be increased to 25–30 %, and the degree of carbonization can reach up to 1 mol CO_2/1 mol DEA. Compared to MEA, a DEA solution has a higher CO_2 partial pressure and lower degree of purification. The absorption rate is low, and the cost is high. Because of the higher boiling point of DEA, less evaporation loss, easy regeneration, and less heat consumption of stripping, the DEA method has a lower construction and production cost than the MEA method.

Activated N-methyldiethanolamine (MDEA) method

The activated MDEA method is a new method developed by the German company BASF in the 1970s to remove the CO_2. This has been successfully implemented in 300,000 tons/year NH_3 plants. In the late 1980s to early 1990s, China's Nanjing Chemical Research Institute, East China University of Science and Technology, and Sichuan Chemical Research Institute launched the activated MDEA decarburization process with their own characteristics.

The CO_2 absorption process of MDEA has two characteristics: physical absorption and chemical reaction. Therefore, when decarburization is carried out by the MDEA alcohol amine method, the requirements of raw material gas pressure, acid gas concentration, and purification gas quality reduce the process energy consumption. The CO_2 partial pressure in raw gas is an important factor that affects the process selection and process. Usually when the partial pressure of CO_2 is higher than 0.5 MPa, the energy saving effect is obvious. The unit energy consumption for CO_2 removal decreases linearly with the increase in pressure. In the actual project, the process can be determined and optimized by analyzing the circumstances.

The results of recent studies show that the addition of a small amount of an amine, diethylenetriamine (DETA) or triethylenetetramine (TETA), to MDEA, significantly accelerates the reaction rate of CO_2 absorption, reduces the solution interface CO_2 partial pressure, increases the CO_2 absorption efficiency, and simultaneously removes H_2S and organic sulfur with CO_2. Compared to a single amine solvent purification process, the CO_2 removal process of a mixed amine solvent has the advantages of low energy consumption and large capacity. The amount of CO_2 removed in the feed gas can be adjusted according to the requirements. CO_2 purification efficiency is high under a lower operating pressure in the absorber. The corrosion rate and solvent loss are low without the addition of corrosion inhibitors.

PSA

The PSA separation method, also known as molecular sieve adsorption, is a normal temperature gas separation and purification technology developed in the 1960s. The

PSA method is chosen when the adsorption capacity of the adsorption agent is different for different substances. The adsorption rate, adsorption force, and adsorption capacity of the adsorbent varies with the pressure, adsorption, and separation of a gas mixture in a completely pressurized system. The adsorbent can be completely regenerated, thus separating the gases. The commonly used adsorbents are natural zeolite, molecular sieve, activated alumina, silica gel, and activated carbon. The entire process has five steps: adsorption, washing, pressure treatment, vacuum treatment, and pressure treatment. The separation effect is related to the properties and affinity of molecular sieves. By selecting suitable molecular sieves with different pore diameters or varying pressure, CO_2, H_2S, moisture, and other impurities can be selectively removed from the biogas. Fig. 4.37 shows the flow diagram of the PSA process. First, biogas enters the bed under pressure. The adsorbent selectively adsorbs the strong adsorbate component in the biogas (CO_2) using the adsorption bed, and the weak adsorbate component in the biogas (CH_4) is discharged from the outlet of the adsorption bed. When the pressure of the adsorption bed is reduced, the adsorbed CO_2 is desorbed from the adsorbent, and the adsorbent is regenerated. To maintain a continuous operation of biogas purification, four adsorbers are needed, where two adsorbers are located in the adsorption phase, one adsorber is located in the regeneration phase, and one adsorber is located in the pressurization stage. The PSA method is suitable for biogas on a small scale without O_2. If the biogas contains O_2 in the concentrated exhaust in PSA, it is possible for CH_4 to reach the explosion limit. Thus, this method has safety risks.

In PSA decarburization, the CH_4 volume content can reach up to 97–99.17 %, and the CO_2 content is lower than 1 %. The recovery rate of CH_4 is > 94 %. The composition and temperature of biogas slightly affect PSA decarburization.

The PSA biogas purification technology has a low cost, low energy consumption, high efficiency, and high degree of automation devices. However, the adsorbent of PSA has high requirements, and several adsorbers should be connected in parallel for efficient adsorption (Fig. 4.36).

Fig. 4.36: PSA engineering examples.

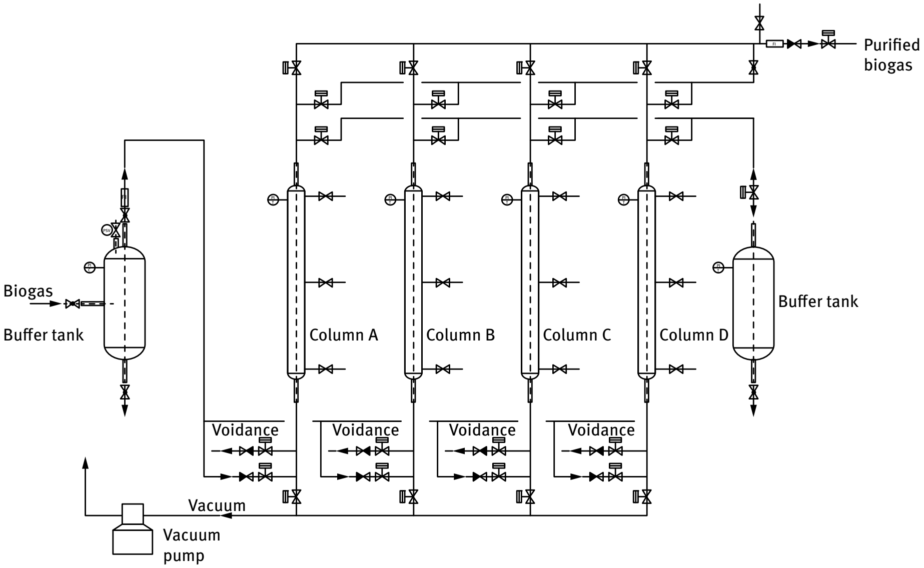


Fig. 4.37: PSA process flow diagram.

4.2.4.3.2 Membrane separation method

From the beginning of the twentieth century for 70 years, many countries in the world carried out industrial experiments on membrane separation technology for gas separation. The first application in industry was achieved by PRISM membrane separator developed by the Mosaton Company in 1979. After decades of development and improvement, membrane separation technology has matured for diverse industrial applications.

The membrane separation method utilizes a selectively permeable membrane as the separation medium. This is because the gas partial pressure of two sides of the membrane is different, depending on the differences in gas solubility in membrane and diffusion rate, thus selectively “filtering” each component to achieve gas separation. Gas separation membrane materials are of three types: polymer, inorganics, and metals. The polymers include polydimethyl siloxanes, polysulfone, polyamide, and polyimide, and cellulose acetate hollow fibers; the inorganics include ceramic films, porous glass membranes, and carbon molecular films; the metal films are mainly rare. A hollow fiber membrane is suitable for the removal of CO_2.

The membrane separation processes can be divided into high-pressure gas-phase separation and gas/liquid-absorption membrane separation. Both sides of the membrane in high-pressure gas-phase separation need high pressure. First, biogas is pressurized to 3.6 MPa to remove halogenated hydrocarbons and partially remove H_2S using an activated carbon bed; then the biogas enters the filter bed, heater, and membrane separation die to achieve the separation of CO_2, H_2O, H_2S, and other polar

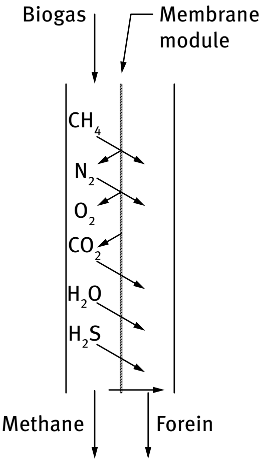


Fig. 4.38: High-pressure gas membrane separation principle.

molecules, but it cannot separate N_2. The gas–liquid phase absorption membrane separation principle is shown in Fig. 4.38. One side of the membrane has the gas phase, and the other side is a liquid. It does not require a high pressure. Gas flows from the side of the membrane. H_2S and CO_2 molecules can diffuse through the the membrane and be absorbed by the liquid in the opposite direction on the other side. The working pressure of the absorber film is only 0.1 MPa, and the temperature is in the range 25–35 °C. The absorbent liquid phase is the amine and alkaline solution (Fig. 4.39).

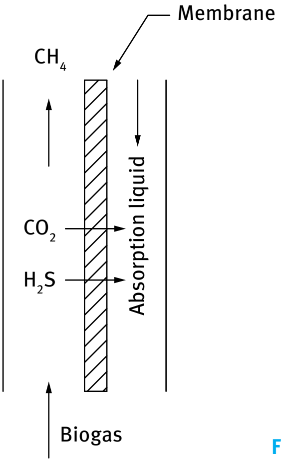


Fig. 4.39: Gas-liquid phase absorption membrane separation principle.

The membrane separation technology has the following advantages: easy operation, convenient switching, long service life, easy installation, small land requirement, light weight, cover a small area, continuous operation, wide adaptation range, convenient maintenance, and low energy consumption. In China, the membrane separation method is mainly used for mixed gas recovery including H_2, purified CO, and N_2 and in the removal of natural gas. No membrane separation process engineering applications have been reported for biogas or land fill gas decarbonization.

Because gas separation efficiency is affected by many factors such as membrane material, gas composition, separation of pressure and temperature, clean lines of feed gas have certain requirements and the membrane is expensive. Therefore, the gas membrane separation processes are generally not used alone and often combined with solvent absorption PSA deep cooling separation and pervaporation processes. The combined membrane separation + MDEA solvent absorption method is simple and has the advantage of a low hydrocarbon loss of MDEA solvent absorption. At the beginning of the membrane separation of raw biogas, a part of the CO_2 in natural gas is separated to reduce the downstream MDEA solvent absorption decarburization load. According to the preliminary optimization results, in the first part of membrane separation, CO_2 is separated using MDEA, and the solvent absorption decarburization load decreases by > 45 %, thus significantly reducing the equipment investment and energy consumption. Gas containing ~73 % CO_2 mixes with a high concentration of CO_2 in the MDEA solvent absorption device; the resulting concentration is close to 90 %. At a low temperature, CO_2 and hydrocarbon can be separated. The separated liquid hydrocarbon is used as the fuel, and CO_2 is directly isolated as the product. Fig. 4.40 shows the principle of the combined membrane separation + MDEA solvent absorption combined method.

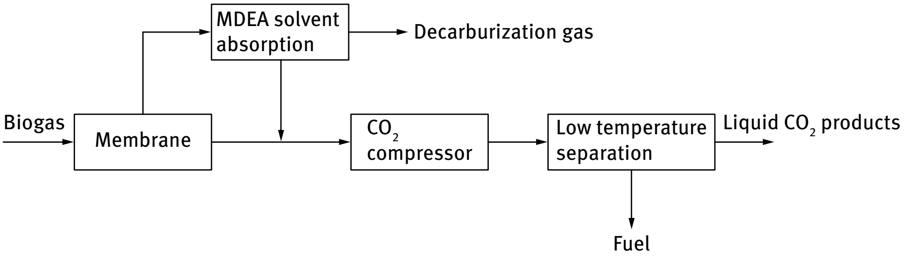


Fig. 4.40: Membrane separation + MDEA solvent absorption combined method principle chart.

Other separation methods are cryogenic separation method, biological method, decarbonization, and hydrate method. The cryogenic separation method refers to segregation of gas mixtures by distillation for gas separation at low temperatures. The characteristics of the technology are low temperature (close to −90 °C) and high pressure (40 bar) to achieve CO_2 separation by liquefaction, and it is still in the early stage of demonstration. The biological method is currently limited to the laboratory stage. The five main carbon sequestration pathways are the Calvin cycle pathway, activated acetic acid pathway, and three tricarboxylic acid cycle reduction pathways. The main substrates are hydroxyl propionic acid glycine, and the main carbon fixation microorganisms are microalgae, cyanobacteria, photosynthetic bacteria, H_2 bacteria, nitrifying bacteria, sulfur bacteria, iron bacteria, methanogen bacteria, and acetic acid bacteria. Although the microbial removal of CO_2 has still not been used for industrial applications, the carbon sequestration capacity of certain microorganisms is still very significant. The principle of gas separation of the hydrate method is as follows: When the gas mixture forms a hydrate, the gas composition in hydrate and gas phases is not consistent, and easily forms a hydrate group branch phase enriched in hydrate, thus separating the components.

4.2.4.4 Deoxidation process and technology

Biogas after traditional biological desulfurization typically contains 0.8–3 % O_2. If the O_2 content is too large in biogas, the biogas utilization process will be very dangerous and even threaten people's lives. The Compressed Natural Gas (CNG) preparation process clearly requires that the O_2 content of biogas is < 0.5 % (GB18047-2000). Therefore, the removal of O_2 in CH_4 is particularly important.

Gas deoxidation mainly includes three types of catalytic deoxidation, adsorption and combustion deoxidation. A noble metal-based deoxidizer, Cu-based deoxidizer, Mn-based deoxidizer, Ni-based deoxidizer, Mo-based deoxidizer, Fe-based deoxidizer, and sulfur-tolerant deoxidizer have been developed and successfully applied to CBM deoxidation, olefin deoxidation, synthetic gas deoxidation, general gas deoxidation, and other industrial applications.

For both biogas and common gases, deoxidation has similar factors and some features of its own. Combining the three deoxidation mechanisms described previously, for biogas deoxidation, hydrogenation deoxidation can be combined with H_2 impurities. Also, the problem of a hydrogen source should be solved. Chemical absorption deoxidation is difficult to reach the depth of deoxidation for industrial requirements. Therefore, the use of a catalytic combustion mode and the use of CH_4 from biogas in the presence of O_2 will be the optimal choice. Catalytic combustion for CH_4 deoxidation utilizes the excess CH_4 with small or trace amounts of O_2 in the presence of a catalyst at a temperature of 200–300 °C without flame. Diverse catalysts have been developed for CH_4 combustion, and they can be divided into precious metal-supported catalysts and transition-metal oxide catalysts. Combined with the characteristics of the composition of the biogas itself, it is advised to use precious metal catalysts for deoxygenation. When the Pd/Pt = 1:4 (wt/wt), using a catalyst content of 0.2 wt %, the O_2 in biogas gas can be removed to 0.09 %, and the activity can be maintained for a long time.

4.3 Projects and models

China has been one of the first countries to utilize biogas. The utilization of biogas is mainly domestic in the “Eleventh Five-Year Plan.” The size of biogas industry, material utilization, technology, and other aspects of biogas utilization have made considerable progress. According to the statistics, at the end of 2011, the total amount of large-scale national livestock waste handling biogas projects is > 5,000, that of industrial organic wastewater sludge is > 2,000 seats, and that of municipal organic waste and sludge is 630 seats. There are 80,500 large-scale biogas projects in China with an annual capacity of 15 billion cubic meters of biogas, amounting to 31 million tons of standard coal and equivalent to 11.4 % of the national annual consumption of natural gas [88, 89].

4.3.1 Cogeneration project

Shandong Minhe Animal Husbandry Ltd. was established in 1997, and it is Asia’s largest enterprise for parent broiler breeding. It has broiler breeding and chick production at its core. It has a relatively complete industrial chain of broiler breeding, slaughter, processing, and biological technology. It has been awarded with the Key State Enterprises of Industrialized Agriculture, National Zones of Demonstration Agriculture, National Representative Area of export chicken standardization, and the honor of being an Outstanding Enterprise of National Animal Husbandry.

The company’s stock was listed on the Shenzhen Stock Exchange in May 2008. Minhe has become the first public and domestic listed broiler breeder breeding company. The company has 37 production units of chick farms, hatcheries, feed mills, commodity chicken base, food companies, export companies, biotechnology companies with an annual 170 million chicks of broiler hatching, 400,000 tons of feed, and 60,000 tons of chicken feed. The company has passed the certification of ISO9001: 2000, HACCP, and EUREPGAP systems; its products have passed the “China Green Food Certification” and won the “China International Agricultural Expo Brand”, “China Safe Food Brand”, “Shandong Famous Brand,” and other honorary titles.

4.3.1.1 Introduction to engineering

The Shandong Minhe Animal Husbandry 3 MW cogeneration biogas power generation project treats livestock manure and sewage as the raw materials, utilizes an anaerobic fermentation process to produce biogas, it also purifies biogas, generates electricity and employs cogeneration. It is the largest agricultural biogas power generation project. The project was completed in November 2008 and first generated electricity in February 2009. The main process facilities contain two of 2,000 m^3 hydrolysis grit, eight seats of 3,200 m^3 anaerobic fermentation tank, one seat of 2,150 m^3 storage cabinet of double-membrane dry gas, two biological desulfurization towers, and three gas turbines. The production of biogas is 32,000 m^3/d, and the daily generating capacity is 65,000 kW · h, which can generate a revenue of 14 million yuan by selling electricity per year. The heat produced by generators can be used to warm an anaerobic tank to maintain the fermentation temperature of 38 °C in winter. The broth can also be used as a fertilizer for Yantai apple and Zhangyu grape plants at neighboring farms. This not only reduces the use of chemical fertilizers, but also achieves the recycling of resources and ensures zero emissions of pollutants. It can generate revenue of 7,000,000 yuan per year. The project can achieve emissions reduction equivalent to 70,000 tons of CO_2 per year, and the income of CDM carbon trading is almost 700 million per year. It is the first agricultural biogas project with successful CDM registration in the UN.

Moreover, the main project of Shandong Minhe Animal Husbandry waste treatment compressed biogas purification was built and operational in september 2013. This will produce 70,000 m^3 biogas every day; after the upgrade and purification of biogas, 40,000 m^3 biogas can be supplied to 1,000 local cars per day. The project can achieve emissions reduction equivalent to 260,000 tons of CO_2 (Fig. 4.41).

4.3.1.2 Technical Characteristics

The main technical innovations and characteristics of the project are as follows:

- **Centralized mode of collecting and processing thermoelectric fertilizer with comprehensive utilization of agricultural waste and cogeneration for the reduction of greenhouse gases**
  The project has developed a replicable mode of processing agricultural waste "dispersion and collection of raw material, centralized anaerobic treatment – biogas manure of dispersed digestion." The project will collect and dispose of wastes from 23 farms, produce biogas by anaerobic fermentation, purify biogas, and then produce electricity for the national grid. The remaining heat will be used for warming the anaerobic systems without an external heat source in winter. The broth can also be used as a fertilizer for Yantai apple and Zhangyu grape plants at neighboring farms, thus reducing the use of chemical fertilizers. The project will achieve significant benefits by mitigating greenhouse gases and reducing emissions equivalent to 70,000 tons of CO_2 per year.
- **Technology for hydrolysis desanding of a high grit content chicken manure**
  Because manure contains a lot of grit, it cannot be removed in the pre-processing stage, causing severe wear and tear to feed pumps, mixers, and other equipment and depositing in the anaerobic tank. This seriously affects the efficiency and stability of system operation. The digestive fluid and sand are bonded together in manure; therefore, physical precipitation cannot separate fecal sand by traditional methods.

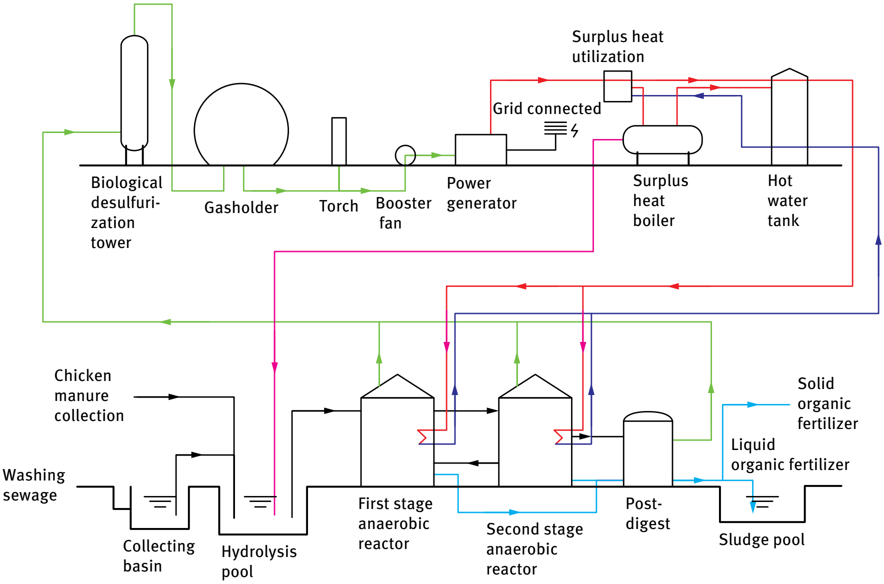


Fig. 4.41: Flow chart of Shandong Minhe Animal Husbandry’s MW biogas power generation project.

This project utilizes hydrolysis desanding technology to remove sand, to set the hydrolysis pool in the pre-stage, and to separate the fecal sand by hydrolysis. The use of spiral desanding machinery removes > 90 % of the sand in the raw material through the bottom of the hydrolysis tank, thus avoiding wear and tear to the equipment and pipelines in the anaerobic tank. This ensures an efficient and stable operation of the system.

- **Key device and efficient technology for anaerobic fermentation of high NH_3 nitrogen**
  Because the anaerobic fermentation of pure chicken manure has the universal problem of a high concentration of NH_3 nitrogen, it is currently international practice to mix chicken manure with cow dung and other organic wastes for co-digestion. A technology has been developed for culturing high NH_3-resistant strains for the anaerobic fermentation of high NH_3 manure materials, thus increasing the acceptable NH_3 concentration from the conventional 3,000 mg/L to 6,000 mg/L or more. This created the conditions for the anaerobic fermentation of a high concentration of pure chicken manure.

4.3.1.3 Financial evaluation

The total investment is ~70 million yuan: ~39 million yuan for facilities and equipment, ~15 million yuan for generator sets and internet devices, and ~16 million yuan for others.

The total revenue is 27.67 million yuan: ~14.3 million yuan from the generation of electricity per year, 6.17 million yuan from CDM per year, 7.2 million yuan from biogas fertilizer per year.

4.3.1.4 Social and enviromental benefits

Environmental benefits

The project collects manure from 23 farms; subsequent anaerobic fermentation converts the agricultural organic waste to biogas, thus not only solving the pollution problem, but also producing clean energy. The digestate can also be used as an organic fertilizer to improve crop production. Thus, green unpolluting of agricultural products can be achieved, improving the quality of agricultural products. Moreover, the project can reduce emissions of greenhouse gases annually by 70,000 tons CO_2 equivalent, achieving significant environmental benefits.

Social benefits

The project can significantly alleviate the environmental pressure on its location, improve the environmental situation, and enhance the quality of life of local residents. Second, the project has become a new economic growth area for Shandong Minhe Animal Husbandry Co., Ltd. The fermented slurry is rich in N, P, K, and various trace elements; it also contains diverse bioactive substances. Thus, it is a high-quality organic fertilizer. The use of digestate as the basal and top dressing of food crops can reduce the amount of fertilizer, increase the crop yield and quality, and achieve safe food production of green fruits and vegetables. This is important for the sustainable development of local agriculture.

4.3.1.5 The main experience

Practical and reliable technical support

The Shandong Minhe Animal Husbandry Co., Ltd.'s 3 MW biogas power generation project selected the local key technologies and equipment of Hangzhou Energy and Environment Engineering Co., Ltd., thus not only ensuring reliable technology and equipment, but also reducing the project's cost. The company developed the key technology for the large-scale anaerobic fermentation of pure chicken manure with a high sand content; high NH_3 and other characteristics solved the main problem in technology, thus reducing project risks and operating costs.

Products of high value and diversification

The products of high value and diversification are clean energy, organic fertilizer, and carbon emissions. On one hand, the project can significantly ease the pressure on the local environment by reducing the manure generated from farms; on the other hand, it can expand the industrial chain of biogas. Moreover, by generating income from the sale of electricity and actively producing organic fertilizer from the digestate, it effectively promotes the local recycling economy and increases the revenue of the company. If the project makes a deal with World Bank about carbon emissions, it will generate new revenue for the enterprise.

4.3.2 Biogas project for vehicles

Purified biogas for use in vehicles is still in the initial demonstration phase in the country. The government clearly stated that it will focus on increasing biogas production for use as vehicle fuel in the field of biomass energy in the "National Five-Year Science and Technology Development Plan." At present, China has partially purified biogas demonstration projects. The Guangxi Wuming Anning starch wastewater project for vehicle gas and the second project of Shandong Minhe biogas purification have been completed.

Guangxi Wuming Tranquility Starch Co., Ltd. was established in 1998. It is a medium, private, high-tech, innovative pilot, and leading agricultural industrialization enterprise, producing and deep processing cassava starch, tapioca starch, alcohol products, and fine chemical products in autonomous regions. The company is located in the resource-rich cassava Luo Bo Town in Guangxi WuMing county; its registered capital is 12 million yuan with an annual output of 10,000 tons of cassava starch, 20,000 tons of modified starch, 30,000 tons of edible alcohol, and 6 million cubic meters of biogas, thus achieving a circular economy industrial model of tri-cogeneration of biogas, tapioca, and cassava ethanol.

At present, the first project involving building an industrial wastewater biogas engineering plant for cassava starch or alcohol preparation has been successfully transferred into commercial operation, and a total of 500 taxis are using biogas produced by the company in Nanning.

4.3.2.1 Introduction to the project

The Anning Company purified biogas project mainly utilizes a large amount of cassava peel, cassava root, cassava residue, alcohol waste, wastewater, and other cassava starch as the raw materials, obtained from the factory that produces cassava starch and ethanol in the production process. Using an efficient anaerobic digestion technology and decarbonization, purified biogas and compressed biogas are produced and can be used as clean energy for urban taxis and buses.

The project was completed in two phases. In the first phase, three anaerobic tanks were constructed with a total of 20,000 m^3 volume from March 2010 to March 2011. They can utilize alcohol and starch wastewater sludge with a yield of 20,000 m^3 biogas and 12,000 m^3 vehicle fuel, sufficient for 500 taxis per day. In the second phase, the original project was upgraded and improved from July 2011 to December 2013. This increased the biogas yield to 60,000 m^3 per day building two new25,000 m^3 efficient anaerobic tanks, collecting the cassava waste and crop residues to produce biogas around the factory. Biogas production will increase to 40,000 m^3 daily, and the total production of biogas will increase to 100,000 m^3 daily after purifying. It can be used for 2,000 taxis.

The residue of anaerobic fermentation can be sold as organic fertilizer, inoculum, and circulating of water; the rest is returned to starch and alcohol production water by aerobic treatment (Fig. 4.42).

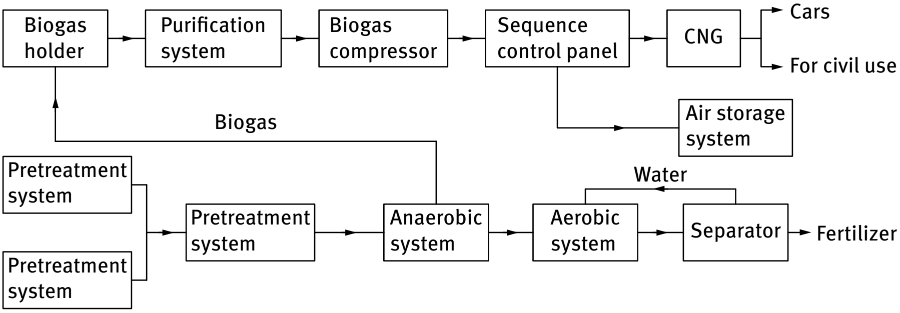


Fig. 4.42: Flow chart of Guangxi Wuming Tranquility Starch wastewater system vehicle gas project.

4.3.2.2 Engineering solutions

The project utilized raw materials such as cassava residue, tapioca starch/alcohol wastewater, cassava stem, and anaerobic water with COD ≤ 20,000 mg/L. The reactors include three 8,000 m^3 fermenters and two 5,000 m^3 fermenters with a feeding rate of 6,000 m^3 daily and production of 100,000 cubic meters of biogas. The CH_4 content of biogas is > 97 % with an annual output of 15 million cubic meters of compressed gas.

4.3.2.3 Technical features

- To achieve fast and efficient biogas production, the engineering includes an automated control system, anaerobic species, and reaction device. It can improve the stability and reliability of the gas system.
- To achieve a high efficiency and low cost of decarbonization, high-pressure water washing can be used.
- The purified biomethane could achieve the GB18047-2000 standard for vehicles with a CH_4 content of > 97 %, removal rate of 98 % H_2S, H_2S content of < 15 mg/m^3, CO_2 desulfurization rate of > 96 % and CO_2 content of < 3 %.
- It uses diverse organic materials for mixed fermentation.

4.3.2.4 Financial evaluation

The total investment by the project was 85 million yuan: ~20.5 million yuan for the biogas system, the remaining 39.5 million yuan for the biogas purification system.

The total revenue was 45.95 million yuan: 45 million yuan from the annual sale of biogas products. The total profit from the sales was 13.587 million yuan. The income from the sales of fertilizer was about 15 million, thus reducing the sewage treatment fee and environmental fines to about 80 million.

4.3.2.5 Social and environmental benefits

Environmental benefits

With the annual emission of 160,000 tons of CO_2 equivalent greenhouse gas, the waste residue produced after the anaerobic treatment of organic fertilizer produces 3,000 tons of combined cassava starch, cassava alcohol, biogas, thus providing a circular economy model for the starch industry and the alcohol industry.

Social benefits

Social benefits include the comprehensive utilization of biomass energy. The purified biogas can be used as a vehicle fuel and gas instead of natural gas for the local residents after purification and compression. This helps to alleviate potential energy shortages for local residents and is good for the environmental governance of the biomass industry.

A deep utilization of biogas can help to utilize the tapioca stalks discarded everywhere in the cassava production areas and manioc residue. It can also use livestock manure and crop straw as raw materials for biogas to change waste materials into valuable products and reduce pollution by organic waste. This is important for the development of a circular economy.

4.3.2.6 The main experience

The main experience includes the degree of automation control of engineering that uses purified CH_4 for biogas production, facilities needed to strengthen employee skills by training, and improve the operating level. At the same time, it is also a very important to care for and maintain these control facilities.

The anaerobic technology and purification process are the key technologies of fuel gas projects. The industry–university–institute cooperation was thoroughly studied to ensure a constant technological innovation, to reduce the project's construction and operating cost, and to gain good economic benefits and ensure a long-term operation of the project.

4.3.3 Pipeline and central gas supply engineering cases

Beijing's Green Source Agricultural Science and Technology Co., Ltd. was established in 2000. This company is dedicated to using new and better technologies to solve the problem of food safety and clean energy supply using joint-stock high-tech enterprises. The company has a registered capital of 280 million yuan. In Beijing, the largest egg production base in Asia was established, achieving a circular economy industry mode by combining laying hens breeding—food processing—clean energy—organic manure—organic farming—contract farming. DE Qing Source also undertook the gas supply task. The 39 villages in Yanqing have ten thousand peasants (Fig. 4.43).

4.3.3.1 Project introduction

During the 12th Five-Year Plan, DE Qing Source conducted the research project MOST that used continuous dry straw fermentation and purified compressed CH_4 gas, implementing a new rural Wanhu key technology research and demonstration. DE Qing Source organized a conference of Biogas Alliance experts to solve a series of key technological issues including the mixed fermentation of many raw materials, biogas desulfurization, deoxidation, decarburization, purge gas, and high-pressure air supply. Thus, a new type of rural energy solution was developed.

Fig. 4.43: Beijing, DE Qing Source's 2 MW cogeneration biogas engineering of fowl manure.

Anaerobic fermentation was conducted using materials such as straw, manure, branches and leaves, and kitchen waste by mixing the raw materials to produce biogas, which was then converted into high-purity gas after purification and compression. Using a high-pressure tank car, the biogas was sent to villages and delivered to farmers as a clean energy source for domestic use.

At present, the first pilot project of the scheme has already started construction in Yanqing. This project was developed by the Beijing Development and Reforming Office. The total planning investment is 143.06 million yuan. It can solve the gas problem of 30,000 peasants in 39 villages and 10,100 households of Yanqing county, Zhang Shan Ying Town and Kang Zhuang Town.

4.3.3.2 Engineering scheme

This project uses straw as the anaerobic fermentation raw material. The amount of raw material required for daily operation is 45 tons. It has two 2,000 m^3 fermentation tanks and two 500 m^3 reactors; 4.6 million m^3 biogas was produced in a year. Using membrane purification, the CH_4 content reached 97 % or higher, the CH_4 yield also reached 99 % or higher, and 2,760,000 m^3 purified biogas was produced in a year.

4.3.3.3 Technical characteristics

- Using two-stage membrane purification, construction costs were 70 % lower than with washing.
- To solve the mid-level farmer's clean energy requirements as the starting point, a new gas supply mode was developed. The mode is biogas production–purified CNG gas–village gas storage–pipe to the home.
- Using a mixture of biogas slurry with straw for fermentation, the C/N was adjusted without extra cost, completely utilizing the living microorganisms of straw to accelerate straw stalk fermentation.
- Diverse mixed fermentation of organic raw materials.

4.3.3.4 Financial evaluation

The total investment of the project is ~143.06 million yuan, including 47.833 million yuan for the biogas project, 76.117 million yuan for the home installation project, 5 million yuan for the purification equipment, and 14.11 million yuan for others purposes.

The income from sales is about 6.899 million yuan. To reduce the cost of peasant household gas demand, a model was used to supply the gas at a lower cost than the cost price per cubic meter of purified gas at $2.5. The 39 villages have 10,100 households, consuming 0.6 m^3 purified gas per household. Considering the actual situation in rural areas, the famers were allowed to pay for the biogas with straw. A ton of straw can be converted into 60 m^3 purified gas (100 m^3 biogas). This helped to produce 985.5 thousand m^3 purified gas, sell 1,883.6 thousand m^3 purified gas to peasants, earning 4.709 million yuan. The total income from selling the purified gas is 4.709 million yuan. The production of solid organic fertilizer is 10,950 tons. According to 200 yuan per ton, the income is 2.19 million yuan.

4.3.3.4.1 Environmental benefits

This project can solve the clean fuel supply problem of > 10,000 peasant households, reducing the consumption of fuelwood or coal by > 10,000 tons, and protecting a large number of trees. Thus, it has a very good environment benefit.

In the countryside, the burning of straw after harvest is very common. This not only means a fire hazard and produces a lot of dust particles such as PM2.5, but also counteracts the maintenance and growth of organic matter in soil. After anaerobic digestion, the straw can yield biogas energy and a lot of organic fertilizer. The organic fertilizer can enhance organic matter in the soil, reducing the fertilizer input and increasing the crop yield and quality.

4.3.3.4.2 Social benefits

This project can solve the clean fuel supply problem of > 10,000 peasant households, reducing the energy input to 200 yuan per household. It could supply > 10,000 tons of organic fertilizer and develop > 2,000 mu of to organic plants, increasing the income of the peasant by more than ten million yuan.

4.3.3.5 The main experience

The supply of clean energy has been a weakness in China's rural areas for a long time. Using a method in cooperation with government, clean energy was provided to the rural population, providing a good economic outlook and social and economic benefits.

Tingzhou Lei*, Yang Jiang, Xiaofeng He, Zhiwei Wang, Weizhen Li, and Shuna Liu

5 Biomass briquette fuel technology

5.1 Concepts and principles of biomass briquette fuel

5.1.1 Concepts of biomass briquette fuel

“Biomass briquette fuel” refers to different-shaped fuel products of high density manufactured from bulk and unshaped agricultural and/or forestry residues at a certain temperature and pressure. Depending on the shape, biomass briquette fuel can be classified into pellets, block-shaped, and rod-shaped fuels as shown in Fig. 5.1. Biomass “pellet” fuel refers to a biomass briquette fuel with a diameter or cross section of less than 25 mm. Biomass “briquette fuel” refers to briquette fuel with a diameter or cross section of more than 25 mm. The raw materials for such biomass briquette fuels include wood, herbage, and other materials. Woody raw materials mainly include sawdust and wood shavings produced during timber processing, wood residues from industrial and domestic buildings, bark, tree branches, and bamboo. Herbage raw material mainly includes reeds, various crop stalks, husks, vinasse, and other organic residues. Other raw materials include any other solid biomass that can be crushed and compressed into differently shaped fuels.

China’s Agricultural Industry Standard NY/T1878-2010 “Technical conditions for biomass briquette fuel” provides the requirements for the basic and auxiliary performance indexes of biomass briquette fuel as shown in Tabs. 5.1 and 5.2.

Biomass briquette fuel offers the advantages of low cost, convenient storage and transportation, high ignitability, good combustion, high energy density and mass den-

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***Corresponding Author: Tingzhou Lei:** Henan Academy of Sciences, Zhenzhou 450008, China; E-mail: leitingzhou@163.com
Yang Jiang: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Xiaofeng He: Henan Academy of Sciences, Zhenzhou 450008, China
Zhiwei Wang: Henan Academy of Sciences, Zhenzhou 450008, China
Weizhen Li: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Shuna Liu: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China

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Pellet fuel

Block-shaped fuel

Rod-shaped fuel

Fig. 5.1: Biomass briquette fuel products.

Tab. 5.1: Requirements for basic performance of biomass briquette fuel.

Item	**Pellet fuel**		**Briquette fuel**	
	Mostly using herbage raw materials	**Mostly using woody raw materials**	**Mostly using herbage raw materials**	**Mostly using woody raw materials**
Maximum diameter or cross section (D), mm	≤ 25		> 25	
Length, mm	≤ 4 D		≤ 4 D	
Density of different shaped fuel, kg/m^3	≥ 1000		≥ 1000	
Water content, %	≤ 13		≤ 16	
Ash content, %	≤ 10	≤ 6	≤ 12	≤ 6
Lower heating value, MJ/kg	≥ 13.4	≥ 16.9	≥ 13.4	≥ 16.9
Broken ratio, %	≤ 5			

sity, uniform nature, stable water content, and high thermal efficiency. The market uses of biomass briquette fuel include the following:

(1) Household energy consumption in rural areas: This type of fuel is mainly used for cooking and heating in agricultural households, and in nursing homes, primary and secondary schools, hospitals and other public facilities in villages and towns, where small coal burners are modified into stoves, kitchen ranges, and heatable brick beds, depending on the case.

Tab. 5.2: Auxiliary performance requirements for biomass briquette fuel.

Item	Performance requirements
Sulfur content, %	≤ 0.2
Potassium content, %	≤ 1
Chlorine content, %	≤ 0.8
Additive content, %	Nontoxic, odorless, harmless ≤ 2

(2) Regional heating in winter: This type of fuel is mainly used for public facilities in villages and towns in northern China such as rural communities, primary and secondary schools, and village and government facilities, where in model projects coal furnaces are modified to accommodate different-shaped heating fuel for heating such public facilities in the winter. Biomass briquette fuels can also be used for heating protected agricultural facilities in the winter such as crop farming (greenhouses) and protected breeding including seedlings, growing vegetables and specialty fruits, and livestock breeding, where a small biomass furnace can be used to provide sectionalized heating.

(3) Substitution of industrial furnaces that would otherwise be fueled with coal, oil, or gas: Such furnaces can be modified to use briquette fuels as a substitute, reducing pollution and lowering the production costs of the enterprise.

5.1.2 History of biomass briquette fuel development

The development of biomass briquette fuel in China occurred in three phases. The first phase covers the period from the late 1970s to the early 1980s when the technologies were introduced and tested. The Ministry of Agriculture introduced the briquetting technology from abroad. Such briquetting equipment included the spiral extrusion briquetting machine, which was tested and improved in Liaoning, Hubei, Guizhou, Henan, and other regions. Because of the poor wear resistance of the core part – the spiral head – its technical promotion was restricted, and with inadequate equipment support, the use of biomass spiral extrusion briquetting machines increased slowly.

The second phase covers the period from the mid-1980s to the late 1990s, which was in fact the initial stage of biomass briquette fuel use. China encouraged relevant scientific research organizations to develop piston-type briquetting machines that used stalks and woody materials to produce rod-shaped biomass fuels, and some progress was achieved.

The third phase covers the period from the late 1990s to present, which has been the developmental stage of biomass briquette fuel in China. During this period, because of the energy crisis and concerns about environmental pollution, much importance was generally given to fuel, and the central and local governments carried out biomass briquette fuel development plans and policies individually, resulting in the diversified development of biomass briquette fuels and many types of briquetting equipment mainly including ring die, flat die, double-roll, and carbonization briquetting equipment, and many types of biomass briquetting preconditioning equipment such as box-, belt-, cylinder-, and plate-type equipment, and other dryers, as well as chopping-type, rolling-cutting-type, hammer, combined, and other types of pulverizers. Biomass briquette fuel automatic production lines were built in many regions to increase the market supply to more than 3,500,000 t, thus initially achieving true mass production and building a biomass briquette fuel industry chain [90].

Research has investigated the natural water loss rate, analyzed the calorific value, porosity, and chemical components, as well as conducted other tests to determine the main physical and chemical characteristics related to drying and has built the corresponding database. Using the volume-averaging theory, representative elementary volumes for drying processes have been established. Starting from the heat and mass balance, theoretical analyses and numerical simulations of drying processes have been conducted to obtain a fundamental formula for the special porous medium drying process. Based on the theoretical analyses of the pulverization of agricultural waste using the classical energy assumption theory and similar design theory, the relationships among the work produced by crushing materials under external forces, energy consumption, and pulverization efficiency have been determined. From the perspective of biomass structure, physical, chemical, and mechanical properties, a mathematical model using ANSYS finite-element numerical simulation was developed, the effects of water content and material type on the compression briquetting process were reviewed, and the bonding mechanisms of compression briquetting were elucidated. Scanning electron microscopy was used to investigate the changes in microstructure before and after compression briquetting under different compression conditions to determine the trend in microstructural evolution and the optimum compression briquetting parameters. In terms of combustion applications, by mastering the combustion kinetic characteristics of biomass briquette fuels and using the high evaporation and low ignition temperature of biomass briquette fuels, a high-efficiency direct combustion technology was developed for biomass briquette fuels. With a spiral anti-slagging structure and a multistage air distribution system, a high-efficiency, anti-slagging combustion furnace equipped with a fully automatic controller was developed to solve the problem of heavy coking and slagging, a low combustion efficiency, and a short service life due to the high content of alkali metal elements in the briquette fuels. In terms of the gasification of biomass briquette fuel, a new type of mixed-flow fixed-bed gasification furnace was developed using the gasification characteristics of the biomass briquette fuel to completely utilize the advantages of downdraft and updraft gasification, featuring a low tar content, strong regulation and control of gas components, sound adaptability to the load, and stable operation.

In summary, China has carried out a significant amount of fundamental research on the raw material characteristics, briquetting mechanisms, and combustion characteristics of biomass briquette fuel, established a fundamental research system for the briquetting process consisting of collection, handling, pulverization, briquetting, and drying of raw materials, built and completed a briquette fuel basic database and technical standard system, set up a solid biomass briquette fuel industry, at least in the development mode, and created an industry chain suitable for China's present situation, reaching a true industrial scale and has taken the lead in achieving large-scale applications using various technologies for converting biomass into energy.

5.1.3 Properties of biomass briquette fuel

5.1.3.1 Relax density

The density is often considered an important parameter in the performance of biomass briquette fuels and briquetting machines. The density of a biomass briquette fuel will gradually decrease due to elastic deformation and stress relaxation after the initial discharge from the die and becomes stable over a certain period of time. The density of the briquette fuel at this point is called the "relax density," which is a key index generally used to measure the physical and combustion performances of a briquette fuel instead of the density of the biomass briquette fuel when it is initially discharged from the die. The relax density is lower than the final compression density of the fuel in the die. The relax density is closely related to the type of biomass and the process conditions of compression briquetting. There are significant differences in the relax density among different types of biomass, depending on the water content and components, even under identical compression conditions. The relaxation ratio (a dimensionless parameter: the ratio between the maximum compression density of raw materials in the die and the relax density) is used to describe the degree of relaxation of briquette fuel. Under the same conditions, the relax density of a briquette fuel is improved using two approaches: The first approach is to control the stress relaxation and elastic deformation of the briquette fuel that is being compressed in the die by using an appropriate duration of compression to prevent a reduction in the compression density of the briquette fuel after it is discharged from the mold. The second approach is to crush the biomass to obtain a minimum particle size, to appropriately improve the pressure and temperature of biomass compression briquetting, and to minimize the quantity of voids in the briquette fuel, thus increasing the bonding forces.

The method used to measure the relax density of biomass briquette fuel is specified in China's agricultural standard "Biomass Briquette Fuel Test Method – Part 7: Density" (NY/T 1881.7-2010). According to this method, a certain quantity of biomass briquette fuel sample is weighed, and its surface is coated with wax (to prevent the entry of water into the voids in the sample). By measuring the difference in the sample's weight measured in the air with that measured in liquid, the buoyancy is determined. The density of the biomass briquette fuel is calculated by deducting the wax volume from the volume of the waxed particle sample. It is possible to measure the mass and volume of a biomass briquette fuel with a regular shape; the density can then be calculated by dividing the mass by the volume.

5.1.3.2 Mechanical durability

Mechanical durability is a key characteristic of briquette fuels and is mainly reflected in the operating and storage performances of the briquette fuel, whereas the relax density alone does not completely and directly reflect the differences in briquette fuels with regard to operating requirements. The mechanic durability reflects the bonding performance of briquette fuel and is determined by the compression conditions and relax density of the briquette fuel.

China's agricultural standard "Solid Biomass Briquette Fuel Test Method – Part 8: Mechanical Durability" (NY/T 1881.8-2010) specifies the requirements and methods for measuring the mechanical durability of solid biomass briquette fuels using a standard testing apparatus: Under controlled vibration, impacts are made between the samples and between the sample and the inner wall of the tester, and the mass of the sample from which the worn and fine particles have been removed is used to calculate the mechanical durability. The durability is related to the relax density to some degree; generally, the higher the relax density, the higher the durability. Mechanical durability includes aspects of deformation resistance, shatter strength, water resistance, and anti-wettability properties.

5.1.3.3 Elemental analysis

The elemental composition of a biomass briquette fuel constitutes the material basis for its thermochemical conversion. The elemental analysis of a fuel, mostly a quantitative analysis of organic elements, shows that the combustible substances mainly include carbon, hydrogen, oxygen, nitrogen, and sulfur. The elements of solid and liquid fuels are similar, mainly carbon, hydrogen, oxygen, nitrogen, and sulfur, plus moisture and ash.

Among these components, the nitrogen and ash are inert; they do not take part in the combustion reaction. Moreover, the sulfide produced by the combustion of sulfur will pollute the environment to some certain extent. The combustion of biomass is mainly due to the presence of carbohydrates, and oxygen facilitates combustion. The existence of oxygen provides a uniformly distributed body heat source within the reactive material. Water content is a variable factor in biomass briquette fuel. Generally, the water content of such fuels is 8–25 %, and the evaporation of water will consume a large amount of heat during combustion. Thus, an appropriate water content in biomass briquette fuel is important (Tab. 5.3).

Tab. 5.3: Results of elemental analyses (dry basis) of biomass briquette fuels (%).

Raw material	A	C	H	O	N	S
Wheat straw	7.2	45.8	5.96	40	0.45	0.16
Corn stalk	5.1	46.8	5.74	41.4	0.66	0.11
Rice straw	19.1	38.9	4.74	35.3	1.37	0.11
Rice husk	15.8	38.9	5.1	37.9	2.17	0.12
Cotton stalk	17.2	39.5	5.07	38.1	1.25	0.02
Sawdust	0.9	49.2	5.7	41.3	2.5	0
Bark	4	50.3	5.83	39.6	0.11	0.07
White birch	0.4	48.7	6.4	44.5	0.08	0

5.1.3.4 Industrial analysis

An industrial analysis was performed to determine the contents of combustible and noncombustible components of biomass briquette fuel. The combustible components include solid carbon and volatile matters, and the noncombustible components include water and ash. The volatile matter comprises simple gases that do not condense at normal temperature, including carbon monoxide, hydrogen, carbon dioxide, and methane, and also those components that condense to liquid at normal temperatures, including water and various macromolecular hydrocarbons. According to the industrial analysis data of biomass briquette fuel listed in Tab. 5.4, the content of volatile matter is significantly higher than that of solid carbon, which is the opposite of the industrial analysis data on coal.

Tab. 5.4: Industrial analysis of biomass briquette fuel.

	Volatile matter	Solid carbon		Volatile matter	Solid carbon
Wheat straw	74.9	17.9	Cotton stalk	62.9	19.9
Corn stalk	80.9	14	Sawdust	77.2	21.9
Rice straw	61.1	20	Bark	80.2	15.8
Rice husk	69.3	14.9	White birch	78.7	20.9

5.1.3.5 Porosity

Porosity refers to the volume of voids in a solid fuel as the percentage of the total volume. The void characteristics refer to the distribution of voids in the fuel, the size of the voids, and whether the voids are interconnected. The porosity of a fuel directly indicates the fuel density. The porosity and void characteristics depend on the biomass briquette fuel; thus, they may have different effects on fuel combustion. The porosities of certain biomass briquette fuels are listed in Tab. 5.5, and the burning performance of wheat straw under different porosities is shown in Tab. 5.6.

Tab. 5.5: Relative porosities of biomass briquette fuels.

Fuel type	Fuel density kg/m^3	Fuel diameter (mm)	Briquetting method	Relative porosity Δ80 (%)
Corn stalks	1,048.7	103	Hot pressing	22.8
Corn stalks	1,003.8	9.1	Cold pressing	26.1
Bean stalks	1,027	103	Hot pressing	14
Bean stalks	986	9.1	Cold pressing	17.4
Sawdust	1,062	103	Hot pressing	16.5
Sawdust	1,050	9.1	Cold pressing	17.4

Tab. 5.6: Burning performance of wheat stalk briquette fuels of different porosities.

Relative porosity (%)	Ignition time (min)	Burning time (min)	Total time of burning (min)	Thermal efficiency (%)	Average smoke concentration (Rb)
11.6	5.5	10.0	59	41.6	1.10
10.8	4.0	9.0	62	40.1	1.03
5.1	6.1	11.0	86	38.6	1.15
3.8	6.6	10.0	102	37.2	1.18
3.4	5.8	10.5	73	39.7	1.10
2.5	7.2	13.0	110	36.8	1.22
2.3	7.0	12.0	106	37.0	1.20
1.4	7.9	13.5	119	35.0	1.26
0.3	8.5	15.0	130	34.0	1.35

5.1.4 Principles of biomass compression briquetting

The major issues regarding the raw materials for biomass compression briquetting include the effects of lignin bonding, particle bonding, water content, electrical potential, and “solid bridge” structures. These are discussed next.

5.1.4.1 Effect of lignin bonding

Generally, biomass compression briquetting mainly uses the softening and bonding effects of lignin, whereas water (a source of free radicals), pectin substances, and colloids composed of sugars work as the bonding agents. Vegetable-source raw materials contain not only cellulose and hemicellulose, but also lignin, resins, waxes, and other materials. Lignin is a high molecular weight compound with aromatic characteristics and a phenylpropane structure, as well as a complex three-dimensional structure. Lignins can reinforce the cell wall and bond fibers in plant tissues. Generally, the content of lignin in broadleaf wood and needlebush is 27–32 % (dry basis) and that in grasses is 14–25 %. Although various plants contain lignins, its composition and structure are variable. At normal temperatures, the major components of lignin will not dissolve in organic solvents. Because it is an amorphous material, it does not have a sharp melting point or softening point. When the temperature reaches 70–110 °C, lignin will start to soften and obtain a certain viscosity. When the temperature reaches 200–300 °C, lignin will melt with a higher viscosity. At this point, if a certain external force is applied, it will be closely bonded with cellulose, thus significantly reducing the volume of the plant material and increasing its density. After such an external force is removed, the lignin will maintain its given shape because of the mutually entangled fiber molecules, and after it is cooled, its strength will increase further to make it a briquette fuel. As different biomasses have different cellulose, hemicellulose, and lignin compositions and structures, their briquetting difficulty and effects also vary [91].

5.1.4.2 Effect of particle bonding

Biomass materials typically have a loose structure, and when piled, many voids are produced, thus reducing the density. Loose and fine biomass particles are separated by these voids, and they will only contact each other at certain points and lines or over a small area. After being subjected to a certain external pressure, biomass particles undergo the following phases: rearrangement of positional relationships, mechanical deformation of particles, plastic rheology, and a significant increase in density [92].

When subjected to a certain external pressure, loose biomass particles are displaced and rearranged to reduce the voids and change the contacts among the particles. One particle contacts many other particles, increasing the contact area, and certain particles are in linear or areal contact. After the finite space inside the die is filled, the particles are rearranged, and the density of original particle increases, thus increasing the bulk volume weight and achieving a dense filling. This process is usually accompanied by the elastic deformation of the original particles and surface damage caused by the relative displacement. When the external force is increased further, the plastic deformation arising from the stress further reduces the voids and increases the density. The mutual filling of particles and the mutual entanglement and twisting among the nonelastic or viscoelastic fiber molecules prevent the recovery of original shapes of particles upon the removal of external pressure, thus achieving compression briquetting. Larger particles are mostly bonded cross-wise; smaller particles (from several to several hundred microns) are bonded by attractive forces (Van der Waal’s forces or electrostatic forces among the molecules).

5.1.4.3 Effect of water content

As a component of biomass, water flows among the biomass granules and mixes with pectin or sugars to become a colloid, which acts as a bonding agent. The water in biomass can also be used to reduce the melting temperature of lignin, thus allowing the briquetting of biomass at a lower heating temperature.

Briquetting often fails due to a too high or too low water content. If the water content is too low, the average of the radial and axial diameters of the biomass particles are too low; the particles are not fully extended and loosely combined with the surrounding particles, thus preventing successful briquetting. If the water content is too high, the average of the radial and axial diameters of the biomass particles is too high; the particles are sufficiently extended in the direction perpendicular to the maximum main stress and engaged with each other. However, due to too much water in the raw material, the water is pushed out and evenly distributed among the particle layers, thus preventing the close combination of the layers. This causes briquetting failure.

5.1.4.4 Effect of electric potential

According to conventional electrokinetic theory, once a solid particle contacts a liquid, the electric charge is preferably absorbed by the surface of the solid particle. This facilitates the solid surface charge to build a diffusion layer of opposite charges to the liquid in contact with the solid surface, thus producing the so-called electric double layer. Such a potential difference between the solid particle surface and the liquid inside is called the “F potential,” which prevents the compression briquetting of biomass. Thus, a reduction in the absolute value of the F potential will increase the strength of the briquette fuel. The F potential varies with the type of biomass, the duration of contact with water, concentration, and temperature of biomass particles, additives, and other factors. An efficient control of these factors and conditions can significantly reduce the absolute value of the F potential.

5.1.4.5 Effect of “solid bridge” structure

Because of the long fiber structure and high content of lignin in certain raw materials, the addition of such materials during biomass briquetting plays the role of a “solid bridge”. This may change the method of combination among the particles during the briquetting, decrease the pressure and temperature necessary for briquetting, and thus reduce the production costs. Under the effects of a “solid bridge”, particles diffuse and combine cross-wise during their mutual contact, and such cross-wise combinations constitute a major contribution to the bonding of the particles. Studies have shown that particles with a “solid bridge” effectively offset the elastic recovery of molded particles and provide better mechanical durability than those particles without a “solid bridge,” thus facilitating the storage and transport of particles.

5.2 Biomass briquette fuel technology and equipment

5.2.1 Biomass briquette fuel preconditioning technology and equipment

5.2.1.1 Biomass pulverization technology and equipment

Several types of size reduction unit are in common use for the pulverization of biomass briquette fuel. Depending on the crushing principle, biomass pulverizers are classified into hammer-type, blade-type, and combined hammer and blade-type pulverizers. According to the pulverization method and approach, biomass pulverizers are also categorized into chopping-type, rolling-cutting-type, hammer-type, and combined pulverization types. Moreover, biomass pulverizers can also be classified as tangential-, axial-, and radial-feed types based on the direction of feeding. According to the purpose and particle sizes of the pulverized materials, biomass pulverizers are further classified into coarse, twist, and fine pulverization types.

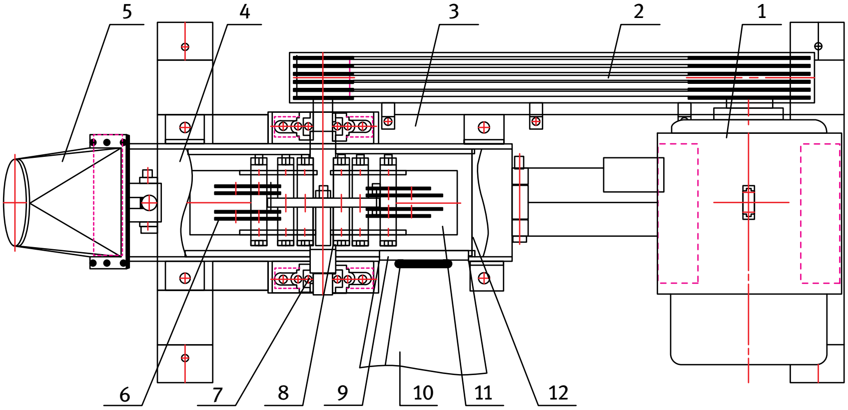
5.2.1.1.1 Chopping-type pulverizers

Chopping pulverizers are used to chop stalks or feedstock, pulverize grains, and knead the stalks and straw. In general, they are classified into straw choppers and forage cutters. The straw chopper type was approved first. This type of product is intended for cutting operations, featuring a simple structure, low power consumption, and high productivity. However, the straw chopper does not crush the stalk nodes, thus influencing the processing quality. Chopping pulverizers can be classified by size into small, medium, and large. Choppers can be classified into cylinder and disc types, according to the mode of cutting. Based on the operating method, they can also be classified into field direct harvester mobile and fixed-type cutters. Small straw choppers are used mainly to chop dry stalks and also ensilage on small-scale farms. Medium choppers are, in particular, used to chop both dry stalks and ensilage, and may also be called “ensilage cutters”. Large choppers are used to throw ensilage, and usually have disc-type cutting; however, the majority of small choppers are cylinder type.

5.2.1.1.2 Hammer-type pulverizer

During the operation of a hammer-type pulverizer, the biomass is fed manually or through a mechanical feed mechanism into the pulverizing chamber from the inlet. The material is first beaten up by the impact of a high-speed rotary hammer to be crushed to a certain extent, and then thrown at high speed onto the toothed plate and sieve fixed in the pulverizing chamber to be further crushed. Further, it is impacted by the toothed plate and kneaded by the sieve. This process is repeated in the pulverizing chamber until the pulverized material becomes small enough to pass out through the sieve mesh. The pulverization effects of a hammer pulverizer can be assessed by using three indexes: the fineness of the pulverization, the capacity within unit per time, and the unit energy consumption of the pulverization operation. Such indexes depend on the physical properties of the material being pulverized, the structure of the pulverizer, the shape of the pulverizing chamber, quantity, thickness, the linear speed of hammers, the shape and diameter of the sieve mesh, and the gap between the hammer and the sieve surface, and other factors.

The overall structure of a hammer pulverizer is shown in Fig. 5.2. Its working process is as follows: Motor power is transferred onto the main shaft after it is speeded up by the V-belt to cause the main shaft to rotate at high speed. Then, the movable blade, fan blade, and hinge fixed on the main shaft rotor rotate together with the main shaft rotating at the highest speed. Materials are fed through a feeding hopper, then cut into small segments by the movable blade, which is rotating at a high speed together with the main shaft and fixed blade. Materials are repeatedly beaten up by the fast-rotating hammer to turn them into fine particles, which are then fed into the lower pulverizing chamber after being screened by the sieve under beating by the fan blade, hammer, movable blade, and the driving airflow. Finally, fine particles are blown out of the pulverizing chamber under high-speed and high-pressure airflow caused by the fan blade, hammer, and movable blade.



1. Electric motor
2. V-belt transmission
3. Frame
4. Pulverising chamber
5. Discharge port
6. Hammer
7. Main shaft rotor
8. Movable blade
9. Fixed blade
10. Feeding chopper
11. Fan blade
12. Sieve

Fig. 5.2: Overall structure of a hammer pulverizer.

5.2.1.1.3 Kneading pulverizer

The kneading pulverizer was developed based on the design of the hammer pulverizer, and it uses a toothed plate in lieu of the sieve. It kneads raw materials into thin filaments under the action of the fast-rotating hammer and toothed plate. Kneading pulverizers mostly knead materials using the spirally arranged hammers, and throw them using the blower. However, the processed materials can get crushed or finely crushed, causing low productivity. The newer-type kneading pulverizers have a double-screw spiral threading and feeding mechanism to knead and convey materials in a forced manner, ensuring sufficient kneading and smooth discharge. Multiple movable blades and fixed blades are employed to cut materials and knead them within the gap between the movable blade and fixed blade. Further, the material is thrown onto the inner wall of the working chamber by the fast-rotating rotor, followed by further kneading, as driven by the rotor, which not only reduces energy consumption, but also ensures good processing quality.

5.2.1.1.4 Combined pulverizer

The combined pulverizer integrates the straw chopping pulverization and kneading functions. Materials are pulverized under the general effects of the movable blade, fixed blade, hammer, and toothed plate. They are discharged under centrifugal force and the action of the blower to improve the pulverization quality and efficiency. The fast-rotating hammer is mounted in the pulverizing chamber; and the fixed blade, movable blade and toothed plate are installed in the upper machine. The fed materials are rapidly pulverized into powder after they have been violently beaten up by the hammer and torn and kneaded between the hammer and toothed plate. Subsequently, the pulverized materials are delivered into the discharge port under the centrifugal force and the negative pressure of the lower chamber of the pulverizer.

5.2.1.1.5 Branch pulverizer

Most branch pulverizers used in China are provided without a traction structure; therefore, they need to be towed. Dual feed channels are provided, which are suitable for the pulverization of medium and small tree branches. During operation, a tree branch with a diameter of 20–75 mm is fed through the thick branch-feeding cylinder, chipped, and then delivered into the pulverizing chamber where braches are turned into wood flour by the fast-rotating hammer. After being sieved, such wood flour is ejected via the discharge port. Branches with a diameter of 20 mm or less are fed into the pulverizing chamber via the fine branch-feeding cylinder. Branches are cut into 50 mm segments, then crushed into wood flour in the pulverizing chamber, and finally sieved and ejected via the discharge port.

5.2.1.2 Biomass drying technology and equipment

Drying is a process intended to remove water from a material using thermal energy to obtain a dried solid product. The wet material is simply heated to evaporate a portion of water. Thermal drying of wet biomasses, such as wood, manures, and sludge is a process in the generation of briquette fuel or the disposal of waste streams. Biomass drying methods include natural and artificial drying.

Natural drying refers to the elimination of moisture by exposing the raw material to the air and solar radiation. The final water content of the raw material is directly related to the local climate, and the water loss by natural exposure of stalks to solar radiation is decided by the water content of the atmosphere, as listed in Tab. 5.7. Natural drying does not require special equipment, thus making the process cost effective. However, it may easily be restricted by natural climatic conditions, and features high labor intensity, low efficiency, and difficulty in controlling the water content of the dried biomass.

Tab. 5.7: Water loss by natural exposure of stalks to solar radiation.

Time (d)		0	10	20	30	40	50
Water content (%)	Corn stalk	67	53	40	27	17	15
	Cotton stalk	55	43	33	24	16	15
	Wheat stalk	51	40	30	21	14	13

The drying conditions are as follows: daily average temperature 15.5 °C, breeze, rainless, straws laid in a single layer on dry ground.

Artificial drying involves the use of an external forced heat source to heat the biomass using a dryer in order to reduce the residual humidity content in biomass in a relatively short time. Such methods include fluid bed, revolving drum, and silo-type drying technologies.

5.2.1.2.1 Fluid bed dryer

A fluid bed dryer is also called an “ebullated bed dryer”. The fluid is completely mixed with the solid particles to create more opportunities for surface renewal, thus significantly strengthening the heat transfer and mass transfer effects. With a higher heat capacity coefficient and a simplified structure, the manufacturing and servicing become easier, and easy scale-up is also possible. With the same equipment, uninterrupted production and intermittent operation are allowed. The particle size of the material to be dried imposes restriction; if the particle size is extremely low, particles may be carried away by the airflow; however, if the particles are significantly large, they may be difficult to fluidize. This type of equipment is not suitable for drying materials with high water content that are liable to become caked. Violent longitudinal back-mixing of materials in the bed, and that the materials are kept in the equipment for a variable period may cause the product to be discharged with uneven humidity.

5.2.1.2.2 Revolving drum dryer

The revolving drum dryer is a direct-contact dryer that works continuously. It consists of a slow revolving cylindrical housing that is tilted to produce a small angle with the horizontal surface, thus facilitating the conveying of materials. Wet materials are fed into the revolving drum through the high point, and the dried materials are discharged at the low point. In the drum, the drying medium and biomass material are in cocurrent or countercurrent flow to pass through the drum in the axial direction. When the materials to be dried are not heat sensitive or require a high dehydration rate, countercurrent flow is used. Nonetheless, cocurrent flow is, in general, suitable for the drying of materials that are heat sensitive or do not require a high dehydration rate. The flow rate of biomass material in the drum depends on the water content and particle size of the material. This type of equipment is suitable for materials with good fluidity and a particle size range of 0.05–5 mm.

5.2.1.2.3 Silo-type dryer

The silo-type dryer features a simple structure, and is suitable for drying different types of biomasses. Materials are piled in the silo, and the material's moisture is carried away by hot air from a hot-blast stove. Materials are relatively stationary in the silo. Compared to other dryers, this type of dryer has a lower efficiency and it is also difficult to control the moisture content of the material. The current common silo dryers do not permit continuous feeding and discharge of materials to influence the production efficiency, while such a device is highly adaptive to raw materials.

5.2.2 Biomass pellet fuel briquetting technology and equipment

Biomass pellet fuel is produced mostly by ring die extrusion briquetting technology, the technical principles of which are shown in Fig. 5.3. During compression briquetting, raw materials are brought into the space between the ring die and the pressure roller by the feed shoe, and the main shaft of the device drives the ring die to rotate. Under the friction force, the roller rotates together with the ring die. The materials are gradually compressed into the ring die holes to be molded while being extruded out of the holes continuously and also being cut into the molded pellet fuel of the required length by the cutter [93].

During the ring die extrusion briquetting process, materials are located at different positions in the compression zone, and are thus subjected to different compression force exerted by the roller. There are four zones, namely, the feed, extrusion, compression, and briquetting zones, as shown in Fig. 5.4.

Ring die extrusion briquetting machines are classified into single-roller, double-roller, and multi-roller types, depending on the number of rollers, as shown in Fig. 5.5. A single-roller type machine features the maximum roller diameter to generate a long-time relative movement along the roller external tangent and at the briquetting hole inlet to extend the extrusion process, thus obtaining the best extrusion effect. However, due to its large mechanical structure and poor balance, its production efficiency

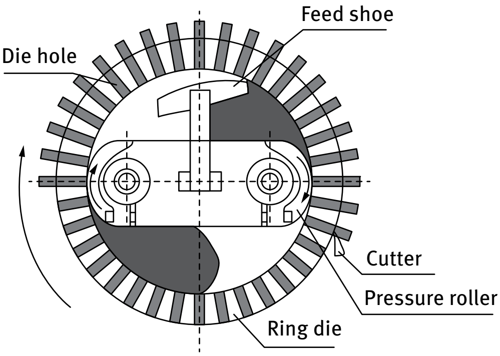
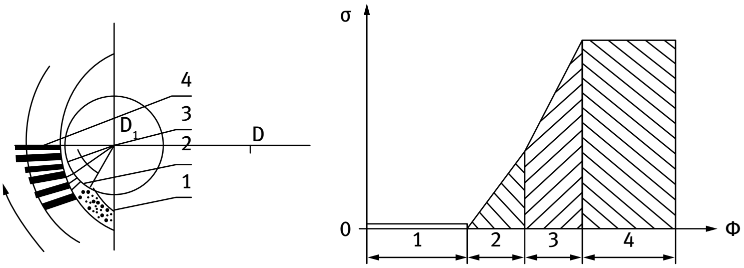
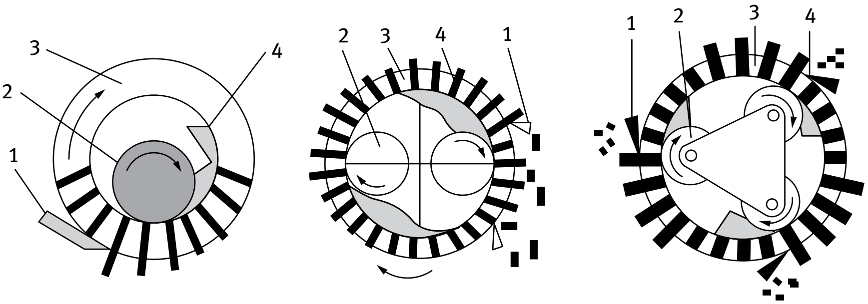


Fig. 5.3: Schematic illustration of ring die extrusion briquetting.



1. Feed zone 2. Extrusion zone 3. Compression zone 4. Briquetting zone

Fig. 5.4: Compression force on materials in different zones.



(a) Single-roller type (b) Double-roller type (c) Three-roller type

Fig. 5.5: Roller types in ring die briquetting machines.

is low. Therefore, it is, in particular, used only in small ring die briquetting machines. The double roller-type machine features a simplified structure and good smoothness and loading capacity, and is currently the most popular type. A three-roller type machine is characterized by good force balance among the three rollers; however, they occupy a large area in the material-mixing compartment to influence the feed, causing low working efficiency. Depending on the direction of the main shaft of the ring die, the ring die extrusion briquetting machines are classified into the vertical and horizontal types, as shown in Fig. 5.6. The vertical type machine has a vertically placed main shaft. Materials fall into the material precompression compartment via the upper feeding hopper by their dead load, and then are evenly delivered into various briquetting chambers by the runner. However, the horizontal type machine has a horizontally placed main shaft. Although the materials are also fed into the precompression compartment via the upper feeding hopper, they must be delivered into the precompression compartment in a slanting manner through the side face of the ring die. This is attributed to the fact that the runner revolves on the vertical plane, and materials in the precompression compartment are unevenly distributed on the inner wall of the ring die (i.e. more material below the ring die and on the side with upward rotation of ring die, and less material above the die and on the side with downward rotation of the die, resulting in uneven forces and wear of the rollers).

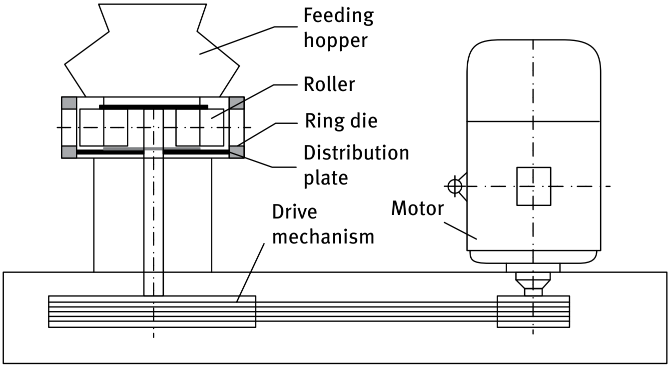


Fig. 5.6: Structural diagram of vertical ring die pellet fuel briquetting machine.

Based on the movement status of the major working parts, ring die extrusion briquetting machines are further classified into the movable roller type, movable die type, and movable roller and die type, as shown in Fig. 5.6. In the movable roller type machine the roller revolves about the fixed shaft. Vertical ring die rod-shaped and block-shaped fuel briquetting machines are generally of the movable roller type. The movable die type machine consists of the ring die fixed on the hollow shaft of the rack wheel transmission and its roller fixed on the solid shaft, which is fastened by a braking device. Horizontal ring die pellet fuel briquetting machines are mostly of the movable die type. The transmission methods of the ring die briquetting machine include a gear drive and a belt drive. The gear drive features high transmission efficiency and compact structure; however, it may produce a lot of noise during operation. A belt drive does not require additional lubrication, and produces a low noise level, and good buffering capacity; nonetheless, it has low transmission efficiency and cannot realize a low-cost two-stage speed change [94].

The ring die briquetting machine consists of the feeding mechanism, feeding hopper, roller, ring die, drive mechanism, motor, and frame. Fig. 5.7 displays the structure of the horizontal ring die briquetting machine, showing that the ring die and roller are the major working parts. During operation, biomass material is fed into the variable-frequency feeder via the feeding port. Then the variable-frequency feeder delivers the material into the forced feeder, which further delivers the biomass material into the cavity between the ring die and roller. The motor drives the ring die and roller to rotate by the shaft coupler and reducer box via the hollow shaft to compress the material in the cavity. The compression-molded biomass fuel is then discharged from the discharge port.

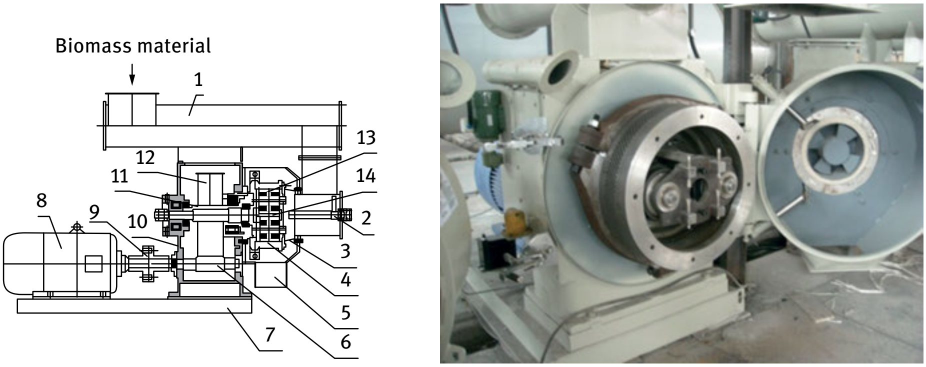
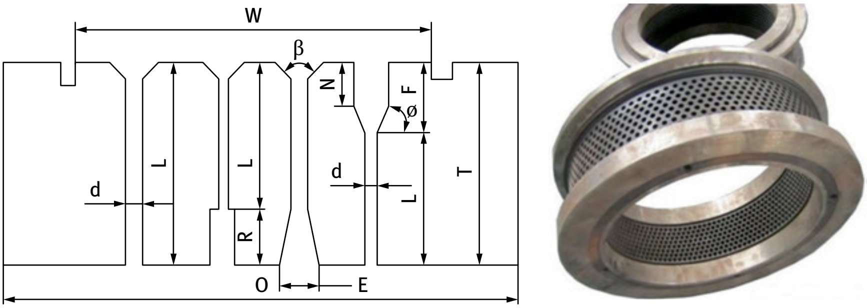


Fig. 5.7: Structural diagram of horizontal ring die pellet briquetting machine.
1. Variable-frequency feeder, 2. forced feeder, 3. feeding plate, 4. ring die, 5. discharge port, 6. drive shaft, 7. base, 8. main motor, 9. bearing coupler, 10. reducer box, 11. hollow shaft, 12. reducer gear, 13. roller body, 14.main shaft.

5.2.2.1 Structure of the ring die

The ring die is the core element of the ring die extrusion briquetting machine; its structure is shown in Fig. 5.8. Shape and thickness of the hole of the ring die are essential factors for ensuring good pellet quality and efficiency. Smaller hole diameter and higher thickness of the ring die lead to lower productivity and higher cost. This leads to loose packing of the particles in the pellet, thus affecting the pellet's quality and efficiency. Thus, the appropriate selection of the shape and thickness of the ring die hole is a precondition for high-efficiency and high-quality production.

O. Overall width of ring die, W. effective width of ring die, d. diameter of ring die hole (diameter of compressed particles), L. effective length of ring die hole, T. total thickness of the ring die, D. diameter of ring die hole tapered inlet, β. tapered inlet



O. Overall width of ring die W. Effective width of ring die
d. Diameter of ring die hole (diameter of compressed particles)
L. Effective length of ring die hole T. Total thickness of the ring die
D. Diameter of ring die hole tapered inlet β. Tapered inlet angle of ring die hole
R. Diameter of counter bore (pressure relief valve)
ø. Transition hole of the positive bore F. Diameter of positive bore
D2/d2. Compression ratio L/d. Length-diameter ratio

Fig. 5.8: Structure of the ring die.

angle of ring die hole, R. diameter of counter bore (pressure relief valve), ϕ. transition hole of the positive bore, F. diameter of positive bore, D2/d2. compression ratio, L/d. length-diameter ratio.

5.2.2.1.1 Hole shape of the ring die

There are four types of hole in the ring die: straight die holes, reverse stepped die holes, external tapered bore, and positive tapered transition stepped holes. Straight holes are easily processed and most widely used. The reverse stepped hole and external tapered bore have a reduced effective length to shorten the extrusion time of materials in the die hole, suitable for particle sizes of less than ϕ = 10 mm. Positive tapered transition stepped holes are suitable for materials with a high content of thick fiber with a diameter of greater than 10 mm and low density.

5.2.2.1.2 Thickness of the ring die

The thickness of the ring die has a direct bearing on the ring die's strength, rigidity, and pellet efficiency and quality. The common thickness range for ring dies is 32–127 mm.

5.2.2.1.3 Effective length of the ring die hole

The effective length of the die hole refers to the length of the die hole for the extrusion (briquetting) of materials. Higher effective length of die hole leads to longer material extrusion time, which results in the fabrication of harder pellets with higher strength and density. Otherwise, particles are loosely packed, with lower density and degraded quality.

5.2.2.1.4 Diameter of ring die hole tapered inlet

The diameter of the feeding hole should be greater than the die hole diameter, which aids in reducing the inlet resistance of materials to facilitate their easy movement into the die hole. There are three basic types of feeding holes: straight, tapered, and curved holes. The curved hole is the best type, followed by the tapered and straight hole types. However, a curved hole requires processing using dedicated tools, and the processing is more difficult when the hole diameter is large. Thus, the feeding hole of a small-hole ring die should be of the curved hole type, and that of a large-hole ring die should be of the tapered hole type, straight hole type, or a combination of both. When the tapered hole is used to produce small diameter particles, the inlet taper angle should be $\beta = 30\,°$. For hard to compress fiber materials with large hole diameter, usually, a positive tapered transition stepped hole is used. Precompression using a larger hole and extrusion using a smaller hole ensure good pellet quality.

5.2.2.1.5 Depth and diameter of pressure release hole

For materials with a high content of fiber and with different pellet characteristics, it is necessary to reduce the resistance encountered when passing through the die hole. Specifically, a pressure reduction is required for briquetting after the rated load is applied to reduce the resiliency rate. Thus, the die hole can be divided into two sections: the feed extrusion section and the pressure-release discharge section. The pressure-release discharge hole has three basic types: straight, tapered, and combination of straight and tapered holes. The combination of straight and tapered holes is the most common type, with a maximum hole diameter slightly greater than the die hole diameter and its depth decided by the effective working length. In certain cases, in particular when the discharge hole is liable to become clogged due to the expansion of the deep pressure-relief hole or when the strength of ring die is reduced due to the pressure-relief hole, the combination of straight and tapered hole or just tapered hole should be used.

5.2.2.1.6 Selection of porosity

The porosity of the ring die's surface has a direct bearing on the pelleting machine output and machining difficulty. Greater porosity results in higher output; however, this leads to consumption of a large quantity of man-hours. When considering the relationship between porosity and output, special attention should be paid to the sufficient supporting surface reserved on the die to ensure sufficient fracture resistance and structural strength and to prevent the surface from being broken when subjected to any load that can otherwise shorten the service life. In general, depending on the die hole diameter, the appropriate porosity range is 20–30 %.

5.2.2.1.7 Compression ratio

The compression ratio refers to the ratio between the die hole inlet area and the die hole area. In general, the higher the compression ratio, the denser the finished pellets. However, it does not mean that the higher the compression ratio, the better the pellet quality. Compression ratio should be calculated based on raw materials for making pellets.

5.2.2.1.8 Length-diameter ratio

The length-diameter ratio refers to the ratio between the length and diameter of the die hole. Compression of different materials requires the use of the best and the most appropriate length-diameter ratio to obtain dense pellet fuel. The length-diameter ratio can reflect requirements of the materials being processed on the die structure parameters. Thus, so long as a die with an appropriate length-diameter ratio is selected, products of the same quality can be produced to achieve high productivity.

5.2.2.2 Material, hole shape, and thermal treatment of the ring die

5.2.2.2.1 Material of the ring die

The material of the ring die is closely related to the service life of the die. The ring die can be made of high-quality alloy steel or stainless steel. The ring die must have good mechanical properties and long service life, and the service life of the die depends on the following factors:

(1) Wear resistance: most damage to the ring die is due to wear. Excessive operation of the ring die leads to surface wear and an expansion of the die holes. The wear resistance of the die varies with its surface hardness, microstructure, and chemical composition. To obtain the best wear resistance, appropriate materials and thermal treatment methods must be selected.

(2) Corrosion resistance: certain components of biomass may corrode the die material at high temperature and high pressure. Thus, corrosion is a key factor influencing die performance and must be controlled. High-chromium and high-carbon dies have the greatest corrosion resistance.

(3) Toughness: during pelleting operations, the die is subjected to very high pressures, which can cause instant damage, and, over time, may also cause fatigue damage to the die. Thus, the selection of die materials, thermal treatment, and number of die holes are important factors in determining die toughness.

5.2.2.2.2 Characteristics of ring die materials

(1) Wear resistance versus toughness: increased die hardness can improve the wear resistance; however, this also reduces the die toughness. That is, improving the wear resistance by increasing the die hardness increases the fragility and reduces

the toughness. Thus, the hardness of the die must be maintained at a desirable minimum structural level.

(2) Corrosion resistance versus wear resistance and toughness: poor metal structural differences and poor components in the corrosion-resistant material of the die impair wear resistance and impact toughness, possibly causing breakage.

(3) Toughness versus number of holes: it is difficult to improve the pellet output by increasing the number of holes if a poor-quality die material is used. Increasing the number of holes leads to cracking of the die. The die materials (with thermal treatment) have different strengths and toughness characteristics. Certain materials require fewer holes to ensure the minimum toughness and structural strength.

Selection of die material: currently, common die materials include alloys, chromium, and carburized stainless steel. The performances of these dies are listed in Tab. 5.8.

Tab. 5.8: Performance of die materials.

Kind of die	Wear resistance	Corrosion resistance	Toughness
Alloy die	70	30	90
Chromium die	60	90	50
Carburized stainless steel	90	75	80

Note: 0 = minimum, 100 = maximum

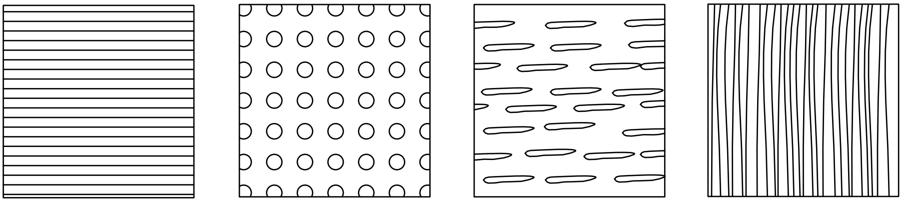
5.2.2.2.3 Rotating speed of ring die

Rotating speed of the ring die is selected depending on the characteristics of the raw material and the particle diameter. A ring die with a small hole diameter should operate at a high linear speed; however, a ring die with a high hole diameter should operate at a lower linear speed. The linear speed of the ring die influences the pellet's efficiency, energy consumption, and particle hardness. Within a certain range, the linear speed of the ring die can be increased to increase the output, energy consumption, and particle hardness; however, it leads to a reduction in the briquetting rate. In general, the selected linear speed is 3.5–8.5 m s^{-1}.

5.2.2.3 Pressure roller

5.2.2.3.1 Function of the pressure roller

The pressure roller is used to press the material into the die hole for briquetting. In order to press the material into the die hole, there must be a certain friction force between the roller and the material. Fig. 5.9 shows that the rollers are provided with various types of rough surfaces to prevent them from slipping.



Wire-drawn roller surface

Recessed roller surface

Grooved roller surface

Tungsten carbide roller surface

Fig. 5.9: Basic types of roller surface.

(1) Wire-drawn roller surface: currently, this is the most common type, and provides high slip resistance. However, the material may also slide sideways. If the wire-drawn channels are closed at both ends, such slip can be reduced.
(2) Recessed roller surface: the recess contains materials to produce a friction surface. The friction coefficient is high, and materials do not slide sideways.
(3) Grooved roller surface: there is a narrow groove on the roller surface to increase the friction force. Similar to the recessed roller surface, materials are not liable to slide sideways.
(4) Tungsten carbide roller surface: tungsten carbide particles are embedded on the roller surface to give a rough surface that is hard and corrosion resistant. This type of roller surface is, in particular, suitable for materials that are highly adhesive and may cause serious wear to the roller surface. A roller with a tungsten carbide coating has a ca. threefold longer service life than that of the wire-drawn roller surface. However, during operation, the roller must be positioned accurately to avoid wear of the die.

5.2.2.3.2 Technical parameters of the pressure roller

The ring die pelleting machine has two or three pressure rollers. The surface hardness of the roller is theoretically lower than the die surface hardness, by HRC2-3, thus ensuring the low wear and long service life of the ring die.

5.2.3 Biomass block-shaped fuel briquetting technology and equipment

The biomass block-shaped fuel briquetting technologies in China primarily include ring die extrusion and flat die extrusion briquetting technologies. The principle of ring die extrusion briquetting technology is identical to that for pellet fuel. The principle of flatdie extrusion briquetting technology is shown in Fig. 5.10. During compression briquetting, with relative movement between the roller and the flat die plate, the biomass materials in the gap are compacted by the roller, and softened under friction heat, and

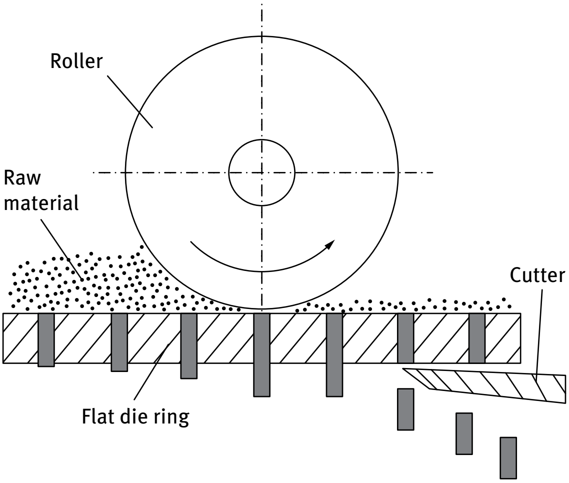


Fig. 5.10: Schematic representation of flat die extrusion briquetting.

thus forcibly pressed into the flat die holes. After the relax density is achieved through briquetting, biomass block-shaped fuel can be obtained.

5.2.3.1 Ring die briquetting equipment

The major difference between the ring die block-shaped fuel briquetting machine and the ring die pellet machine lies in the type of ring die and roller. Common structural types of the ring die block-shaped fuel machine include the integral, sleeve, and split die types.

The integral ring die has a structure similar to the ring die of the ring die pellet fuel briquetting machine, as shown in Fig. 5.11, the difference being the structure of the ring die hole. When the hole diameter is more than 25 mm, the ring die can be used to process the molded block-shaped fuel.

Major structural parameters of the integral ring die include the ring die diameter, ring die thickness, ring die effective width, die hole shape, die hole diameter, die hole effective depth, thickness of wall between holes, compression ratio, and roughness of the ring die. The ratio between the ring die hole length and diameter is customarily termed the compression ratio of the ring die, and is a key index reflecting the extrusion strength of the pellet fuel. The higher the compression ratio, the higher the density of extruded fuel. For stalk-type biomass, the compression ratio is generally 10. The roughness of the die hole not only affects energy consumption, but also directly influences the briquetting effect. Higher ring die porosity leads to higher output. This can improve productivity; however, decreasing the thickness of the wall between the die holes reduces ring die strength, which may cause cracking. Thus, an appropriate wall thickness must be selected to ensure required ring die strength and porosity. In

Fig. 5.11: Structure of the integral ring die.

general, the higher the die hole diameter, the higher the ring die porosity; and the higher the porosity, the lower the ring die strength. For materials with high extruding forces, the ring die porosity should be appropriately lower to ensure required ring die strength in order to prevent the die from cracking. The thickness of the ring die has a direct bearing on the product quality, and the working area of the die is directly proportional to the design power. When the power is provided, the ring die should be of the corresponding effective width, which is generally 10–14 cm. A worn integral ring die must be replaced as a whole, which not only adds to the service cost, but also seriously influences normal production. Thus, the selection of ring die material is crucial. Presently, integral ring dies are typically composed of 42CrMo4 alloy steel.

The sleeve-type ring die was developed based on the design of the integral ring die; specifically, a sleeve is installed in the die hole to reduce ring die wear and improve the die's service life. A ring die with the sleeve type die hole is, in particular, used to process block-shaped fuel with a diameter of more than 25 mm. The sleeve-type ring die consists of a mother ring and a sleeve. The sleeve is fitted on the mother ring. The die hole in the sleeve can be designed separately according to briquetting theory. The structure of the die hole consists of the pre-pressure briquetting section, briquetting section, and shape-maintaining section. The sleeve can be fitted into the ring die by threading or embedding. With the use of a sleeve-type die hole, the sleeve die hole can be rapidly replaced after it is worn out, reducing equipment processing and service costs, thus from this perspective the sleeve-type ring die is superior to the split die ring die.

The split die-type ring die is provided with a die assembly structure. Each split die can be designed and processed separately, and two semi-molded chambers are provided on both sides of the single die. By placing several single dies into the assembly fixture, an integral ring die can be assembled, as shown in Fig. 5.12 (a) and (b). As each split die is individually processed, worn parts can be handled or repaired separately to extend the service term. The shape of the die hole of the assembled split die can be square or round, to process block-shaped fuel, as shown in Fig. 5.12 (c) and (d). The production procedure of the split die is complex, leading to high production cost; however, facilitating batch production and an easy standardized design of the briquetting chamber to ensure high quality briquette fuel.

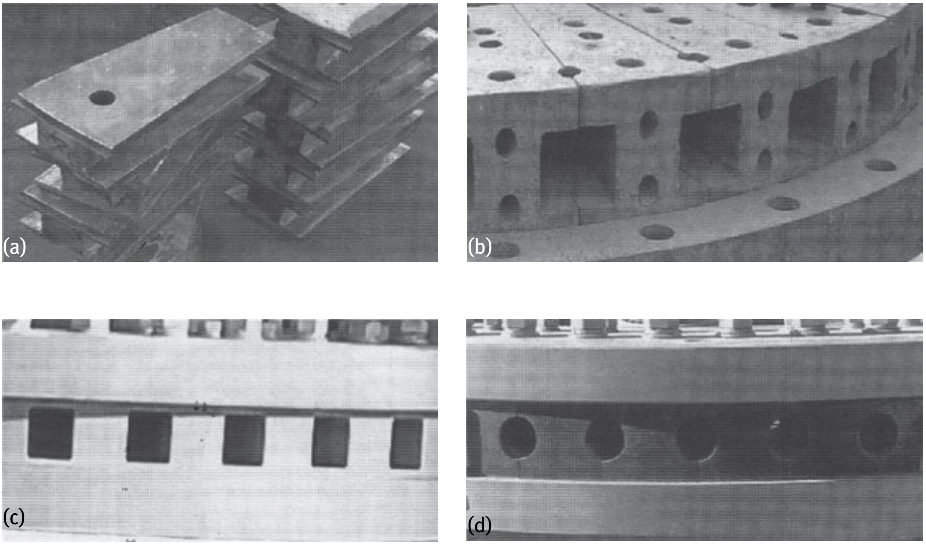


Fig. 5.12: Structure of the various ring dies.
(a) splited ring die; (b) assembled ring die; (c) square-hole ring die; (d) round-hole ring die.

The split die is the core part of the ring die. The structure at the die inlet is one of the key technologies in biomass compression briquetting; and the structural sizes, processing quality, and accuracy have a direct bearing on the service life of the ring die, on the production capacity and product quality of the briquetting machine, and on the operating cost. Based on biomass briquetting theory, the briquetting chamber of the assembled die can be divided into three phases: the precompression phase, briquetting phase, and shape-maintaining phase. The time elapsed from the entry of biomass material into the briquetting chamber and into the gap between the die rollers, and to the termination of compression is called “precompression phase”. The manhole groove of the split die hole, clearance between the die and roller, material layer thickness, roller speed, and other parameters influence the precompression effects. If the clearance between the die and roller is large, the material thickness is high and the roller speed is also high, which results in poor precompression effects, with accelerated wear and increased energy consumption. The time elapsed from the delivery of materials at the die hole groove to the start of the shape-maintaining phase is called the “briquetting phase”. This part of die hole structure is designed to be of an internal conical type, with a briquetting angle of 1–3. This phase is essential for attaining the extruding force necessary for the plastic deformation of the raw materials and briquetting density, during which the raw materials cause the most serious wear to the die hole materials. It requires high thermal treatment, especially to enhance wear resistance. After briquetting components are changed due to wear, the briquetting rate reduces, and ultimately, replacement of the split die is urgently required. It has been found that dies are best replaced in batches; individual replacement is not advisable. After the briquetting phase, the dense raw materials enter the shape-maintaining section. The diameter of this section is slightly greater than the size of the outlet of the briquetting section, which is used to eliminate the internal stress of the briquetting phase to meet the relax density requirements and obtain the final product. Currently, the split die-type briquetting machines available in the market have a low die thickness and a short shape-maintaining section, which cause poor briquetting effects and quality. To process 30–50 mm block-shaped fuel, the length of the split die die hole should not be less than 10 cm, and the ratio between this length and the fuel cross section size is generally 1:6–8. In general, machines used to process block-shaped fuel use components composed of No. 35 or No. 45 high-quality carbon steel, and other steel alloys. Significant importance has been given to the thermal treatment and the worn part recovery methods for these machines and materials. Group replacement and repairs are required after the split die-type ring die becomes worn; therefore, the labor required and the cost can be very high, and the work is difficult. For the fuel producer, operating difficulty is high; therefore, this issue must be addressed in terms of improved engineering.

The influences of the ring die’s structural parameters on the quality of the briquette fuel vary according to ring die structure type. Thus, for different biomass materials, ring dies of different structures are used.

A direct roller is used in a ring die block-shaped fuel-briquetting machine, with a small roller width, as shown in Fig. 5.13. The width of the roller used in the integral ring die die briquetting machine is higher, and the outer edge structure of the roller is similar to that of pellet ring die and pellet flat die briquetting machines, including close-groove, open-groove, concave hole, and herringbone chute types, as shown in Fig. 5.14. A wider roller is more wear resistant than a narrow one, and a closed groove-type is more wear resistant than an open groove-type roller. According to ring die briquetting technology research, it is common to use sleeve-type and split die-type ring dies and the corresponding rollers in the ring die-type block-shaped fuel briquetting machines.

Fig. 5.13: Direct roller.

Fig. 5.14: Examples of common roller types.

The roller is a major wearing part of the ring die briquetting machine. Rollers function under unfavorable conditions, and are easily subjected to high friction forces and vibrations during operation, resulting in rapid wear under high-temperature conditions. If the roller loading bearing is not strictly sealed and lubricated, it rapidly gets heated up and the biomass powder and mud adhere to it, leading to serious wear until the machine ceases functioning. Thus, it is more important to solve the sealing problem of the loading bearing than to solve the wear problem of the roller. Anti-wear and dust-proof sealing rings with good sealing performance must be selected to address this problem.

The roller speed is a key factor influencing roller wear. In pursuit of productivity, the initial roller design speeds are mostly high, 200–300 rpm. The sleeve-type and split die-type ring dies use narrow rollers, which further accelerate roller wear. Even if many wear-preventing measures are used for the roller outer edge structure and materials, the roller service life may remain less than 100 h. The higher the roller speed, the higher the tangential force and the lower the positive pressure. More resulting force in the tangential force direction results in more serious wear.

With overall productivity unchanged, when the roller speed is reduced to 50–100 rpm, the energy consumption of the briquetting machine may be reduced by 30–50 %, and the wear in the briquetting chamber and roller wear get reduced significantly. The clearance between the roller and the ring die not only influence the wear resistance of the roller and the die hole inlet, but also affect the productivity and energy consumption. When the clearance between the die and the roller is too large, the material at the die hole inlet is liable to come loose from the extrusion zone, thus reducing the briquetting efficiency. Noteworthy, the above mentioned effects become more noticeable with larger clearance between the rollers. If the clearance between the die and roller is too small, the friction force increases, thus worsening the wear of the roller and ring die end and increasing the temperature and energy consumption. Moreover, as less material is fed in per unit time, the productivity is reduced. During the design, the clearance between the die and roller is determined by the roller speed. If the speed is high, the clearance can be smaller. It is generally 0.8–1.5 mm for pellet fuel briquetting; however, higher for blocked-shaped fuel briquetting. If the roller speed is 50–100 rpm, the clearance may be 3–5 mm. If the clearance is small, the produced rotating torque is also low in order to reduce the motor load and improve the production efficiency. After a period of use, as the clearance increases due to wear, a clearance regulator should be provided to regulate the clearance between die and roller. To improve the service life of the roller, the selection of roller material is important. Worn narrow-type rollers can be re-used in combined roller structures through processing, with added roller gear rings, which are made separately. The gear rings can be repaired using bearing steel, molded steel, or tempered and quenched steel and build-up welding [95].

5.2.3.2 Flat die briquetting equipment

Flat die roller-type briquetting machines are classified into movable roller, movable die, and movable die and roller types, depending on the moving conditions of the actuators. The movable die-type and movable die and roller-type are typically used in small briquetting machines; however, the movable roller type is, in general, used in larger flat die briquetting machines. Depending on the roller shape, flat die roller-type briquetting machines are classified into direct roller and tapered roller types, as shown in Figs. 5.15 and 5.16, respectively. Both ends of the tapered roller have a linear speed consistent with the inner and outer rings of the flat die plate, and dislocation

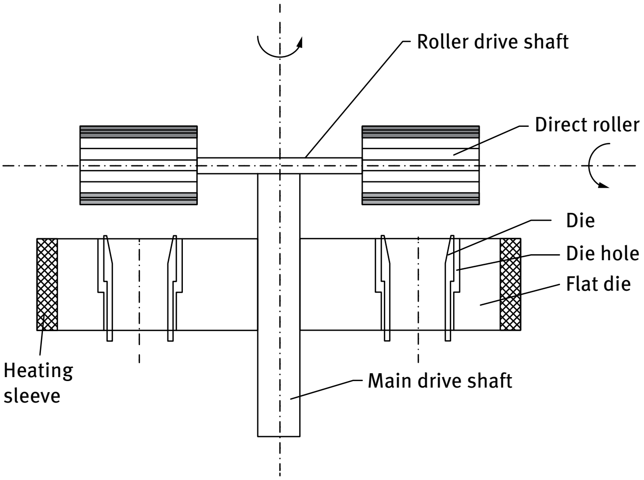


Fig. 5.15: Schematic representation of direct roller type briquetting machine.

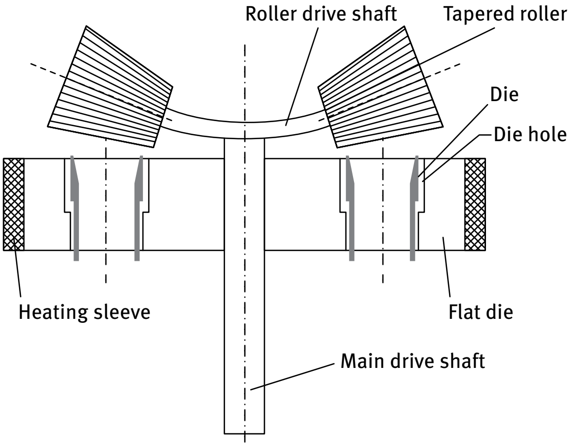


Fig. 5.16: Schematic representation of tapered roller type briquetting machine.

friction is not generated between the roller and flat die plate. Both the resistance and energy consumption are low, resulting in long service life of the roller and the flat die plate. Flat die block-shaped briquetting machines are mostly of the movable direct roller type.

A flat die block-shaped fuel briquetting machine consists of a feeding hopper, roller, flat die plate, reducer and drive mechanism, and electric motor and frame, as shown in Fig. 5.17. During operation, the cut or crushed biomass material is delivered into the feeding chamber of the briquetting machine through the feeding mechanism. An electric motor drives the main shaft of the briquetting machine to rotate through

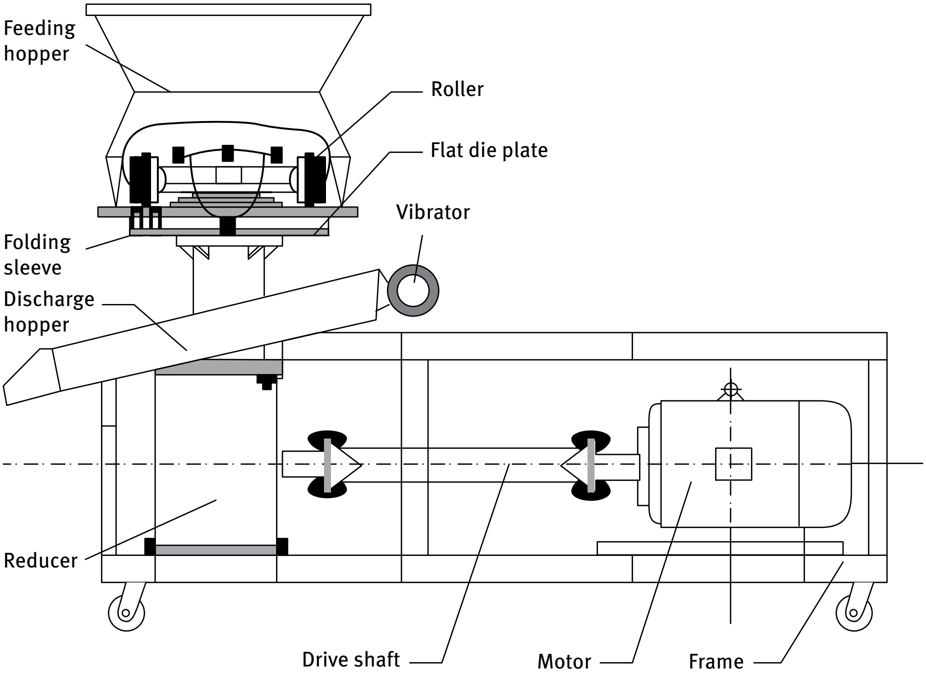


Fig. 5.17: Schematic representation of flat die-type block-shaped fuel briquetting machine.

the reducer mechanism, and the roller shaft above the main shaft follows at a lower speed. As there is a clearance of 0.8–1.5 mm between the roller and the flat die plate (the clearance between die and roller); the roller, which is fixed on the roller shaft via the bearing, first revolves about the main shaft. The biomass material that is fed into the feeding chamber is evenly distributed on the flat die under the common action of the distributor and scraper blade, to enter into the gap between the roller and flat die plate. When the roller is revolving about the main shaft, the biomass material exerts a counterforce on the roller, and the horizontal component of this counterforce forces the roller wheel to rotate about the roller shaft, and the vertical component of this counterforce forces the roller to press the biomass material into the flat die hole. Under the continuous circulated extrusion by the roller, the materials in the flat die hole are subjected to continuous push and pressure from the top new material entering into the briquetting segment. With the increase in the temperature and density under these multiple actions, the materials get adhered together on entering into the shape-briquetting segment. As this segment has a larger section than the briquetting segment, the internal stress arising out of the forced compression is relaxed in order to gradually reduce the temperature, and the block-shaped fuel is discharged from the die hole. When the required length and weight are attained, the fuel is released from the die hole or is cut off by the cutter.

The flat die plate is the core technical part of the briquetting machine, being the carrier of the briquetting hole. It has two major structural types, namely, integral flat die plate and sleeve-type flat die plate. The integral block-shaped fuel flat die plate is shown in Fig. 5.18, with the die hole cross section size of more than 25 mm and the die plate thickness being 5–6 times that of the plate diameter. The sleeve-type flat die plate has been developed for flat die-type block-shaped biomass briquetting machines. The sleeve hole can be round- or square-shaped, with the internal shape designed according to the briquetting principle. The outer edge of the sleeve and flat die plate can be assembled by threading a tapered pedestal, or by embedding. The parent material of the flat die plate can be cast steel or cast iron, which can provide the required high strength. The sleeve seat hole should be made with high precision, and the spacing between holes should be sufficient to avoid cracking under impact. The flat die plate has a permanent life. The most important advantage of the sleeve-type flat die briquetting machine lies in its permanent parts, and the briquetting chambers can be designed to have different shapes to produce briquette fuels of different materials. The sleeve can be made of relatively inexpensive cast iron or even ceramic nonmetallic materials, and is suitable for mass production. However, there are several outstanding problems associated with the sleeve: the first is the ideal fit between the sleeve and the new plate, the second is the ease of changing the sleeve by the user, and the third is the positive correlation between output and quality [96].

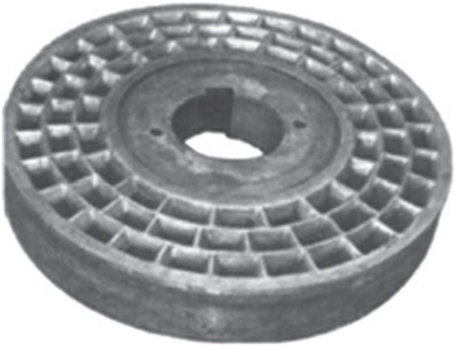


Fig. 5.18: Integral block-shaped flat die plate.

The flat die plate, intended to mold the extruded biomass material in its die holes, is the key part of the flat die biomass briquetting equipment, and also the part most subjected to wear. Presence of numerous holes in the plate, leads to significant reduction in the resistance to deformation. Whether the structural parameters of the flat die plate are reasonable, directly determines the quality of the molded products. Different materials require the machine to be equipped with different flat die plates. The hole area, porosity, die hole size, die hole shape, and die hole arrangement are essential for the briquetting effects. If the plate die has a large hole area, high porosity, large die hole sizes, and compact hole arrangement, productivity increases. The lower the ratio between the die hole length and diameter, the higher the productivity; however, the shape-maintaining time is shortened and the product density and briquetting rate are reduced. If this ratio is too high, the material moves over a long route after being extruded out of the die hole, causing high resistance and frequent clogging. The integral flat die plate is a wearing part; indeed, it is subjected to rapid wear. Therefore, to extend the service life of the flat die plate and reduce production costs, the following measures can be taken during the design and manufacturing of the flat die plate: (1) A symmetrical flat die plate structure should be designed, allowing the use of both sides of the plate. Once the first side is worn, the plate can be reversed for further use to double the service life of the flat die plate and reduce the service cost. (2) Depending on the die hole sizes, the flat die plate should be provided with double-row or multi-row die holes in lieu of the single-row holes to increase the briquetting speed and efficiency, as shown in Fig. 5.19. (3) The die holes of the flat die plate should be provided with linings or sleeves. The die orifice and die hole of the plate are also major wearing parts of the flat die plate. The integral flat die plate uses a fixed die orifice; therefore, after the die orifice and die hole become worn, the briquetting efficiency rapidly deteriorates. The only solution is to replace the entire flat die plate, which eventually results in a high service cost. By placing a fixed die hole into a lined and sleeved structure, it is necessary only to change the lining or sleeve in the hole, which not only eases the servicing, but also reduces the service cost. The die hole sizes are optimized. The integral flat die plates can be designed into series of plates with different die holes. The sleeve of the sleeve-type flat die plate can be designed as series sleeves, having the same outer edge structural sizes and different die hole shapes and lengths to adapt to the briquetting of materials of different physical characteristics, which ensures the briquetting effects and reduces the wear of die holes. (5) Appropriate flat die plate, lining, and sleeve materials should be selected. The lining and sleeve can be made of 40Cr materials, which maintain hardness and wear resistance after they are quenched, or can also be made of nonmetallic materials.

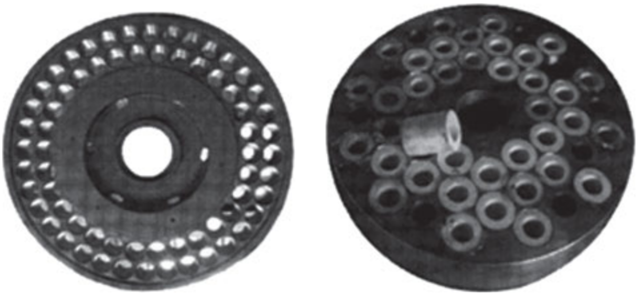


Fig. 5.19: Flat die plate with double-row die holes. Nonmetallic sleeve flat die plate.

Flat die block-shaped briquetting machines are usually provided with direct rollers, as shown in Fig. 5.20. The width of the roller used in the integral flat die plate is high. The diameter of the roller of the sleeve type flat die plate is as large as possible to reduce the speed. The rotating speed of the roller is, in general, 50–100 rpm, and the roller outer edge structure is similar to the roller of the integral ring die, including closed-groove and open-groove types. Presently, from the perspective of briquetting technology development, there is a tendency to equip flat die block-shaped fuel briquetting machines with sleeve flat die plates and corresponding rollers.

Fig. 5.20: Roller of a flat die block-shaped fuel briquetting machine.

The roller is used to extrude the biomass material entering the briquetting chamber into the flat die briquetting hole, which requires a certain clearance between the roller outer edge and the flat die plate. The size of this clearance affects the productivity of the briquetting machine. With a view to energy efficiency, the material layer on the flat die plate should not be too thick, which restricts the fuel productivity. However, in order to improve productivity, the roller radius can be increased. During extrusion of the material, the direct roller rotates, accompanied with relative sliding. The relative linear speeds between the roller inner and outer ends and the flat die are different. The higher the flat die diameter, the higher the speed difference between inner and outer ends. The presence of this speed difference accelerates roller wear to some extent. Higher roller speed leads to rapid wear and higher energy consumption, causing uneven wear and higher noise. Thus, an appropriate roller rotation speed must be considered during the design.

The roller is a key part of a flat die briquetting machine. The structure, diameter, number, arrangement pattern, rotating speed, and material of the roller are all related to the briquetting effects and service period. During design, in addition to determining the basic parameters of the roller according to the design requirements, consideration of its coordinated use with the flat die plate is also required. During actual operation, attention should be paid to the following issues: (1) The roller speed should be as low as possible. If the roller speed is low, slippage is weakened, thus reducing roller wear, increasing the service life of the roller, and saving on repair costs. (2) The roller diameter should be increased as much as possible to add to the contact time between the roller tangent line and the briquetting hole and increase the material input. For flat dies with a diameter of greater than 80 cm, the number of rollers can be increased; however, this leads to off-contact of fed materials, which reduces the feeding speed. (3) The structural shape of the roller outer edge can be changed. Changing the toothed outer edge of the roller into trapezoidal toothed or trapezoidal helical toothed edges not only increases the friction force between the roller surface and biomass, to increase the compaction efficiency of the raw materials, but also enhances the raw material feed input. (4) The most rapidly wearing part of the roller outer edge, the gear ring, should be designed separately and be fitted on the roller shaft of the bearing. The roller gear ring can be made of high-quality alloy steel, such as 27Mn or thermally treated 12MoV, which significantly improves wear resistance. After the gear ring is worn out, it can be replaced separately, facilitating removal. (5) An appropriate roller material must be selected. The integral roller can be made of 20 Cr with good wear resistance, and its tooth face obtains a higher hardness after carburizing and quenching treatment to extend its service life.

5.2.4 Briquetting technologies and equipment for biomass rodlike fuel

5.2.4.1 Briquetting technologies for biomass rod-like fuel

The process flow for a biomass rod-like fuel briquetting system involves smashing the biomass raw materials with a pulverizer, followed by drying or adding water to the smashed materials (different briquetting units require different water contents. The raw materials with a higher water content should be dried using drying equipment, whereas water is added to the raw materials with a lower water content to increase the water content.), and finally transporting the acceptable raw materials to a briquetting unit to produce biomass rod-like fuels. The common rod briquetting machines include a piston press and a screw extrusion press.

5.2.4.2 Piston press

A biomass rod-like fuel piston press mainly consists of a piston, heating ring, and briquetting venture as shown in Fig. 5.21. Piston presses can be divided into two types according to the drive source: mechanical-drive and hydraulic-drive piston presses. Under hydraulic or mechanical drive, the piston moves back and forth. Under the force of the piston and the action of the heating ring, the lignin present in the pulverized biomass raw materials is softened, becomes adhesive, and is extruded and molded at the venture. When a piston press is operating, the allowable water content of the materials is up to 20 %, the unit energy consumption is 80–140 kW · h/t, [97] and the density of solid rod-like or briquette fuel is between 0.8 g/cm^3 and 1.1 g/cm^3. The advantages of a piston press are as follows: The abrasion of the briquetting components is improved, the briquetting density is higher, the raw materials do not need

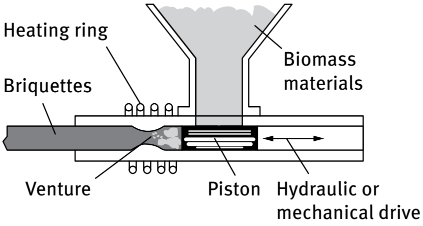


Fig. 5.21: Structural diagram of piston press components.

heating and drying, and the product cost is lower. The disadvantages of the piston press are as follows: The product quality is unstable, the operating stability of the equipment is poor, the machines are noisy, lubricating oil pollution is a serious issue, and the briquetting chamber wears easily and has to be repaired every 100 operating hours. Although for the biomass materials with less SiO_2, this can be extended to 300 h, the productivity ratio is 300 kg/h, higher than a screw extrusion press, but still low, and the cost of each unit is up to 100,000 yuan.

5.2.4.3 Screw extrusion press

The screw extrusion press was the first type developed and is now the most popular type of equipment. It uses external heating to maintain the briquetting temperature at 150–300 °C to soften the lignin and cellulose and transform them into adhesives, then uses a screw to continuously extrude the biomass, and finally produces a biomass rod-like fuel using a briquetting die. A screw extrusion press mainly consists of an extrusion screw, a sleeve, and a heating ring as shown in Fig. 5.22. Under the action of an extrusion screw, the pulverized biomass raw materials are pushed into the sleeve. Then, under the action of a heating ring surrounding the sleeve, the biomass raw materials are heated in the sleeve until the lignin is softened. Along with the continuous feeding of biomass raw materials into the sleeve, the biomass is molded under extrusion and adhesion, and the molded rod-like fuel is produced continuously. The length of the rod-like fuel can be cut as required. When a screw extrusion press is operating, the temperature should be maintained at 150–300 °C, the water content of raw materials is 8–12 %, and the granularity of raw materials is less than 40 mm. The products of screw extrusion presses are mostly 50–70 mm rod-like fuels with a briquette density of 1,100–1,400 kg/m^3 at a unit energy consumption of 70–120 kW · h/t and a production capacity of 100–200 kg/h. The advantages of screw extrusion presses include stable operation, continuous briquetting, good briquette quality, and the briquetting pressure can be adjusted using the dimension of the screw entering the sleeve. The disadvantages of screw extrusion presses are high unit energy consumption and high product cost when including the cost of the equipment. The fixed costs are typically above 280 yuan. During the operation of a screw extrusion press, the briquetting components rapidly become worn, particularly the screw. The service life of heat-resisting materials may not be more than 80 h; the cost of a new unit

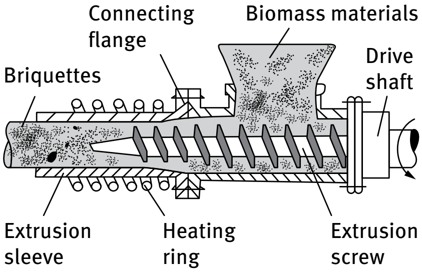


Fig. 5.22: Structural diagram of screw extrusion press.

is up to 1,000 yuan/unit, thus severely hindering the large-scale development of screw extrusion presses. Using new technologies, a screw can be divided into two parts: the screw head and body. Costs can be reduced by replacing the screw head only, which can be easily replaced [98].

5.2.5 Industrial production system for biomass briquette fuel

5.2.5.1 Processes

An industrial production system for biomass fuel mainly consists of subsystems for each step: primary pulverization, secondary pulverization, drying, dedusting, material conveying, briquetting, cooling, screening, and packaging as shown in Fig. 5.23. Moreover, each subsystem has a quality monitoring system to ensure product quality [80].

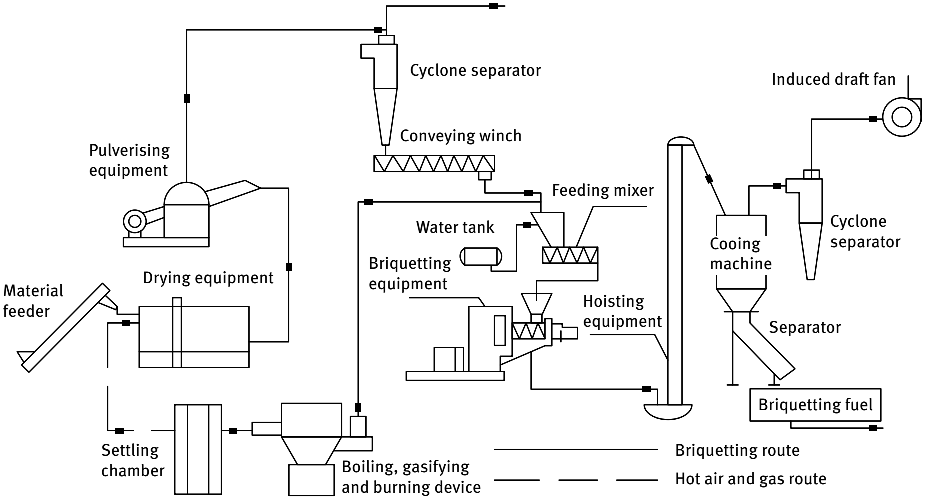


Fig. 5.23: Process flow chart of the integral production of biomass briquette fuel.

5.2.5.1.1 Primary pulverization

According to the pulverization principles, the pulverizing equipment is divided into a hammer, blade, and combined hammer plus blade pulverization technologies. According to the pulverization mode and method, pulverizers can be divided into cutting, chopping, rubbing, hammering, and combined pulverizers. According to the material feeding direction, pulverizers can be divided into tangential, axial, and radial types. According to the purpose and granularity of pulverized materials, pulverization can be divided into coarse and fine pulverization. According to the raw materials, two pulverizing methods are applicable to primary pulverization: A cutter pulverizer is used for wood materials, whereas chopping and rubbing pulverizers are used for crop stalks.

5.2.5.1.2 Drying

Biomass molded materials have a strict requirement for water content; the required water content varies with the raw materials. Because the initial water content of materials is typically 25–50 % and the water content required during briquetting is 12–15 %, normally the materials are dried. The drying equipment can be equipped with belt drying, roller drying, or horizontal circular drying systems.

5.2.5.1.3 Secondary pulverization

After primary pulverization, the granularity and water content of raw materials may not satisfy the pellet requirements; therefore, secondary pulverization is used to further reduce the granularity of raw materials to satisfy the briquetting requirements.

5.2.5.1.4 Dedusting

Much dust can be produced during the pulverization and briquetting of raw materials. To maintain the air environment and the safety and health of the operators, an effective dedusting system should be provided. Both cyclone and bag dust collectors are acceptable.

5.2.5.1.5 Material transportation

The pulverized biomass raw materials need to be transported to the briquetting equipment for pressing and briquetting. Conveying systems, spiral conveyors, hoists, and scrapers can be used to convey materials to briquetting equipment.

5.2.5.1.6 Briquetting

As the key equipment in an industrial production system, briquetting equipment for biomass briquette fuel presses and molds the pulverized and dried raw materials into the desired form. The briquetting equipment can adopt different briquetting modes for different target products.

5.2.5.1.7 Cooling

Following the briquetting of biomass raw materials, the products are discharged at a high temperature and can be easily damaged; therefore, a cooling system is required. A reverse-flow cooling system is often used. After cooling to ambient temperature, the products are packaged and then warehoused or conveyed to a silo using belt conveyors and hoists. A reverse-flow cooling system is equipped with a cooling fan and cyclone separator to return the separated powder to the previous process for re-briquetting.

5.2.5.1.8 Screening

The cooled briquette fuel is screened using a vibrating screen to separate the crushed materials and ensure the delivery quality of biomass briquette fuel. The separated crushed materials are returned to the previous process for re-briquetting.

5.2.5.1.9 Packaging

A packaging conveyor can be used to measure and package the products and then send the packages to the finished product warehouse.

5.2.5.2 Industrial production system for biomass briquette fuel

5.2.5.2.1 Pulverizing section

The conveyor belt is typically fitted with an IR water content meter to test the water content of the raw materials on-line. Under the conveyor belt, a belt balance is installed to measure the weight of the conveyed materials. An adjustable feeding baffle is used, and its position can be adjusted according to the water content of materials, thus controlling the pulverizing fineness of the biomass material. An atomizing watering system is used to add water to the materials when the water content is lower than the required setting. The granularity and water content of materials should satisfy the production requirements.

The system consists of three main parts: the main pulverizer, a discharge belt, and a control system as shown in Fig. 5.24. The pulverizer is the main component of this system and involves material feeding, material pulverization, and material discharge. The discharge system is composed of a discharge belt and watering device; the discharge belt is fitted with a pressure sensor, material flow switch, on-line water test, and other devices. The pressure switch detects the weight change of materials on the belt and thus measures the weight of materials. The IR on-line water tester determines the water content of materials in real time. The material flow switch detects the presence of materials on the belt. Controlled by the control system, the watering device uniformly distributes water as needed. The rotary feeding barrel feeds the materials under the drive of the feeding motor, and the rotation speed of the feeding barrel determines the material feeding rate.

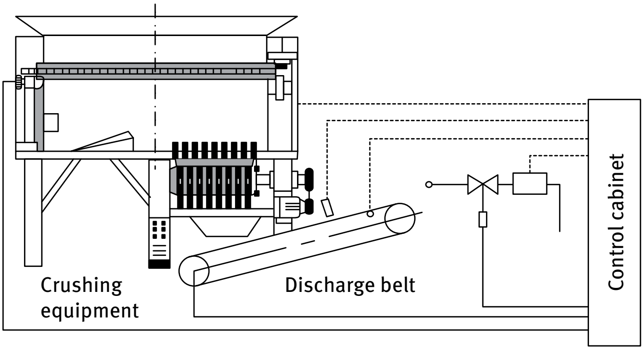


Fig. 5.24: Automatic material pulverization system.

5.2.5.2.2 Drying section

Drying is an important process; it ensures the clean production of briquette fuel from biomass. A roller drier is composed of a roller and shoveling plate, which is an advanced structure. After entering into the roller, the materials are continuously scattered in hot air under the action of the shoveling plate so that the particle surfaces efficiently contact with the hot air, resulting in an optimal drying effect.

A drier rapidly dries the materials using hot air. The wet materials to be dried are sent into a hopper using a belt conveyor and then conveyed to the feeding end by the material feeder of the hopper through the feeding pipeline. The gradient of the feeding pipeline is used to facilitate the flow of materials into the drier. The drier cylinder is a rotary cylinder with a slight tilt against the horizontal. The materials are fed from the higher end, but the heating medium is added from the lower end, meeting the materials in a counter flow direction. With the rotation of the cylinder, the materials move to the lower end under the action of gravity. When moving forward in the cylinder, the wet materials are heated and dried directly or indirectly by the heating medium, and then the dried materials are sent out from the discharge end through the belt. The shoveling plate installed inside the cylinder shovels and scatters the materials to increase the contact surface between the materials and airflow, boost the drying speed, and accelerate the movement of the materials. The heating medium is made of hot air and flue gas. After passing through the drier, the heating medium is passed through a cyclone dust collector to trap the carried materials. To further reduce the dust content of the tail gas, the heating medium is passed through the bag dust collector before discharging.

The heat for the drying equipment is supplied by the hot blast stove of biomass. When the system detects that the water content of the raw materials is higher than the setting, the raw material drier is started. After air distribution, the hot air produced by the hot blast stove is controlled at about 350 °C and flows into the drying equipment to ensure that the water content and uniformity of materials satisfy the production requirements.

5.2.5.2.3 Briquetting section

Enclosed belt conveyor

The use of an enclosed belt conveyor to replace double-screw conveyors has been studied. Because the raw materials are not crushed completely, many materials may be wrapped. However, the structural limits of a screw conveyor cause material wrapping during transport. Crushing of the materials produces much dust, and fly ash can be produced during transport.

Feed bin

Bridging and arching often occur at the front feeding device of biomass briquetting equipment, particularly for soft materials. Bridging and arching are common during each feeding process because of the material's light and flexible quality, poor flowing performance, serious wrapping, and hard cutting. Therefore, it is difficult to maintain pieces of ideal length. A key technology of the feeding device in biomass briquetting equipment is that various biomass materials piled, compressed, and tangled in the bin can be loosened continuously and adjusted through a kicking process, and the loosened materials are sent to the hopper of the briquetting equipment through an enclosed belt conveyor. A special design of the kicking device is used for soft crop stalks, sugarcane leaves, thatches, and other biomaterials. The kicking device can convert a compressed and tangled mass of materials at the bin bottom into a looser state on a belt conveyor and avoid mechanical wrapping or clogging.

The bottom plate of the automatic feed bin is movable and includes a rotary kicking shaft. The rotation speed of the rotary kicking shaft determines the different outputs of materials, thus achieving automatic feeding. During production, the biomass materials are fed into the bin using a grabbing device; with the rotation of the horizontal shaft, the materials in the bin uniformly drop onto the belt below and then are conveyed into the briquetting equipment through the conveyor, thus achieving automatic feeding. The movable bottom plate of the automatic bin avoids the arching of raw materials and thus eliminates the need for manual de-arching and generation of fly ash, thus maintaining a clean environment and reducing the labor necessary.

The structure of the bin is shown in Fig. 5.25. The process flow of the new bin is as follows: The biomass fuel materials inside the bin are uniformly conveyed onto the flat belt conveyor for discharge using the kicking device and then transported to the chute through the flat belt conveyor. Next, the chute spreads the materials onto the feeding belt of the briquetting equipment, and finally the materials are conveyed to the hopper of the briquetting equipment.

Flat die briquetting equipment

Flat die briquetting equipment with a production capacity of 300–2,000 kg/h uses an optimized wheel-pressing mechanism, thus protecting the inner and outer bushings, improving the lubricating effect, and prolonging the service life by 10 %. The use of

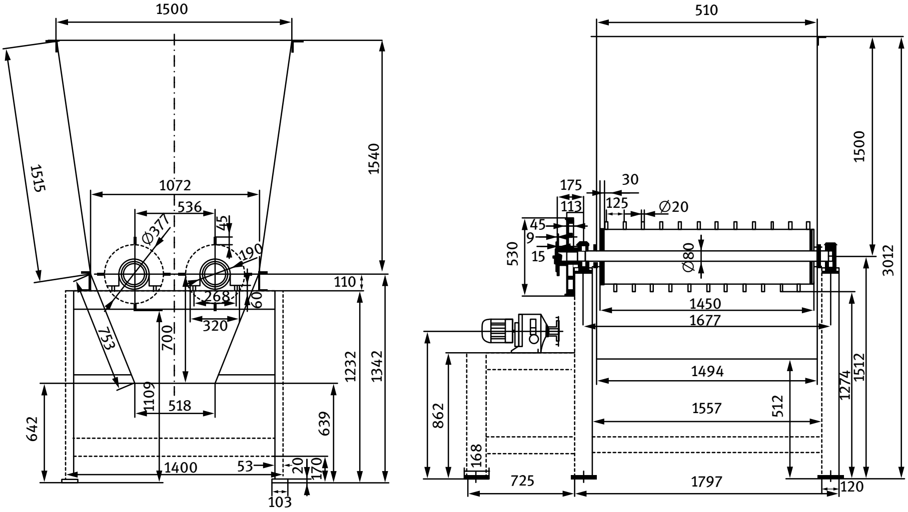


Fig. 5.25: Structural diagram of automatic biomass material feed bin.

a material level sensor eliminates clogging because too much material is fed into the briquetting machine. A material level switch is installed inside the briquetting chamber. If the raw materials become piled, material feeding stops automatically. After the briquetting equipment has been operating for a while, the piled raw materials in the chamber must be removed before more materials are fed. This technology achieves the system integration and automatic control of the production of biomass briquette fuel and solves problems such as dusty production systems, low automation of production, and high energy consumption.

Sealing of equipment joints

In the past, biomass briquette fuel production systems were not continuous. During production, piled materials were removed by hand; therefore, the system was usually designed as an open system. However, during production and operation, such an open structure can produce a large quantity of dust and vapors, which are the major sources of pollution in the workshop. Material clogging has been significantly eliminated by developing key equipment. Each equipment joint can be sealed, and the dust concentration in the workshop is now typically 3.8 mg/m^3, a reduction of 80 %.

Cooling and drying equipment

When molded materials flow out of the outlet of the briquetting equipment, their temperature is 60–80 °C, and the water content is 12–20 %. At this moment, much vapor is produced, thus severely damaging the equipment in the workshop. The discharge outlet of briquetting equipment is usually fitted with a mesh-type cooling and drying equipment that removes the moisture from the workshop and takes in fresh air into the workshop under a negative pressure, thus achieving a clean production environment. The molded materials directly enter a cooler through the inlet and drop onto the unloading mesh at the bottom. When the materials are piled to the upper limit of the material level gauge, the unloading mesh driven by a motor starts to move relatively and discharges the materials. The cooling and drying duration is shortened to less than 1 h, the temperature of briquette fuel is up to 30 °C, and the water content is 5–12 %. Therefore, the products can be packaged directly.

5.2.5.3 Automatic control system

The automatic control system is a distributed control system (DCS). When the downstream computer completes the control task, the storage capacity and other data can be collected and sent to the main computer. Furthermore, the production report is produced. Using the configuration monitoring software, the main computer shows and monitors the flow and parameters in real time, and the equipment monitoring information of each section such as pulverization, drying, briquetting, and cooling is shown, thus achieving the automatic control of the production process of biomass briquette fuel. Both automatic and manual controls are applicable. Some operating parameters of the production line can be adjusted automatically according to the type and water content of the raw materials. For the characteristics of different raw materials, different control procedures are selected from a database according to the requirements of the briquetting parameters, thus maintaining the optimal operation. For various briquetting processes, the corresponding subsystems maintain the optimal operation of equipment in each section.

The process flow of an automatic control system is shown in Fig. 5.26. Thus, the process can be divided into a hot air control system, drying equipment control system, pulverization equipment, water control system, and briquetting equipment control system.

The automatic control of the hot blast furnace ensures the supply of hot air at the corresponding temperature and volume according to the requirements of the master program. The automatic control of the drying machine ensures that it dries the biomass raw materials to a suitable water content at the highest heat use rate required by the master program. The automatic control of the chopping machine controls the feeding speed. The watering system is controlled, thus adding water to the biomass that has been chopped but not molded. This satisfies the requirements of the briquetting process when the water content of the biomass is lower than the optimal value for the briquetting process. The automatic control of the briquetting machine ensures the measurement and control of the briquette fuel material level, moisture and temperature of briquette fuel materials, and ambient temperature.

The main detection functions include the control center that detects the water content of biomass on-line before the briquetting equipment (including the hot air system

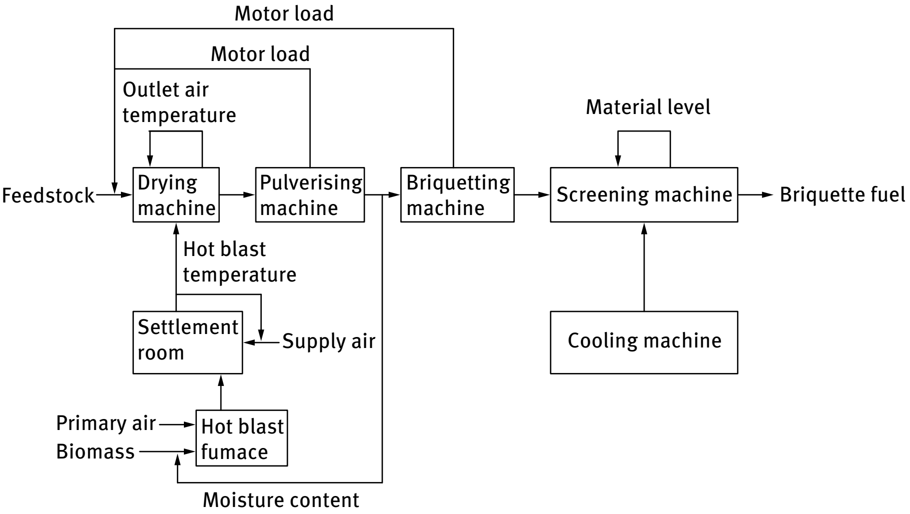


Fig. 5.26: Diagram of the control system.

and drying equipment), the current state of the chopping and briquetting equipment, the temperature of the hot air and moisture before and after the drying equipment, and the temperature of the briquetting bin. The main regulatory functions include the following: The control center continuously regulates the material feed and blowing of air from the hot blast stove, feeding belt conveyor of the drying equipment, air distribu-

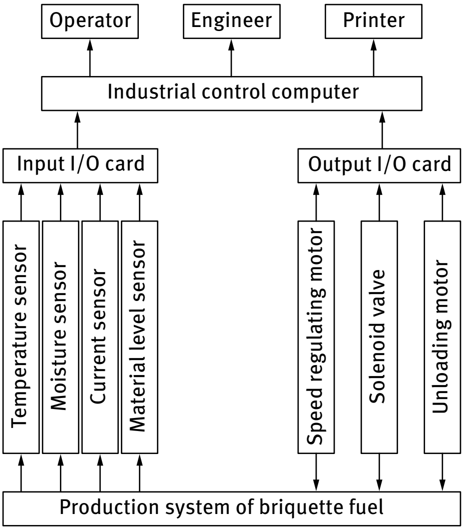


Fig. 5.27: Hardware configuration diagram of the control system.

tion motor, and dragging motor of the drying equipment. The hardware configuration of the control system is shown in Fig. 5.27.

In the control process, when the water content of the raw materials for briquette fuel is higher than the required level, the control center activates the hot air control program to increase the output of hot gas, maintains the temperature at its setting, reduces the speed of the dragging motor, and maintains the heat use rate of the drying equipment at a higher level. When the water content is lower than the setting, the control program performs the reverse regulation and activates the watering program to increase the water content of the raw materials and satisfies the material's water content requirements for the briquetting equipment. When the operating current of the main motor of pulverization or briquetting equipment is higher than the setting, the control center reduces the speed of the feeding belt of the drying equipment to decrease the material feed rate, and also decreases the air output of the hot blast stove and increases the speed of the dragging motor of the drying equipment.

5.3 Application technologies and equipment for biomass briquette fuel

5.3.1 Burning technologies and equipment for biomass briquette fuel

5.3.1.1 Direct-fired boiler

Considering the presence of highly volatile components and low burning point of biomass briquette fuel, a high-efficiency and direct-fired boiler for biomass briquette fuel was developed, as shown in Fig. 5.28. Using a spiral anti-slagging structure, a multistage air distribution system, and an automatic control device, a high-efficiency anti-slagging burning boiler was developed. It mostly avoids severe coking and slagging, a low burning efficiency, and a short service life caused by the high content of alkali metals in briquette fuels [99].

5.3.1.2 Circulating fluidized-bed boiler

A circulating fluidized-bed boiler for biomass briquette fuel is shown in Fig. 5.29. This can be used for various biomass briquette fuels and wastes produced during biomass conversions. For a circulating fluidized-bed boiler with 10–35 t/h steam capacity, the design should satisfy the following requirements: [100]

(1) The boiler should adapt to the design and check fuels and consider changes in the water content of crop stalks within the range 10–30 %.

(2) When the load of the boiler fired with a design fuel is equal to the rated evaporation, the heat efficiency of the boiler is above 89 % (based on the low calorific value and an ambient temperature of 20 °C);

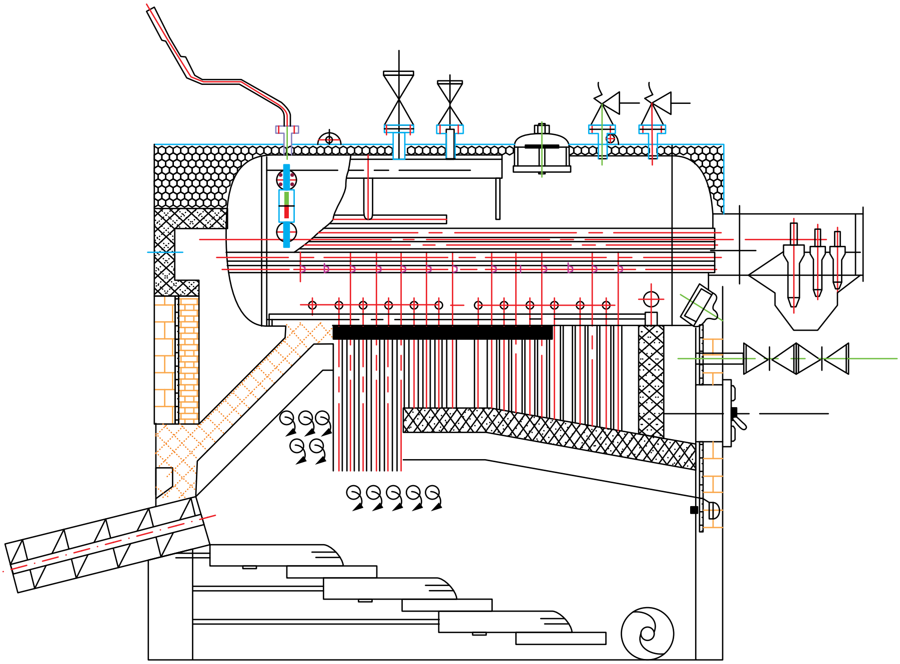


Fig. 5.28: Structural diagram of a direct-fired boiler for biomass briquette fuel.

(3) When a boiler is fired with a design fuel, using a flexible secondary air allocation, establishing the secondary burning control model, and maintaining the minimum stable burning load, a long-term safe and stable operation should not be higher than 20 % of the boiler rating.

5.3.1.3 Segmented burning equipment for biomass briquette fuel

Segmented burning equipment for biomass briquette fuel mainly consists of a furnace, an ash-clearing damper, a radiation-heating surface, a convection-heating surface, a reciprocating fire grate, and a chimney. The furnace is divided into primary and secondary combustors. The material filler and primary air inlet are located on top of the primary combustor, and the slag shield and slag-removing dampers are located on the sides. The ash chamber is located under the ash-clearing damper. The ash-clearing damper is fitted with an air inlet and air volume adjusting plate; a heat insulation layer is located outside the boiler. Its structure is shown in Fig. 5.30. After entering the air inlet, the air enters the furnace in three steps. The primary air enters the top of the primary combustor through the upward duct and is used as gasifying air. The secondary air enters the furnace through the slag shield damper and fire grate and reacts with the vaporized fixed carbon. The third air enters the secondary combustor from its bottom through the top of the ash chamber and mixes and burns with

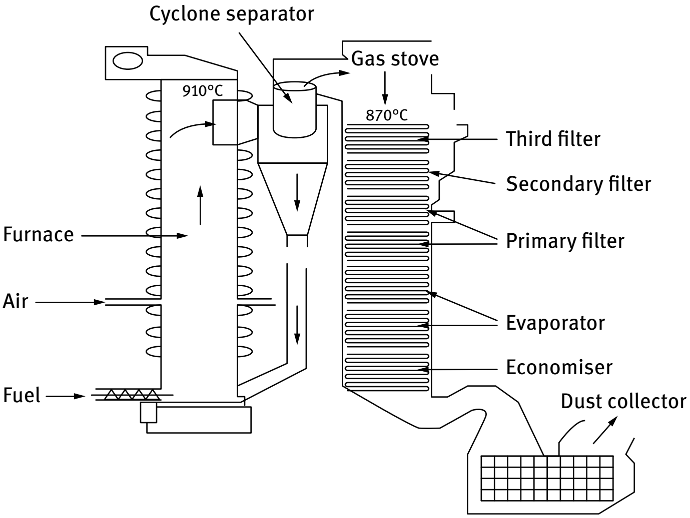


Fig. 5.29: Burning process of a fluidized bed of biomass briquette fuel.

the flammable gases entering from the side surface. The produced hot gas passes through a conversion-heating surface and is then discharged via the chimney. This boiler uses a side-draft biomass gasifying and volatilizing technology: A combustor specialized on volatile component burning with a fixed carbon burning technology takes in air from two positions. Such a side-draft biomass gasifying technology and the combustor specialized on volatile component burning ensure an adequate burning of the volatile components in the biomass, and the fixed carbon burning that takes in air from two positions decreases the heat load of the fire grate and the burning temperature of fixed carbon, thus effectively avoiding the slagging of biomass ash and volatilization of alkali metal residues such as potassium in the ash and allowing the use of biomass ash as potash fertilizer.

5.3.1.4 Biomass boiling, gasification, and burning devices

The main components of biomass boiling, gasifying, and burning devices include a distribution plate, a spiral feeder, a furnace, a fan, heat insulating and resisting materials, and a motor. A specific design is shown in Fig. 5.31. (1) A hood side-flow distribution plate is used, and the air passes through the entire plate surface, thus eliminating the dead bed, forming a good initial fluidifying condition, and avoiding material leakage and clogging. (2) The reaction of biomass in the furnace is more complex; to ensure sufficient boiling and gasification of the biomass, the furnace is divided into three stages: vertical, spreading, and suspending stages. The dimensions of the furnace are designed with these three proportional stages according to its design load. (3) A high-pressure centrifugal machine can satisfy the demand of three air supplies needed by

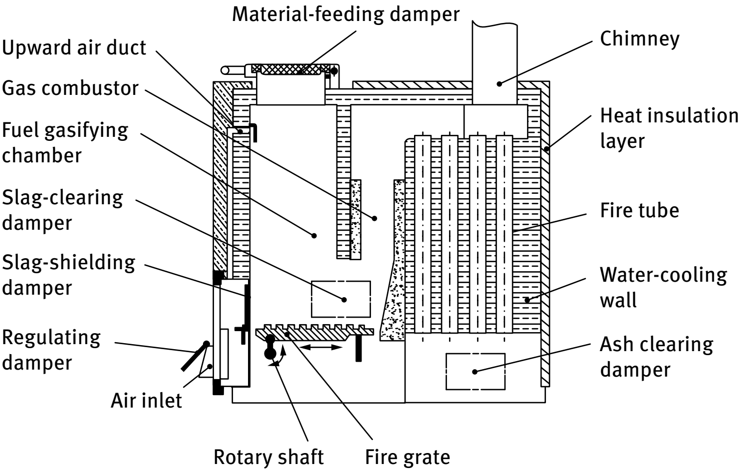


Fig. 5.30: Structural diagram of a hot water boiler for biomass briquette fuel.

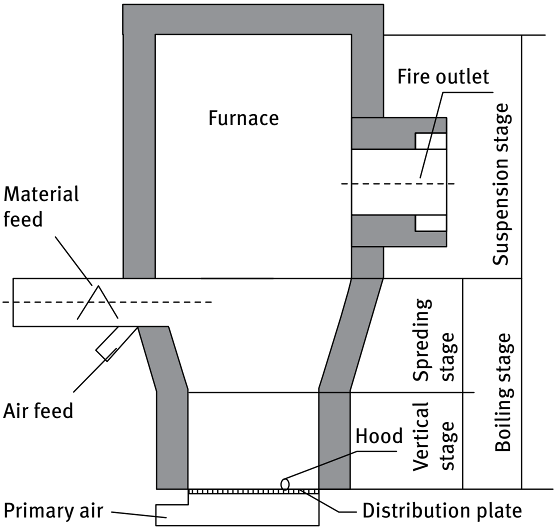


Fig. 5.31: Stove of a biomass boiling, gasification, and burning device.

the equipment. A tangent cyclone in the furnace is directly transferred by the motor, and a cooling impeller is used for cooling. (4) The housing of the biomass boiling, gasification, and burning device is typically composed of iron; inside the iron housing, a heat insulation padding layer is used to fill and apply the pasty, loose, or fibrous heat insulation materials onto the special mesh of the stove housing. Primarily mineral wool is used as the heat insulation material. (5) During the operation of the equipment, tar is directly burned in the gas form, mostly solving the technical difficulty related to the high tar content in biomass gasification and avoiding the secondary pollution of water caused by tar rinsing. (6) The system can be used for various biomass briquette fuels with water contents < 30 % and dimensions of < 30 mm.

5.3.2 Gasification technologies and equipment for biomass briquette fuels

The gasification technology for biomass briquette fuels uses biomass briquette fuel as the raw material. The common updraft fixed bed, downdraft fixed bed, lateral-draft fixed bed, open fixed bed, single fluidized bed, circulating fluidized bed, double fluidized bed, and other gasification equipment can be used for the gasification of biomass briquette fuels. Considering the characteristics of biomass briquette fuel such as its high energy density, high mass density, uniform granularity, and stable water content, the use of biomass briquette fuel as a gasification material has the following principal advantages [101].

The unstable feeding of biomass is effectively eliminated. The energy and mass densities of biomass powder are lower; therefore, bridging and arching often occur, thus making it difficult to seal the feed system. However, both the energy and mass densities of biomass briquette fuel are higher, thus enabling the continuous feeding of materials and effective sealing during gasification.

A biomass gasifier stove has good fluidifying performance, stable operating conditions, and a higher gasification efficiency. The fluidifying performance of biomass is generally poor. To improve it, “inertia ions” are usually added to a gasifier stove. However, biomass briquette fuel has uniform granularity, stable water content, and better fluidifying performance; therefore, inertia ions are not needed in gasification, thus making the operating conditions of a gasifier stove more stable and enhancing the gasification efficiency.

The fuel gas quality is stable and has a high calorific value. Because of the good fluidifying performance of biomass briquette fuel, it is easy to establish a stable material layer in a biomass gasifier stove and stabilize the operating conditions. Thus, the quality of biomass fuel gas content is more stable, and the calorific value is higher.

Less fly ash is produced, and the tar content is low. The uniform granularity, stable water content, and higher energy and mass densities of biomass briquette fuel can reduce the quantity of materials removed during the operation of a biomass gasifier stove. Therefore, the fly ash and tar contents in the flue gas are lower.

The productivity is high. The uniform granularity and higher energy and mass densities of biomass briquette fuel and the stable operation of the gasifier stove increase the gasifying strength and gas production, thus enhancing the productivity of the gasifier stove.

5.3.3 Household technology and equipment for biomass briquette fuel

Household stoves for biomass briquette fuel can be divided into cooking, heating, and cooking plus heating stoves according to the purpose, or direct burning, gas burning, and semi-gas burning. Common household stoves include direct-fired cooking stoves, gas pellet stoves, semi-gas pellet fuel stoves, and pellet fuel burners.

5.3.3.1 Typical semi-gas cooking stove for biomass briquette fuel

In a semi-gas biomass stove, the gasified gas and fixed carbon produced by the biomass fuel burn within the furnace. A secondary gas inlet pipeline is added to the furnace top. By controlling the gas inflow, the dwelling time of the gasified gas in the furnace is improved, ensuring sufficient burning without dust or tar generation. This further improves the utilization rate of the burning. By supplying oxygen, the secondary air inflow enhances the gas disturbance, thus ensuring more effective and complete burning.

A typical cooking stove for biomass molded pellet fuel uses a double-layer furnace, and the secondary air duct is located between the inner and outer furnaces. The stove mainly consists of a primary air duct and air damper, secondary air duct and air damper, material filler, water jacket, furnace, filter grate, radiation heating surface, stove opening, pot ring, flame shielding ring, flue, and chimney. The structural arrangement is shown in Fig. 5.32.

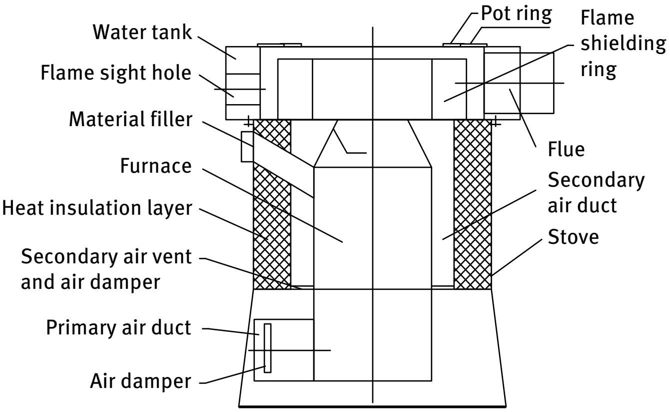


Fig. 5.32: Stove of a biomass boiling, gasification, and burning device.

5.3.3.2 Gas cooking stove for biomass briquette fuel

Fig. 5.33 shows a popular gas cooking stove for biomass briquette fuel in China. This uses a split gasification chamber and consists of a gasification generator and burner.

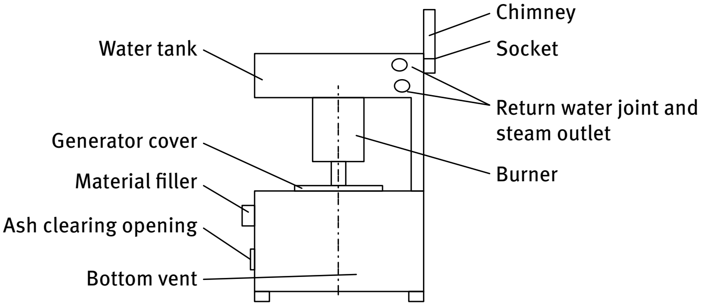


Fig. 5.33: Gas cooking stove using biomass briquette fuel.

The briquette fuel entering into the gasification generator through the material filler is first decomposed and gasified within the gasification generator, then reacts with the oxygen and carbon in the air, and is converted into a flammable gas. The lighter gas moves upwards into the burner in which the gas burns and produces heat for the second time. Today, most of the popular briquette fuel stoves use this semi-gas burning technology.

5.3.4 Carbon-based slow-release fertilizer technology and equipment

A slow-release fertilizer slowly releases the nutrients to crops over a long period owing to the chemical composition or physical function of the nutrient. Compared to a traditional fertilizer, it is characterized by lower consumption, high use rates, easy application, easy and safe handling, and increases production and yields.

A biomass carbon-based slow-release fertilizer uses biomass carbon as the base; biomass carbon has a low production cost, simple preparation, and widespread availability of materials. Currently, three popular technologies are used to prepare carbon-based slow-release fertilizers using biomass: (1) The biomass materials are first carbonized, then the components of a slow-release fertilizer are uniformly mixed and melted in a roller-type pellet maker to produce the slow-release fertilizer. (2) The biomass materials are first pulverized and pressed, producing biomass material pellets. Then, the pellets are carbonized, finally producing a slow-release fertilizer. (3) A biomass-based active carbon is produced first through the thermal activation of the biomass, and then using the biomass-based active carbon as the carrier, fertilizer, adhesive, and other additives are added proportionally to produce a pellet of carbon-based slow-release fertilizer. The carbon-based slow-release fertilizers produced by the first two technologies are coated, whereas those produced by the third technology are not coated (Fig. 5.34). The coatings of the coated slow-release fertilizers are mostly composed of highly polymeric materials, involving a high technical level, complex production process, and more requirements for process equipment. Therefore, they

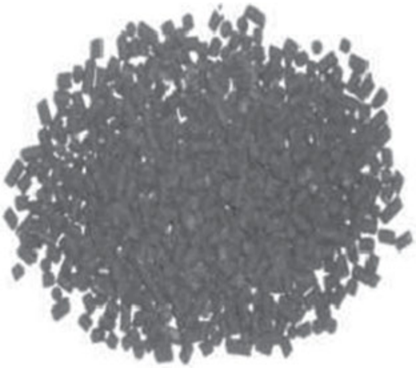


Fig. 5.34: Biomass carbon-based slow-release fertilizers.

are often only be used for crops with a high additional economic value. They are even referred to as “noble fertilizers” and are not widely used. The preparation of uncoated slow-release fertilizers is characterized by low production costs, environmental protection, and good slow-release effects, and they are used and promoted widely.

The preparation process for uncoated carbon-based slow-release fertilizers is shown in Fig. 5.35. All the raw materials for the fertilizer are first transported into the distributor by a feeding hopper through a bucket-type hoist and then distributed into each bin using the distributor. The raw materials in the bin are measured by an

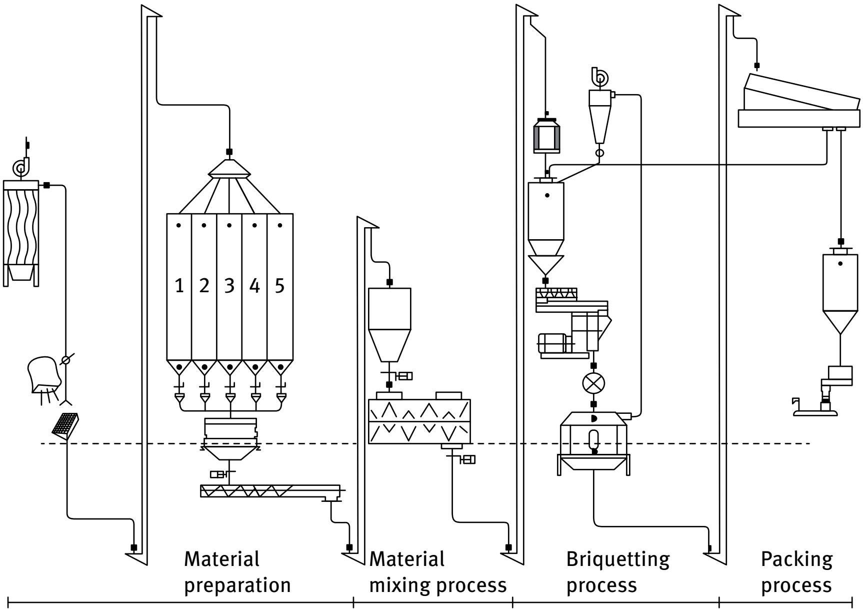


Fig. 5.35: Briquetting process flow of an activated carbon-based slow-release fertilizer.

electronic balance and then conveyed to the bucket-type hoist using the spiral conveyor, finally transported to the dosing bin using the bucket-type hoist. In the dosing bin, the raw materials are uniformly mixed using a mixer and then transported to the pellet-making bin using a bucket-type hoist through the iron remover. After the raw materials are molded in the pellet-making bin, the raw materials are sent to the cooler for cooling. The cooled products are conveyed to the filter using a skip hoist. The filtrated finished products are conveyed to a finished product warehouse where the products are packaged and warehoused by automatic packaging equipment as required. The cooler is fitted with a cyclone separator to separate and return the dust produced during the cooling to the pre-pellet bin for remolding; meanwhile, the unacceptable pellets that are filtered out are also returned to the pre-pellet bin for re-briquetting.

5.4 Example applications of biomass briquette fuel

5.4.1 Application example of scaled production of biomass briquette fuel

5.4.1.1 Ruzhou production base for stalk briquette fuel in Henan

The Henan Academy of Science Energy Research Co., Ltd. is a domestic company engaged in the research, development, and production of biomass solid briquette fuel equipment. In recent years, the company has developed a series of standing biomass briquetting equipment based on the integral flat die pressing and rolling principles, and this equipment is used widely in China. A biomass briquette fuel production demonstration project of the company is located in Ruzhou City, Henan Province, as shown in Fig. 5.36. This system can produce 30,000 ton biomass briquette fuel annually at present and will be expanded to a production base with an annual output of 50,000 t. This project covers an area of 73,333 m^2, including 26,666 m^2 construction land, 44,167 m^2 raw materials site, and a 2,500m^2 workshop. With a total fixed investment of 5,000,000 CNY, this project is equipped with six sets of briquetting equipment, each with an output of 1 t/h, eight sets of wheat stalk binding machines, four sets of grabbing machines, three pulverizers, and four tractors. In terms of collection, the company is responsible for binding wheat stalks directly in the field, organizing the transportation, and transporting them to its site. The usual collection radius is 8 km. The main costs include the binding and transport costs of ~150 CNY/t. The wheat stalks are compressed and used to produce biomass briquette fuel with a density in the range 0.5–1.1 g/cm^3.

Basic performance parameters, technical specifications and features of a briquette fuel production system are as follows:

(1) The biomass briquette fuel and auxiliary equipment to improve the products.
   - Comprehensively optimize the design of the opening rate, the structure of the molded opening and grabbing angle of the biomass briquette fuel die, the

(a) Material collection (b) A series of briquetting machines

(c) Material transmitting system (d) A glance of workshop

Fig. 5.36: Briquette fuel production base (30,000 t/year) in Ruzhou, Henan.

structure, material, and thermal treatment of the wearing parts such as ring die to increase the service life of the briquetting equipment and reduce the production cost of biomass briquette fuel.

- Scaled fuel briquetting equipment with high output, wide applicability, and low electricity consumption per ton of materials was used to ensure the briquetting rate of > 95 %; the electricity consumption per ton of materials is < 80 kW · h/t; the service life of the briquetting die is > 600 h, and raw materials with a water content in the range 8–30 % can be handled [102].
- Optimize the design of the biomass drying equipment, and focus on the adaptability of drying equipment to changes in the biomass type and water content to ensure that the heat use rate of the drying equipment is not < 60 %.
- Optimize the design of pulverizing equipment with high efficiency, wide biomass applicability, and power consumption not > 15 kWh/t. The pellet length of the pulverized materials can be adjusted according to the demand.

(2) The key technologies of drying, pulverizing, briquetting, and other steps, and achieve largely automatic operation of the briquetting system.
  - Integrate and optimize the key technological parameters to further improve the technical integration level of the equipment, reduce the production costs, increase the output, and significantly improve the operating stability and high-load continuous productivity of the equipment.

(3) Solve a series of problems caused by stand-alone operation. In the case of stand-alone operation, after operating for > 1 h, manual feeding with high labor intensity will reduce the production rate, so that the preset requirements of the briquetting equipment will not be met. Moreover, uneven mixing will also reduce the briquetting rate and the density of the pellets.

5.4.1.2 Jiangtang Production Base of Jinhua Branch Company of Ningbo Aoke Lvying New Energy Development Co., Ltd.

In June 2011, Ningbo Aoke Lvying New Energy Development Co., Ltd., a wholly owned subsidiary of Beijing Aoke Ruifeng New Energy Development Co., Ltd., established a branch in Jinhua City, Zhejiang Province and constructed a biomass solid briquette fuel production base with an annual output of 100,000 t in Jiangtang Town, Wucheng District. This project has been registered with the Development and Reform Bureau of Wucheng District, Jinhua City.

The Jiangtang Base is located in Jiangtang Town, Wucheng District, Jinhua City, where the timber processing enterprises of Jinhua City are located, and there are many small/medium-sized log-processing enterprises with a total of 585 timber processing enterprises. The company takes advantage of Jiangtang Town and the many log-processing workshops for the supply of raw materials. The base covers an area of 6,475 m^2, including almost 3,984 m^2 of building area and is equipped with six automatic production lines, six 9SYX-4B biomass dense briquetting equipment, four stalk pulverizers and one dryer of ø1.8 M added in November 2012. The base can produce 100,000 t of solid biomass briquette fuel annually (Figs. 5.37, 5.38, 5.39, 5.40).

The construction of this base changed the operational mode of the traditional workshop with one unit and one production line. From raw material pulverizing and drying to product briquetting, packaging, and warehousing, all steps are preformed automatically; therefore, this base has become the first true industrial-scale production line in this industry in China.

Products made at the base are delivered mainly to the Hangzhou Bay Industrial Park. Since construction and start of production, the base has produced almost

Fig. 5.37: Material supply system.

Fig. 5.38: Briquetting system I.

Fig. 5.39: Briquetting system II.

Fig. 5.40: Discharge system.

50,000 t biomass briquette fuel, which can substitute for more than 30,000 t of coal. This switch has made a significant contribution to energy saving and emissions reduction in Zhejiang.

5.4.1.3 Zhiziying Production Base of Hebei Aoke Ruifeng Biomass Technology Co., Ltd.

This production base, located in Gu’an County, Langfang City, Hebei Province, uses sawdust as its main raw material. Hebei Aoke Ruifeng Biomass Technology Co., Ltd. has converted the biomass dense briquetting technology developed by the company, changed its formal stand-alone production mode, and combined the pulverizing, drying, water content control, conveying, pressing, briquetting, cooling, drying, and other processes to construct an integral automatic production line, providing the company with a scaled production ability (Figs. 5.41, 5.42, 5.43, 5.44, 5.45, 5.47, 5.48, 5.49). In the course of implementation, the company further improved the structural parameters of the equipment for the automatic production line, the wear resistance of the die, the applicability to other raw materials, reduced the unit energy consumption, and boosted production efficiency. In 2013, the company produced 50,000 t biomass dense briquette fuel.

Fig. 5.41: Briquetting equipment and dust collector.

Fig. 5.42: Roller drier.

Fig. 5.43: Drying stove.

Fig. 5.44: Feeding system.

Fig. 5.45: Roller drier.

Fig. 5.46: Feeding system for drying stove.

Fig. 5.47: Sundries separator.

Fig. 5.48: Integrated discharge system.

Fig. 5.49: Cooling and drying system.

5.4.2 Example applications of burning heat supply with biomass briquette fuel

5.4.2.1 Heat energy service project of Excelic Food Technology (Nanjing) Company

Through a heat energy service, the company modified its former 15 t coal-fired steam boiler into a biomass boiler and added necessary energy saving equipment (Figs. 5.50, 5.51). The current operating conditions of the boiler are: pressure: 1.6 MPa, boiler output: up to 13 t/h. The boiler is safe, environmentally friendly, and meets the enterprise requirements and has not only guaranteed the steam required by the enterprise but also reduced the annual energy costs by . ~3,000,000 yuan. The project has been inspected and accepted by the relevant authorities and is operating routinely.

Fig. 5.50: Boiler house of the Excelic Food Technology Company.

Fig. 5.51: Biomass boiler of the Excelic Food Technology Company.

5.4.2.2 Heat service project of Zhengzhou Songshan Hotel

Zhengzhou Songshan Hotel is the largest garden-type tourist hotel and the appointed service organization for Henan Province meetings and official receptions. The hotel originally had three boilers, one of which had been out of service, and the other two received normal annual inspections; the total evaporation capacities of the boilers are 14 t/h. Those boilers have been operating for many years; however, their outputs were not sufficient and their working conditions were poor, and the auxiliary equipment needed frequent repairs. Through a heat energy service and energy saving modifications, the boilers were modified to comply with biomass briquette fuel, and they not only reduced the energy consumption but also met the environmental protection and energy saving requirements.

5.5 Technological and industrial development trends for biomass briquette fuel

The biomass briquette fuel technology industry aims to achieve scaled production and industrialized modes of biomass briquette fuel production with efficient use of agricultural and forestry biomass as the raw materials. In addition, improved conversion and application technologies and the construction of an industrial chain based on the distribution and variety of biomass materials available should be developed. There are also moves to speed the construction of agriculture and forestry biomass material collection, storage, and transport systems applicable to different scales, produce conversion technology and equipment of high efficiency and low energy consumption. Further significant achievements such as boosting the automatic level of briquette fuel production systems, establishing the heat supply modes and systems suitable for different regions, and improving the whole industrial chain from raw material supply to fuel production, distribution, and application have been realized [103].

5.5.1 Technological development trends

The main technological development trends concerning briquette fuel are to improve agriculture and forestry biomass material collection, storage, and transport systems suitable for different regions and scales. Further research on the conversion technology and equipment of higher efficiency and lower energy consumption, solving the difficulties of the various production processes, and boosting the on-going updating within the industry is required. A breakthrough in the key application technology is required to establish heat supply systems suitable for different scales and achieving the industrial-scale development of biomass briquette fuel. With briquette fuel as a base, further development of cost effective carbon-based slow-release fertilizers with a good slow release is very important. Improving policies to encourage biomass briquette fuel use and develop an industrial guarantee system for biomass briquette fuels are also required.

5.5.1.1 Development trends in raw materials supply system

Agriculture and forestry biomass materials are dispersed and seasonal. The collection of raw materials mainly depends on human labor and small-scale machinery; therefore, the collection, storage, and transportation efficiencies are low and meeting the demand for the large-scale use of biomass materials is difficult. Thus, a collection, storage, and transportation system specialized in the large-scale supply of raw materials should be established.

The collection, transportation, and storage of agriculture and forestry biomass materials are key problems affecting the industrial development of biomass briquette fuels. Therefore, it is important to establish means for the collection, transportation, and storage of agriculture and forestry biomass materials suitable for local conditions, solve the problems associated with those biomass materials, possibly using the personnel and sites of former grain and cotton collection and storage organizations. In addition, effectively organizing the farmers, developing agriculture and forestry biomass material broker teams or professional companies, actively boosting the construction of cooperative organizations specialized in the supply of agriculture and forestry biomass materials, bringing the production and supply of those biomass materials into a logistics system, increasing farmers’ incomes, and advancing farmers’ organizations are very important.

For briquette fuel manufacturing plants in different regions and scales, the key factors are as follows: further developing appropriate collection, transportation, and storage of local agriculture and forestry biomass materials, determining the reasonable collection radius, researching collection, storage, transportation, and preprocessing, and solving conflicts between the dispersion and periodic supply of biomass materials and the production concentration [104].

5.5.1.2 Technical development trends in briquetting equipment

The biomass briquette fuel equipment used in China today has the following problems: too short service life of core components, poor equipment stability, low continuous operating ability of equipment, small applicability of briquetting equipment, and the absence of normative references. Thus, current trends in briquette fuel equipment involve the development of briquetting units with higher reliability, anti-wear dies, lower energy consumption, higher output, and automatic operation technology.

Good performance and certain breakthroughs have been achieved in the production technologies for biomass carbonized fuel; however, the following problems still remain: the applicability of briquetting equipment and processing the raw materials are poor; the key components wear easily and have a short service life; the unit output and briquetting density are low, necessitating the improvement of the degree of automation. Thus, development trends regarding biomass dense briquetting and carbonized fuel include developing the equipment and components with wider applicability to more raw materials and longer service life, and increasing the unit output, briquetting density, and degree of automation through technical research and innovation.

5.5.1.3 Technological development trends in briquetting processes

According to the characteristics of biomass resources in different regions of China, it is important to study briquette fuel production technologies to select and optimize the equipment, to achieve cooperation and coordination among all the systems and procedures, develop on-line monitoring and control systems, achieve automated operation and real-time monitoring of systems, and finally establish automatic, continuous, high-efficiency, and environmentally friendly briquette fuel production lines. These measures are required to solve the current problems largely characterized by low-output stand-alone operations, no production line reasonably linking each procedure, and poor cooperation and coordination of systems of briquette fuel production in China. The key to the development of briquetting processes is the establishment of continuous, stable, environmentally friendly, and smart production lines, solving the difficulties of each production procedure and promoting continuous upgrading within the industry.

5.5.1.4 Applications of briquette fuel equipment and technical development trends

The scope of applications of biomass briquette fuel on the market today is not large; therefore, the main development trends in biomass briquette fuel application technology are active study of new methods and new technologies for use of biomass briquette fuels in industrial boilers, power generation, gasification, public heating, and the production of slow-release fertilizers.

In the near future, burning equipment with higher efficiency burning and lower emission of pollutants for biomass briquette fuel should be developed. The burning equipment should be upgraded gradually by fully integrating modifications to the existing coal, fuel, and gas industrial boilers. Disadvantages such as coking and slagging should be reduced gradually; scaled and stable larger biomass briquette fuel boilers should be developed according to the requirements of biomass power generating technology. Cost-effective and easier handling burning stoves should be developed according to the requirements of household cooking stoves.

As a gasifying raw material, biomass briquette fuels offer stable feeding, good fluidization, and high gas productivity. The principal trends in the future development are to develop gasifying equipment applicable specifically to the characteristics of biomass briquette fuels and provide a stable process with a high output and low tar content.

Very recently, briquette fuel has been used for the preparation of carbon-based slow-release fertilizers. Nowadays, most slow-release fertilizers in China are coated, and the majority of the coatings used are composed of high polymer materials involving a high technical level, complicated production process, and increased requirements for process equipment. After being carbonized, briquette fuel can be used to prepare cost-effective and *uncoated* slow-release fertilizers, which can be widely used and promoted. Thus, the preparation of carbon-based slow-release fertilizers with biomass briquette fuels as the basis is a new trend in the application of briquetting.

5.5.2 Industrial development trends

5.5.2.1 Industrialization flow of briquette fuel

Considering the technical, equipment, and other problems in the briquette fuel industrial chain in China, further research is needed to develop new, higher-efficiency briquetting equipment to integrate and study sustainable material supply guarantee technology and methods, production processes and system integration, material mixing plans, and material distribution technologies and methods suitable for typical regional characteristics of China. Research and development of automatic and high-efficiency burning technology and equipment for briquette fuel is also needed to establish integrated heat supply systems for villages and towns and improve the application system of briquette fuel burning industries and the whole industrial chain system from material supply to fuel production, distribution, and application [105]. The flow of biomass briquette fuel in an industrial setting in China is shown in Fig. 5.52.

5.5.2.2 Briquette fuel industrialization mode

The industrialization mode of biomass briquette fuel is mainly in the form of energy management control (EMC) or new energy service companies. The biomass briquette

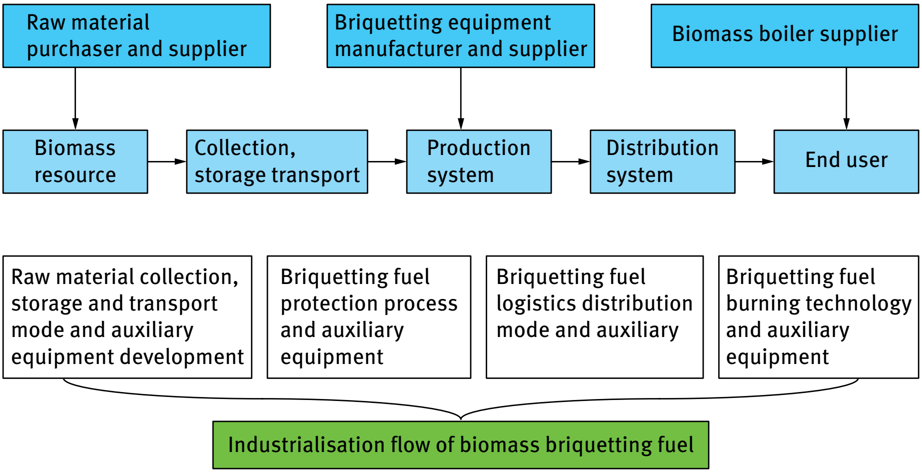


Fig. 5.52: Industrialization flow chart of biomass briquette fuel in China.

fuel manufacturer will be engaged in the production of briquette fuel, acting as an EMC service to maximize corporate profits. Manufacturers will likely enter the application market of biomass fuels and continuously increase their market share to promote the transfer of biomass briquette fuel from the fuel production in the upstream base to the end user in the market and realize a reasonable profit.

5.5.2.3 Briquette fuel industrialization guarantee

Compared to European and American countries, especially northern European countries, the Chinese briquette fuel industry has larger gaps in encouraging policies and standards, particularly subsidy policies for conversion and application stages, in addition to the production ability and technical developments. Thus, according to the regional characteristics and actual conditions in China, further improvement of encouraging policies and standards for using biomass briquette fuels is vital for the development of the industry in the near future.

Desirable steps for the further development of biomass briquette fuels are as follows: (a) setting out a different subsidy system; (b) cancelling and substituting the single raw material subsidy system with combined policies; (c) establishing a quota system and green trade certificate system; implementing conditional coal limits and prohibition measures in different regions; (d) improving the consumption of biomass briquette fuel in industrial production by means of compulsory restriction methods and setting consumption limits for some industries; (e) improving financing policies, actively supporting the establishment of large enterprise groups through reorganizations; (f) guiding large enterprise groups to establish stable cooperative relationships and profit unification systems with various small manufacturers; making full use of the advantages of scaled integration, technical transfer, and information gathering, and improving the market position of manufacturers, and enhancing their abilities to withstand market risks.

The state should establish comprehensive regulations, especially including those regarding the effective and reasonable applications of biomass resources, clean production and environment protection regulations in the use of biomass energy, the use of biomass energy, the comprehensive use of biomass products, and national support and encouragement of enterprises using biomass energy.

At present, there is no inspection method or technical standards regarding briquette fuels; therefore, it is necessary to establish a standardized system with optimal structure and clear stratification to improve the relevant standards and generate a standards system framework for China according to the standards requirements of the entire briquette fuel production process based on the steps comprising the briquette fuel industrial chain. The standards system should consist of the following three parts: (1) preprocessing standards such as quality evaluation, collecting equipment, storage, and pulverizing of raw materials, (2) processing standards such as the specifications of the main briquetting equipment in China, series designs, and standards for the parts of briquetting equipment subject to wear for the briquette fuel, and (3) biomass briquette fuel applications such as standardization of biomass boilers, water heaters, air heaters, household heaters, household cooking boilers, public-use large-scale stoves, and household cooking stoves. Establishing such a system of standards will result in the standardization of the construction of biomass briquette fuel projects, ensuring quality biomass briquette fuel products, improving the level of enterprises and products, and facilitating the healthy and ordered development of the biomass briquette fuel industry.

Xiaodong Zhang*, Min Xu, Huacai Liu, Zhaoqiu Zhou, Xiuli Yin, Ying Guo, Lei Chen, Xiaoxu Fan, and Rongfeng Sun

6 Biomass gasification technology

Among all biomass thermochemical conversion routes, gasification is the most developed and widely applied technology. With the main objective to obtain gaseous fuel, gasification can realize the effective conversion of solid biomass waste, which is of low energy density and inconvenient to store and transport, into fuel gas that is apt for transportation and application. Biomass gasification technology can be applied with wide feedstock adaptability, and high energy efficiency. The fuel gas from gasification can be utilized as cooking gas, heating source, engine fuel gas, and also be used for power generation and chemical industry feed gas.

***Corresponding Author: Xiaodong Zhang:** Energy Research Institute of Shandong Academy of Sciences, Jinan 250014, China; E-mail: xd_zhang77@aliyun.com
Min Xu: Energy Research Institute of Shangdong Academy Sciences, Jinan 250014, China
Huacai Liu: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Zhaoqiu Zhou: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Xiuli Yin: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Ying Guo: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Xiuli Yin: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Ying Guo: Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences; CAS Key Laboratory of Renewable Energy; Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, China
Lei Chen: Energy Research Institute of Shandong Academy of Sciences, Jinan 250014, China
Xiaoxu Fan: Energy Research Institute of Shandong Academy of Sciences, Jinan 250014, China
Rongfeng Sun: Energy Research Institute of Shandong Academy of Sciences, Jinan 250014, China

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6.1 Fundamentals of biomass gasification

6.1.1 Principle of gasification

The main objective of biomass gasification is to achieve maximum conversion of solid biomass feedstock into gas. During gasification, limited oxygen is supplied to achieve incomplete combustion, which can lead to the production of heat for the decomposition of large molecules inside biomass. The decomposition products further react with gasifying agent, homogeneously or heterogeneously, resulting in the production of permanent gases such as carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), etc. The gasifying agent provides limited oxygen for the gasification process and is also involved in the gasification reaction schemes. The type and addition ratio of gasifying agent significantly influence the final product distribution. Gaseous fuel from gasification mainly consists of a mixture of combustible gases such as CO, H_2, CH_4, and inert gases including CO_2 and nitrogen (N_2). Apart from gaseous product, there is also the possibility of forming a small amount of solid residue mainly composed of char and ashes, and liquid product comprising mainly large molecule fragments from biomass decomposition.

Almost all types of agriculture and forestry residues can be used as feedstock in gasification, for example, residues from log production, tree trimming and wood processing, charcoal, woodchip, rice straw, rice husk, corn stover, wheat straw, and so forth. Biomass wastes are always abundant, reliable, and affordable. Moreover, sometimes, pretreatment such as drying and milling is required for specific biomass feedstock to fulfill the requirement of gasification equipment.

The gasifying agent serves as oxygen supplier and reaction medium in gasification, which is vital for the operation of gasification process and final product quality. Air, with its low cost and great abundance, is the most commonly utilized gasifying agent. Furthermore, oxygen, oxygen-rich air, steam, mixture of air and steam, and mixture of oxygen and steam are also possible choices.

The large content of nitrogen in air, about 78 %, is an unfavorable factor for quality gasification. Nitrogen is inert for the gasification reaction process. It dilutes the product gas, resulting in low calorie gas, deteriorated application value, and also increased energy consumption in gas compressing and transportation. Therefore, the products of air gasification are always utilized for cooking gas within a nearby community, small-scale heating, and power generation.

Oxygen or oxygen-rich air is used as gasifying agent to mitigate the dilution effect of nitrogen. The quality of gas product is improved with increased gas calories, ordinarily 10–12 MJ /Nm^3, and condensed gas volume. However, the production of oxygen consumes large amounts of energy, which increases the cost of the gasification process. Oxygen gasification is mostly applied for the production of feed gas for the synthesis industry.

Superheated steam is applied for high quality gas production. Steam provides both oxygen and hydrogen donor for gasification. In other words, steam participates in the reactions with gaseous product and char from biomass pyrolysis. The product gas from steam gasification is always of high calorie, reaching above 16 MJ Nm^{-3}, with high hydrogen content. However, the high energy consumption of the steam generator and superheater should be considered from the perspective of technical and economic viability. Moreover, an external heating source is required for steam gasification, which significantly increases the operating cost of the gasification process with complicated equipments.

In order to balance both process economics and gas quality, mixed gasifying agent can be applied which combines air, oxygen, and steam. Oxygen or air is introduced into the system to realize the energy sustainability of gasification. Steam is introduced to improve the quality of the product gas. This leads to a significant decrease in the dilution effect of nitrogen and also in the consumption of oxygen. The combination of different gases depends on the final gas application and specific gasification process.

The composition and calories of product gas from gasification vary greatly with the type of gasifying agent and gasifier. Moreover, the quality of product gas determines the final application of gasification technology. After a long history of development over about one century, the application for biomass gasification has expanded significantly. The main fields of application of gas generated by gasification include domestic cooking and heating, drying of grain, timber and fruit, tea frying, as fuel gas for internal combustion engines and gas turbines for power generation, substitution of coal for co-firing boilers and industrial furnaces, feed gas for chemical industry producing synthetic methanol, ammonia, gasoline and diesel fuel, oxygen-containing chemicals, and as feed-gas for fuel cells.

6.1.2 Thermochemical reactions involved in gasification

The reaction process of biomass gasification is extremely complex, varying with different types of gasification reactors, process flow, reaction conditions, gasifying agents, and composition and granularity of feedstock. According to the numerous studies on gasification reaction system, it is generally believed that the gasification process is a thermal chemical reaction system consisting of multiple separate, consecutive reactions among biomass feedstock, gasifying agent, and biomass pyrolysis products. During this process, substance conversion occurs simultaneously with energy transfer and mass transportation. The following reactions are some basic and important ones that are involved in most gasification processes.

The typical updraft gasifier is considered as an example to illustrate the main processes in gasification. In updraft gasification, biomass feedstock flows downward and the gas flows upward, as shown in Fig. 6.1. When fed from the top into the gasifier,

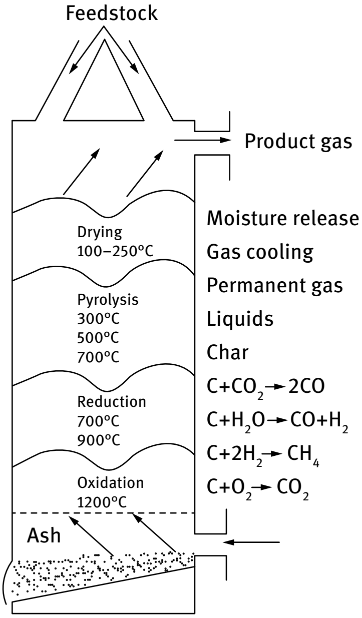


Fig. 6.1: Main reactions involved in biomass gasification.

continuously or intermittently, the feedstock experiences four roughly divided reaction regions inside the gasifier, namely, drying, pyrolysis, reduction, and oxidation. Air is supplied from the bottom of gasifier, and the product gas is piped out from the top.

- Oxidation region (combustion region): In this region, oxygen supplied from the bottom of the gasifier reacts with char produced from biomass pyrolysis to release CO_2 and heat for downstream reactions. The temperature in this region reaches ~ 1200–1300 °C or higher. CO_2 is the main reaction product, with a small portion of CO in some regions where deficient oxygen is supplied.

$$C + O2 = CO_2 \tag{6.1}$$

$$2C + O_2 = 2CO \tag{6.2}$$

$$2CO + O_2 = 2CO_2 \tag{6.3}$$

- Reduction region: CO_2 and steam from the oxidation region are reduced into CO and H_2 during the reaction with biomass char falling down from the regions above the reduction region. The reaction region temperature decreases to about 700–900 °C for the following endothermic reduction reactions:

$$CO_2 + C = 2CO \tag{6.4}$$

$$H_2O + C = CO + H_2 \tag{6.5}$$

$$2H_2O + C = CO_2 + 2H_2 \tag{6.6}$$

$$H_2O + CO = CO_2 + H_2 \tag{6.7}$$

$$C + 2H_2 = CH_4 \tag{6.8}$$

- Pyrolysis region: The main decomposition occurs in the pyrolysis region. Biomass feedstock is further heated by the high temperature gas transferred upwards from lower regions. Thermal decomposition occurs to release volatiles and char which experience further conversion in downstream regions. The temperature in this region should be kept above 400–500 °C.

$$\begin{aligned} \text{Biomass} \xrightarrow{\Delta} &\ \text{Permanent gas } (H_2, CO, CH_4, CO_2, \text{etc.}) \\ &+ \text{Liquid phase} \begin{pmatrix} \text{tar,} \\ \text{and other large molecule compounds, etc.} \end{pmatrix} \\ &+ \text{Char} \end{aligned} \tag{6.9}$$

- Drying region: In this region, fresh feedstock is heated to release moisture by hot gases from the pyrolysis region. Product gas from the pyrolysis region is cooled down to about 100–300 °C holding part of liquid phase products for gas cleaning.

The oxidation and reduction regions can be considered as the main gasification regions with most reactions occurring. Further, the drying and pyrolysis regions can be considered as the preparation regions, wherein the reactants are prepared for the gasification regions. The division of reaction regions in gasification is not as distinct as depicted above with blurred boundaries. As gasification reactions proceeds, the boundary between reaction regions might even move forward or backward, revealing the relative intensity of individual gasification processes.

From the application point of view, it is ordinarily expected that the content of combustible gases such as CO, H_2, and CH_4, should reach as high as possible. From inspecting the main reactions involved in different regions, the reduction region emerges as the vital section that contributes most to the quality and quantity of output gas. High temperature favors the reduction reaction from CO_2 to CO, which indicates that the temperature of the reduction region should be maintained at 700–900 °C. Moreover, the reduction reaction approaches equilibrium if adequate contact between CO_2 and the high temperature char can be guaranteed. However, the CO content in gas product should be strictly controlled in view of safety considerations for domestic cooking applications.

6.2 Biomass gasification system and devices

6.2.1 Biomass gasification system

A biomass gasification system is mainly composed of feeding device, gasifier, gas cleaning and cooling device, gas delivery device, and connecting pipes. According to the device's pressure, the biomass gasification system can be classified into positive pressure system, negative pressure system, and blast-draft combined system, as shown in Fig. 6.2.

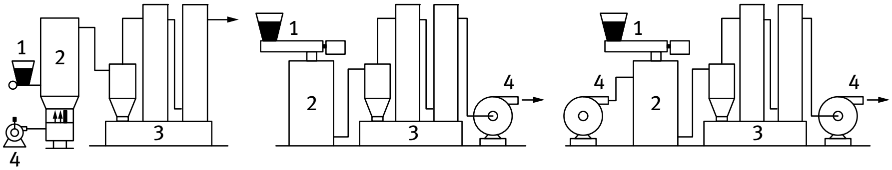


Fig. 6.2: Biomass gasification system.
1. Feeding device, 2. gasifier, 3. gas cleaning and cooling device, 4. gas delivery device

In a positive pressure system, the gas delivery device is positioned in front of the gasifier. The gasifier and the gas cleaning and cooling device are all operate under micropositive pressure. In general, the positive pressure system is adopted in the updraft gasifier and fluidized-bed gasifier. The advantages of the positive pressure system are that gas delivery equipment works in mild condition with clean air as the transport medium at room temperature. Besides, the air pressure is sufficient when entering the gasification device for organizing airflow to achieve ideal working conditions. However, the disadvantage of a positive pressure system is that the feeding point of feedstock is under positive pressure. Therefore, sealing measures must be taken to prevent gas leakage. Usually, the intermittent feeding or dual valve seal is used for the feeding process.

In the negative pressure system, the gas conveying device is positioned at the end of the whole system. The gasifier and the gas cleaning and cooling device are all operate under micro-negative pressure. In general, the traditional downdraft fixed-bed gasifier uses the negative pressure system. The advantages include stability of the system and strong self-balancing ability. Besides, the top of the gasifier can be opened for continuous feeding. Moreover, the feedstock can be forced inside when materials do not move smoothly in order to ensure a completely uniform reaction layer, which prevents problems such as material bridging and perforation in the gasification device. The disadvantages of negative pressure systems include the passive intake of gasifying agent into the gasification device, which results in worse reaction conditions.

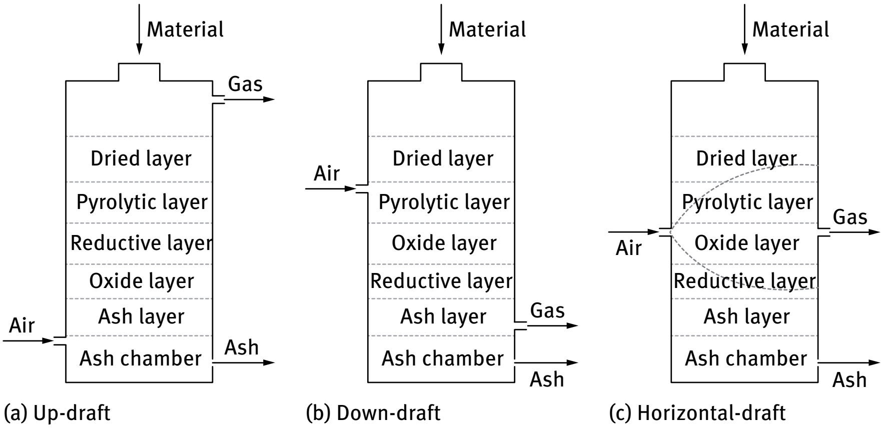
The blast-draft combined system is equipped with a gas conveying device both at the front and at the back of the gasification device in order to control the pressure balance of the system. However, the blast-draft combined system is very sensitive to pressure control and its operation is relatively complex.

6.2.2 Types of gasification device

The biomass gasification process is extremely complex. The reaction process varies with different gasification reactor types, process scheme, reaction conditions, gasification agent types, feedstock properties, and size of ground particles. According to extensive studies on gasification systems, the gasification process is comprising of many independent and consecutive reactions between biomass feedstock, gasification agent, and biomass pyrolysis product, not only including material conversion, but also energy transmission.

A gas generating device, namely the gasifier, is the core equipment of gasification system. According to the flow velocity and direction of combustible gas in the gasifier and biomass materials, gasifiers can be divided into fixed-bed gasifiers and fluidized-bed gasifiers.

In a fixed-bed gasifier the fuel is supported on a grate. Thus a fuel bed is formed between the feeding inlet and the grate. After shredding or briquetting, biomass fuel is fed at the top and moves down slowly by weight. The materials then come into contact with the gasification agent, which then results in the completion of each of the reactions according to the layer level. Compared to the gas flow, the fuel layer moves slowly. Product gas is extracted from the reactor by external device. Ashes are removed from the bottom of the gasifier. Fixed-bed gasifiers exhibit some advantages such as simple structure and high flexibility for feedstock. Nonetheless, the reaction rate and heat load are always relatively low. Therefore, they are suitable for small-scale applications. According to the gas flow direction and the relative position of the reaction layer, fixed-bed gasifiers can be subdivided into updraft, downdraft, and horizontal-draft (crossflow/crossdraft) gasifiers, as shown in Fig. 6.3.



(a) Up-draft (b) Down-draft (c) Horizontal-draft

Fig. 6.3: Types of fixed-bed gasifier.

In an updraft gasifier, intake of the gasifying agent occurs at the bottom. The product gas leaves from top as shown in Fig. 6.3. The fuel bed can be divided into the following layers from the top to the bottom: dried layer, pyrolytic layer, reductive layer, oxide layer, and ash layer. In contrast, the gasifying agent in a downdraft gasifier enters the gasifier at a certain height below the top (usually the dried layer or thermal decomposition layer). The product gas flows downwards and leaves from the bottom of the grate. The gas and solids are in concurrent mode. The fuel bed can be divided into the following layers: dried layer, pyrolytic layer, oxide layer, reductive layer, and ash layer. The gasifying agent in a horizontal-draft fixed-bed gasifier is introduced from one side of the reactor and the product gas is released from the other side. The pyrolytic layer, oxide layer, and reductive layer may be at the same horizontal level.

Fluidized-bed gasifiers usually involve the use of small particles with uniform size as fuel. Fuel enters the gasifier through the gas conveying device. Gasifying agent is usually blown in the form of primary air by a blower from the bottom of the furnace. Sometimes secondary air is introduced to adjust temperature in the upper part of the reactor. Fuel is kept in a semi-suspended condition (fluidized state) blown by the gasifying agent at sufficient velocity. Thus, excellent uniformity of temperature and gas–solid mixing can be obtained. Various gasification media or catalysts can be used conveniently. The fluidized-bed gasifier is the first choice for large-scale and high quality gas production. According to the gas flow velocity in the bed, fluidized-bed gasifiers can be further divided into bubbling fluidized-bed gasifiers and circulating fluidized-bed gasifiers, as shown in Fig. 6.4. For fuels with bad fluidization characteristics, bed materials should be added as fluidizing medium.

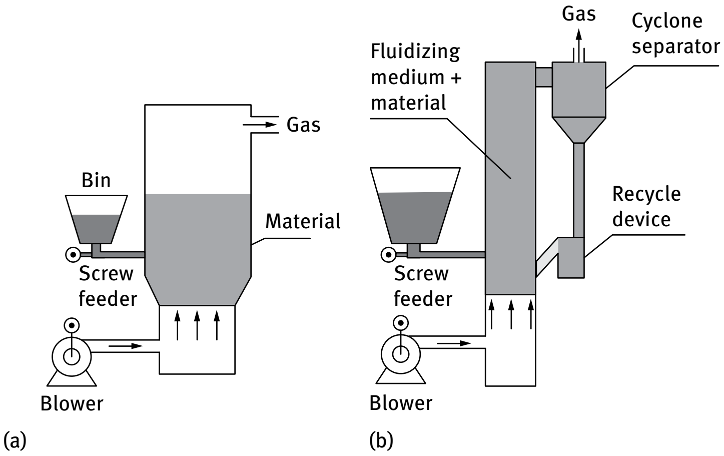


Fig. 6.4: Types of fluidized-bed gasifier.

In a low-speed bubbling fluidized-bed gasifier, the empty bed velocity is usually less than 2 m/s. In order to prolong the residence time of fuel, bubbling-bed gasifiers are specifically designed with the upper part being bigger than the lower part. Biomass fuels are completely fluidized at the bottom of the reactor. In the upper part, the velocity of gas and solid fuel decreases due to the larger area, and sufficient residence time for reaction can be obtained. The empty bed velocity of a circulating fluidized bed is usually designed to be above $3\,\mathrm{ms}^{-1}$. A cyclone separator is employed at the gas outlet to separate solid particles. Most of the carbon particles and bed materials are recycled to the bottom of the gasifier. Circulating fluidized-bed gasifiers require strict pressure control and complex operating mechanism.

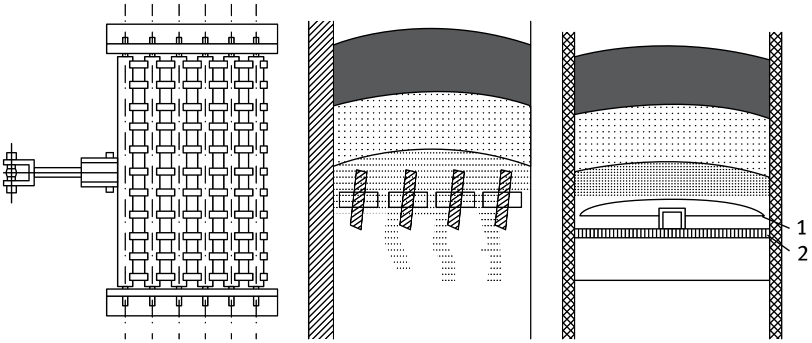
6.2.3 Fixed-bed gasifier and applications

6.2.3.1 Structural characteristics of the fixed-bed gasifier

A fixed-bed gasifier is mainly composed of feeding device, furnace, grate, and ash discharger. In the gasification process, the fuel bed moves down step by step with the fuel consumption. Fuel is continuously supplied to the gasifier through the feed inlet in order to maintain the stability of the gasification process. The feed inlet is at the upper part of the gasifier. Differences in shape, size, density, and gasification mode of the feedstock lead to the selection of various feeding methods, such as pneumatic conveying, auger, belt, bucket elevator, double bell jar, and double flap. A downdraft gasifier which operates under micronegative pressure can be kept open after feeding. Sealed feeding should be employed in an updraft gasifier to prevent gas leakage because both the feeding inlet and gas outlet are in the upper part.

The main role of the grate is to support the fuel bed, and remove ash and loose feedstock layers. Grates can be divided into fixed grate, moving grate, and rotary grate. The moving grates are of three types, namely, reciprocating, turnover, and shifting fork (Fig. 6.5). In turnover and reciprocating grates, active fire bars are connected with an external rocker. Rocker motion drives the movement of the fire bars, and the grate is shaken artificially. That’s what commonly happened in small gasifiers without continuous operation. The shifting fork grate is composed of a fixed grate and a rotating shift fork. Uniform holes are distributed on the fixed grate. The rotating upper fork can make the ash fall into the ash chamber through the holes. The shifting fork grate can be used for small-scale gasifiers. A rotary grate rotates slowly in the furnace and can eliminate material bridges in the furnace and the stirring bin, uniformly distribute wind, and break slag blocks. Ash cleaning can be completely mechanized. Rotary grates commonly used can be divided into pagoda type and fish scale type (Fig. 6.6). A rotary grate can run continuously and it is suitable for relatively large biomass gasifiers.

The ash discharge can be operated in two patterns, intermittent and continuous. Gasifier operation should be stopped when it is subjected to intermittent ash discharge, which is used only for small intermittent gasifier. The ash door is often of



(a) Reciprocating (b) Turnover (c) Shifting fork

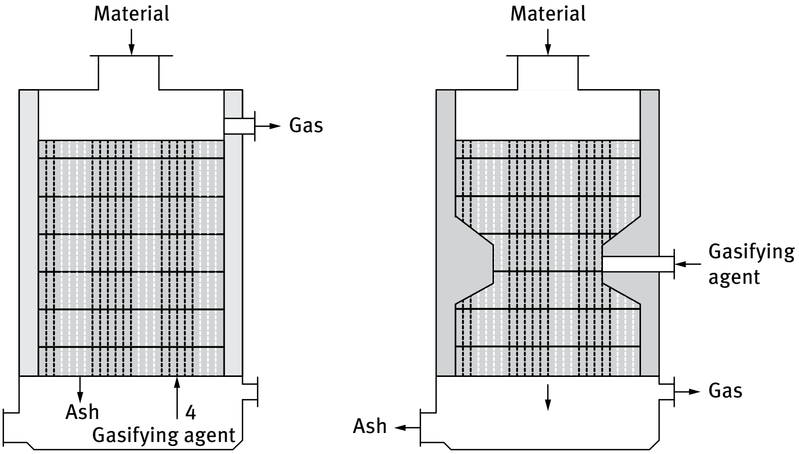
Fig. 6.5: Types of moving grate.

(a) Pagoda type (b) Fish scale type

Fig. 6.6: Rotary grate.

quick-opening form. The structure of a continuous ash discharge device is complex and is suitable for a large-scale continuous gasifier. The pattern of continuous ash discharging can be divided into dry mechanical and water-seal wet ash discharging. The ash discharging space needs to be sealed in dry mechanical mode. A double flip-plate valve discharger or other seal structure can be used to separate the ash discharging space from the furnace cavity during the discharge of the ash. Wet ash discharging uses water seal to prevent leakage.

The furnace chamber of the gasification device is used to accommodate fuel and to provide space for the gasification reactions. The size and shape are determined mainly by the thermal load of the furnace cross section and material properties. The types of fixed-bed furnace chamber generally include cylinder type and shrink type (as shown in Fig. 6.7). The structure of the cylindrical furnace is simple and the feedstock layer moves smoothly. However, the reaction intensity of oxide is not high. It is often used in both updraft gasifiers and downdraft gasifiers. A furnace with a shrink is mainly used in downdraft gasifiers. The shrink mouth is located in the oxidation zone. However, the shrink is apt to form fuel bridges that affect the stability of the gasification process. Considering low intensity and significant volume contraction of biomass carbon after



(a) Cylindrical furnace

(b) Furnace with shrink mouth

Fig. 6.7: Fixed-bed furnace chambers.

pyrolysis, a downdraft gasifier with reverse cone shape shrinking in the lower part has been designed.

A fixed-bed gasification device has a relatively simple structure and reliable operation. It is used widely in China. Currently, the largest capacity of a fixed-bed gasifier has reached 5,000 m^3 h^{-1}. The calorific value of fuel gas produced by air gasification is about 4,000–5,000 kJ Nm^{-3}. In practice, the updraft and the downdraft gasifiers are the most commonly used fixed-bed gasifiers. The horizontal-draft gasifier is less popular. With the significant development of biomass gasification technology in recent years, some novel gasifiers have also emerged, including a two-stage gasifier in which drying and pyrolysis are separated from oxidation and reduction; and a hybrid gasifier that combines the updraft and the downdraft gasifiers.

6.2.3.2 Updraft gasifier

Biomass is fed into the updraft gasifier from the upper part, and it descends by gravity. The gasifying agent enters the gasifier from the lower part of the grate and flows upward through various reaction layers. The product fuel gas leaves the gasifier from the upper part. First, biomass feedstock dehydrates when contacting the rising hot air flow. Second, the pyrolysis reaction begins when the temperature increases to more than 200 °C, with volatiles released gradually, and the remaining carbon reacts with the gasifying agent. On the other hand, the gasifying agent is first heated by ash layer after it enters the gasifier, and then it undergoes oxidation with the carbon in the oxide layer, which results in the production of CO_2, steam, and a large amount of heat leading to a rapid increase in temperature. This upward current undergoes the reduction reaction with hot carbon in the reduction layer, which produces CO, H_2, and other combustible gases. Finally, the airflow mixes with the volatiles from the pyrolysis layer and leaves the gasifier as crude gas.

In an updraft fixed-bed gasifier, the oxide layer is located at the bottom. The gasifying agent and feedstock form a countercurrent flow. Therefore, the updraft gasifier has the advantages of high gasification efficiency, low pressure loss, and low ash content of product gas. When high-temperature gas from the oxide layer flows through the pyrolysis layer and drying layer, heat is transferred to the feedstock for pyrolysis and drying, which improves thermal efficiency. The pyrolysis layer and the drying layer act as filters, which separate ash from the gas. Nonetheless, updraft gasifier exhibits disadvantages such as inconvenient feeding and high tar content. To prevent gas leakage, special sealing measures and a complex feeding device must be employed. Intermittent feeding mode can also be used. The upper part of the gasifier should be sealed when the furnace is in operation. Furnace operation has to be stopped for feeding when fuel is exhausted. Tar from the pyrolysis layer is directly mixed with combustible gas; therefore, the product gas has high tar content. Tar may condense and deposit in pipelines, valves, meters, and gas equipment, which affects the normal operation of the system. The updraft gasifier is generally employed to produce gas that can be used without cooling and purification, for example, to provide fuel gas for a boiler or furnace.

6.2.3.3 Downdraft gasifier

The fuel in downdraft gasifier enters the furnace from the upper part and descends by gravity. Ash is removed from the bottom. Gasifying agent is added in the oxidation zone which is located in the upper or middle part of the gasifier. The gas is drawn out from the lower part. At the top of the gasifier, feedstock is dried first. Pyrolysis reaction begins when the temperature increases to more than 200 °C and volatiles are released gradually. The pyrolysis reaction is substantially completed at 600 °C, where the addition of air causes severe combustion. The combustion reaction uses the carbon layer as the substrate, and further degradation of volatiles occurs in the process of combustion. The combustion products are reduced by the carbon layer and change into combustible gas.

In a downdraft gasifier, the gas flow and fuel flow are in countercurrent mode. Therefore, some shortcomings of the updraft gasifier can be overcome. For example, sealing is not necessary when feeding fuels which makes the fuel feeding more convenient. Thus it is easy to achieve continuous feeding, fuel bed inspection, and fire stirring when the reactor is in running mode. The pyrolysis gas which passes through the hot oxide layer can lead to complete cracking of tar in the gas. Therefore, the tar content of product gas is low. However, the downdraft gasifier has the disadvantages of lower gasification efficiency, larger pressure loss, and higher ash content. High temperature and high content of carbon particles of the product gas lead to lower efficiency of gasification. The gas flows out directly through the ash layer, thus bringing out much ash. Moreover, the pressure drop of fuel bed is high because the gas flows in a direction opposite to the thermal flow.

6.2.3.4 Improved fixed-bed gasifiers

6.2.3.4.1 Two-stage gasifier

The gas produced by traditional fixed-bed gasifiers contains a certain amount of tar, which results in heavy work for the gas purification system. The Technical University of Denmark has proposed a two-stage gasifier to reduce the content of tar, as shown in Fig. 6.8. Biomass fuels first enter into dry-pyrolyzer. Then biomass fuels are dried and pyrolyzed by heating with an external heat source. Pyrolysis gas and char enter into the gasifier and then experience a strong oxidation reaction with air in the oxidation zone for tar decomposition. Subsequently, gas enters into the lower part of the reductive layer to complete the gasification process. The hot product gas can meet the application requirements after simple purification and cooling.

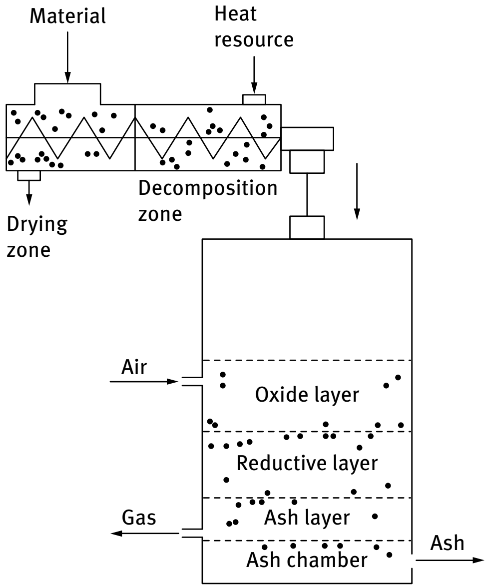


Fig. 6.8: Two-stage gasifier.

The pyrolysis process and gasification process are separated in a two-stage gasifier. Compared to a traditional fixed-bed gasifier, a two-stage gasifier can more effectively provide a stable and uniform high temperature environment. It can ensure the residence time of gas in the reactor and complete decomposition of tar. After pyrolysis, solid fuel changes into char with better mobility. It also overcomes the instability caused by bed material bridges. Practice shows that the reaction process of a two-stage gasifier is stable and uniform. After passing through a cyclone and bag filter, the total content of tar and impurities in the product gas becomes less than 20 mg m^{-3}, which can meet the conventional gas requirements and avoid secondary pollution during gas purification process, thus improving the stability and reliability of the system [106].

6.2.3.4.2 Combined up- and downdraft gasifiers

The Energy Research Institute of Shandong Academy of Sciences has developed the combined up- and downdraft fixed-bed biomass gasifier in order to reduce the tar content in the product gas (Fig. 6.9). The gasifier combines the advantages of both updraft fixed-bed and downdraft fixed-bed gasifiers. The upper part of the gasifier can be kept open for feeding. The gasifying agent which passes into the gasifier from the bottom of the furnace can protect the grate. The central secondary combustion area results in tar cracking. By adjusting the proportion of primary and secondary air and controlling the reaction temperature, the gasifier can achieve controllable gasification. Finally, high-quality gas with low tar content can be obtained. The process exhibits high thermal efficiency and carbon conversion, and the content of tar is very low. The tar content is less than 20 mg Nm^{-3}, calorific value is ~ 4.2–5.0 MJ Nm^{-3}, energy conversion efficiency is more than 80 %, and carbon content in gasification ash is less than 25 % when using air as the gasification agent [107].

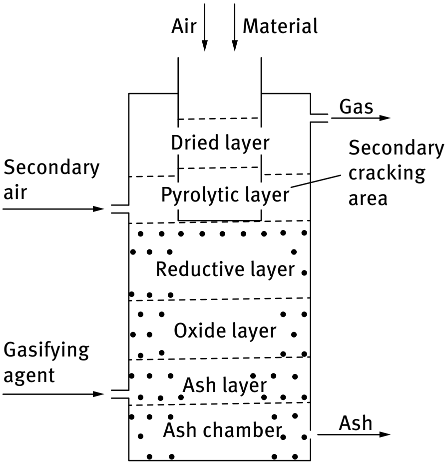


Fig. 6.9: Combined up- and downdraft gasifier.

6.2.4 Fluidized-bed gasifier and its applications

The main gasification reaction that occurs in a fluidized bed is almost identical to that in a fixed bed. Fuel and bed material in the fluidized bed remain in the liquid state. Therefore, the reaction mechanism of the fluidized bed is much different from that of the fixed bed. Based on the fluidization condition in the reactor, fluidized-bed gasifiers are classified into three types: bubbling, circulating, and dual fluidized bed.

6.2.4.1 Bubbling fluidized-bed gasifier

In a bubbling fluidized-bed gasification system (as shown in Fig. 6.10), biomass enters the gasifier through a gas barrier screw-feeder which is located in the lower part of the gasifier. Gasifying agent enters the gasifier through the air distribution plate located in the lower part of the gasifier. Biomass, which is blown by the gasifying agent, stays in a fluidized state. Therefore, the heat and mass transfer is in good condition. The volatile releasing of biomass and the oxidation–reduction reaction of fixed carbon both occur simultaneously in the furnace. Biomass is converted into fuel gas. Ash obtained from biomass leaves with the fuel gas from the upper part of the furnace in the form of fly ash. A bubbling fluidized-bed usually has a conical structure. The bed section varies with height and there is a velocity gradient in the furnace. The sectional area is small at the bottom, but the flow speed is high, thus ensuring the fluidization of large particles. However, the sectional area at the top is large and the flow speed is low, thus preventing the particles from blowing out. Therefore, at certain fluid flow rates, particles with different sizes can be fluidized in the bed. On the other hand, the gas velocity in the fluidized-bed axial direction is basically unchanged and the entrainment of particles in flow is reduced effectively. So the flexibility of the equipment is improved. In general, a steel structure is used for the gasifier, while refractory cement is used as insulation material in the internal part [108, 109].

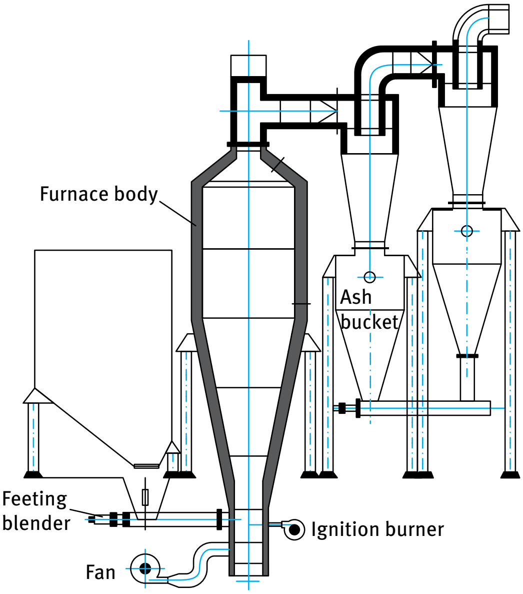


Fig. 6.10: Bubbling fluidized-bed gasifier.

The air used for the gasification inside a fluidized-bed gasifier is provided by the air distribution system (as shown in Fig. 6.11). The air distribution system is located at the bottom of the furnace and is composed of the pressure equalization plenum and air distribution plate. The air distribution plate is composed of plate and blast, which is an important wind distribution device. In a fluidized-bed gasifier, the air distribution plate is also used to support a static fuel layer and prevent leakage. At the same time, the air distribution plate can provide a certain resistance to airflow, which results in obtaining a uniform distribution of airflow velocity and good fluidization conditions.

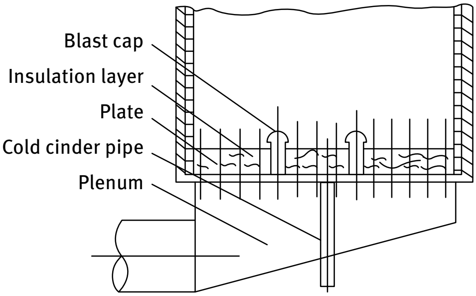


Fig. 6.11: Air distribution system.

6.2.4.2 Circulating fluidized-bed gasifier

In a circulating fluidized-bed gasifier, air enters from the bottom of the air distribution plate and makes the hot bed material (river sand or slag with appropriate particle size) move at boiling state. Biomass enters the gasifier from its bottom. The biomass completes the gasification reaction with air by heating of the hot bed material. The gas and the circulating ash together enter the cyclone separator. After separation of gas and solid, the gas leaves the gasifier. Circulating ash and part of the unreacted carbon fall by the dipleg and return to the gasifier through recycling device. The ratio of the amount of circulating biomass and that of biomass fed is known as the circulating ratio. In general, the circulating ratio of a circulating fluidized-bed is 10–20 [108, 109].

The main bed of a biomass circulating fluidized-bed gasifier (riser) usually adopts a cylindrical structure to ensure an empty tower velocity above 3 m s^{-1}. A cyclone separator is used to ensure the efficient collection of unreacted char. Further, the unreacted char is sent back to the furnace through a recycling device (as shown in Fig. 6.12). The key to circulating fluidized-bed gasification is to achieve efficient separation of high temperature char and its smooth return to the main bed furnace. The separation effect of circulating ash is related to the gasification efficiency and carbon conversion rate. If the separation efficiency is low, the gas brings with it a significant amount of carbon particles, which results in increased losses of mechanical incomplete combustion and pipe blockages. Requirements of a cyclone separator for a circulating fluidized-bed gasifier mainly include high temperature resistance, abrasion resistance, low flow resistance, and the capability to treat a dusty airflow with high concentration (particle content of gas up to 100–300 g m^{-3}). The recycling device mainly completes the reversion and prevents gas channeling to the cyclone separator. When the recycling device transfers circulating ash, it also avoids furnace gas channeling into the cyclone sep-

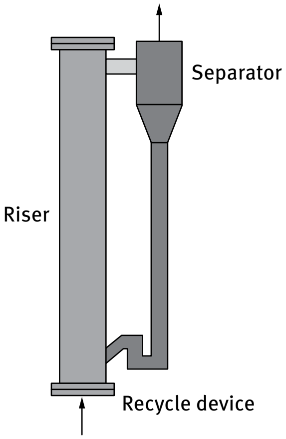


Fig. 6.12: Circulating fluidized bed.

arator which will reduce the separation efficiency. At present, a U-valve (Fig. 6.13) is commonly applied to reverse the backflow and prevent the blowing of the bed material or blockage of the circulating pipe.

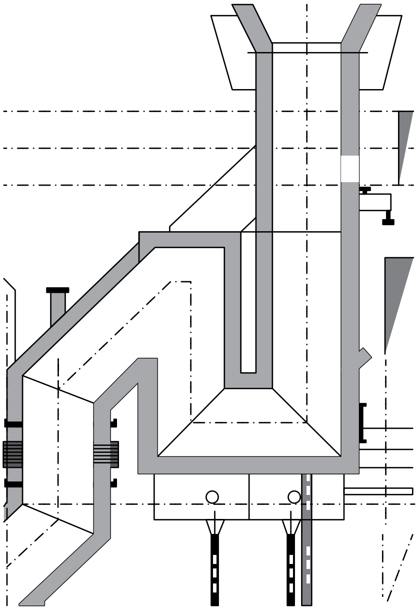


Fig. 6.13: The common type of U-valve recycling device.

6.2.4.3 Factors influencing fluidized-bed gasification

The reaction conditions and factors influencing fluidized-bed gasification mainly include the properties of biomass, the gasifying agent, operating conditions, and conditions of air distribution. This section focuses on the influence of operating conditions on the fluidized-bed gasification process.

6.2.4.3.1 Influence of bed temperature

For the gasification system, an increase in temperature can promote the reduction reaction and secondary cracking reaction of tar. Therefore, the content of CO and H_2 in the gas increases, as well as the calorific value and carbon conversion. The operating temperature of the gasification device is limited by the fusibility of biomass ash. At the same time, different slag discharge modes and requirements for temperature resistance of the furnace lining should be taken into consideration. Thus the operating temperature should, in general, be controlled in the range 700–850 °C.

6.2.4.3.2 Influence of bed material

When the bed material is used as an auxiliary fluidized medium, large size biomass can be used to reduce the difficulty and cost of biomass pretreatment. Without bed material, a fluidized bed can only deal with biomass (particle size below 10 mm) with good fluid characteristics, such as rice husk, sawdust, etc. However, after the addition of auxiliary bed materials such as quartz sand, feedstock adaptability becomes better. The fluidized bed can then deal with biomass (particle size below 10 mm) with poor fluid characteristics, such as guillotine-cut straw, wood chips, etc.

6.2.4.3.3 The distribution of primary/secondary air

For a fluidized-bed gasification device, the proportion of primary/secondary air is related to furnace temperature distribution, gasification efficiency, and quality of gas. Primary airflow should ensure a sufficient fluidized state of biomass at the bottom. Moreover, sufficient oxygen should be supplied to the exothermic reaction to maintain a high temperature condition at the bottom. The role of secondary air is to increase the temperature of the upper furnace body. Secondary air usually enters the gasifier at the juncture between dilute phase and dense phase. Secondary air primarily reacts with combustible components in the dilute zone. It has little effect on the temperature of the bed material layer and mainly affects the temperature in free space (above the secondary tuyere). With the increase in secondary air, the temperature of the space (above the secondary tuyere) obviously increases. After the addition of secondary air, the tar content in the fuel gas decreases significantly. The best ratio of secondary air distribution varies with biomass and gasifying agent. Theoretical calculation shows that addition of secondary air is beneficial to increasing the calorific value of gas, gas production rate, carbon conversion rate, and gasification efficiency, with decreasing tar content in the fuel gas when the ratio of secondary air is below 30 % [108, 109].

6.2.4.3.4 Comparison between circulating fluidized bed and bubbling fluidized bed

The bubbling fluidized bed exhibits the advantages of simple structure, low operating gas velocity, lighter equipment wear, and reliable work. The circulating fluidized bed has the advantages of high gasification efficiency and great gasification intensity. Currently, the circulating fluidized bed is being applied in some large biomass gasification projects. The gasification intensity of a circulating fluidized bed can reach 2,000 kg m^{-2} h^{-1}, which is about 3–5 times higher than that of a bubbling fluidized bed.

6.2.4.4 Dual fluidized bed

Conventional biomass gasification technology has some associated problems such as low gas calorific value and gasification efficiency. Researchers have tried pure oxygen and high pressure gasification to increase gas calorific value. However, these techniques increase the complexity of the equipment and costs of construction and operation. As a new gasification technology, dual fluidized-bed gasification can operate at lower temperature and use air gasification to produce middle calorie gas. Char combustion and volatile pyrolysis are operated in different parts to realize the decoupling gasification of fuel. By circulating ash as a heat carrier, energy for gasification is supplied by combustion and the dilution of the combustion gas for the gasification gas can be avoided. Therefore, gas with improved quality is obtained.

The dual fluidized-bed device is composed of a biomass gasification device and a char combustion furnace, which are coupled by circulating ash. In the gasification process, biomass enters the gasifier, absorbs the heat from high temperature circulating ash, and undergoes the pyrolysis reaction. In the reaction, circulating ash and hard-to-gasify char are transported back to the combustion furnace. Then heat released by burning char is used to reheat circulating ash. As the heat carrier of the double fluidized bed, circulating ash continuously supplies the gasifier with the heat generated in the combustion furnace. The energy balance of the system is crucial for stable operation. Under ideal conditions, the stable operation of the system can be achieved when the energy released by char combustion is greater than that required by the pyrolysis of biomass. Through theoretical analysis and practical test, most biomass can meet the requirement [108].

Dual fluidized-bed biomass gasification is studied by many institutions. However, different furnace structures have been employed. Several typical forms are shown in Tab. 6.1 and Figs. 6.14, 6.15, 6.16, and 6.17.

The combustion furnace of a dual fluidized bed usually adopts a fast bed. Under higher empty tower velocity, high temperature circulating medium is provided by the fast bed to carry energy into the gasifier. Char combustion is a rapid reaction that can release energy in the fast bed with a relatively short residence time. However, the gasification reaction is a slow reaction. To improve the gasification efficiency, many research institutions use different structural forms of gasifier to strengthen the mixing

Tab. 6.1: Different forms of double fluidized-bed gasifier.

No.	Combustion furnace	Gasification furnace	Research Organization
1	Fast bed	Fast bed	Battelle Research Center, Columbus, USA
2	Fast bed	Bubbling bed	Vienna University of Technology, Austria
3	Fast bed	Bubbling bed	Ishikawajima-Harima Heavy Industries Co. Ltd, Japan
4	Fast bed	Two-stage bubbling bed	Ishikawajima-Harima Heavy Industries Co. Ltd, Japan

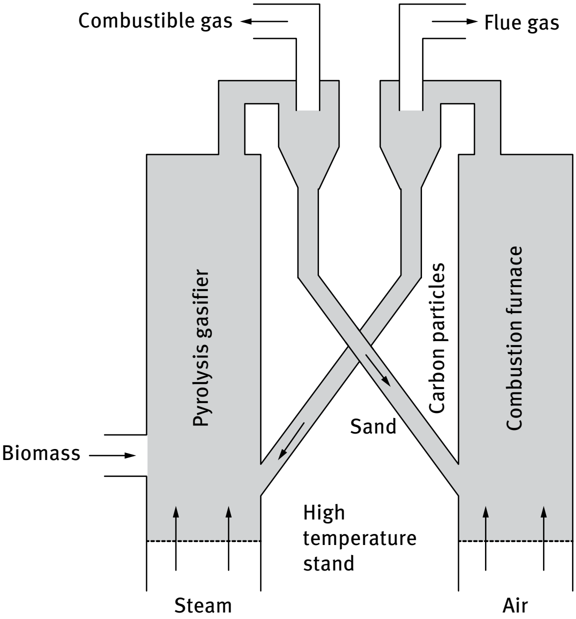


Fig. 6.14: Double fluidized bed developed by Battelle.

of recycled material and biomass and prolong the reaction time. The key to realizing stable operation of a dual fluidized bed lies in the smooth circulation of solid material with energy. Solid materials can pass through the connecting part between gasifier and combustion furnace, thus preventing the mixing of gasifier gas and combustion furnace gas. To ensure the energy transfer from combustion furnace to gasifier, furnace temperature should be kept at 850–1,100 °C. Moreover, improper handling can easily lead to coking. In general, a dual fluidized bed has the advantages of higher gas purity and hydrogen content and calorific value (usually 12–15 MJ Nm^{-3}). However, its structural form is more complex, which leads to difficult start-up and operation. The technical requirements and operation costs of the dual fluidized bed gasifier are relatively high. Although industrial trial operations have been carried out in many countries, it will take some time for the commercial application of the technology.

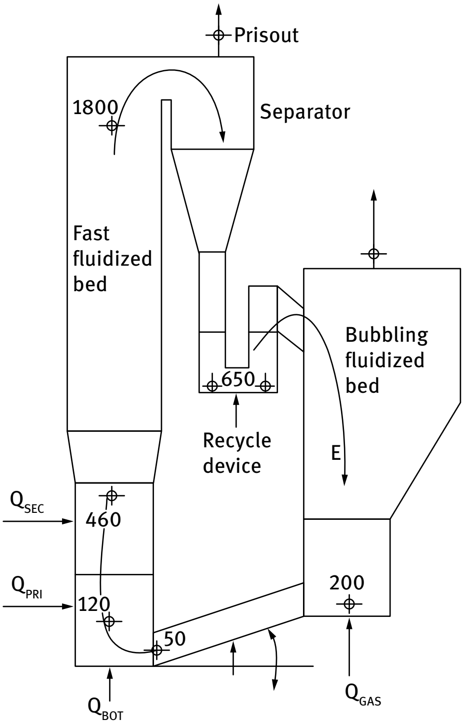


Fig. 6.15: Double fluidized bed developed by Vienna University of Technology.

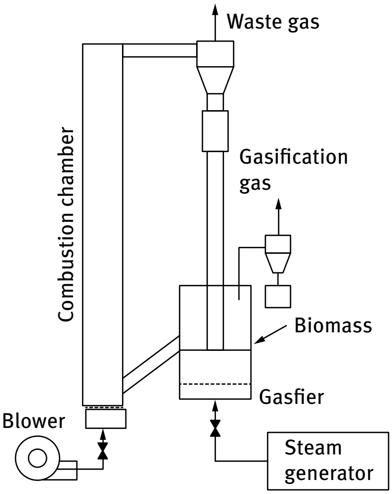


Fig. 6.16: Double fluidized bed developed by Ishikawajima-Harima Heavy Industries.

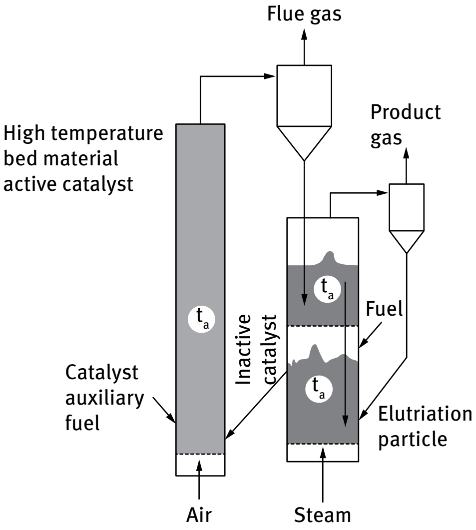


Fig. 6.17: Two-stage double fluidized bed developed by Ishikawajima-Harima Heavy Industries.

6.2.5 Performance and important parameters of gasification devices

Process calculation is the foundation of gasification craft design and engineering construction. The primary parameters that characterize the performance of the gasification device include: gasification intensity, gas quality, gasification efficiency, gasification agent consumption, and gas production capacity.

6.2.5.1 Gasification intensity

Gasification intensity indicates the production capacity of the gasifier, it represents the biomass quantity per cross section area of the gasifier per unit time, and its unit is kg m^{-2} h^{-1}. Gasification intensity is related to device operating conditions, gasifier structure type, and biomass materials. The gasification intensity of fixed-bed gasifiers ranges from 100 to 250 kg m^{-2} h^{-1}, and it can reach up to 2,000 kg m^{-2} h^{-1} [110, 111] for fluidized-bed gasifiers.

6.2.5.2 Gas quality

The evaluating indicators for biomass gas quality mainly include gas composition, calorie, tar content, and dust content. Biomass gas is mainly composed of H_2, CO, CO_2, CH_4, N_2, insignificant amounts of hydrocarbons with low carbon content, and O_2. The higher the volume percentage of combustible gas is, the higher the heat value. The composition of biomass gas is closely related to pyrolysis/gasification device structure and gasification agent properties. Table 6.2 lists some typical data on gas composition for various pyrolysis/gasification device structures. Due to the effects of type of biomass materials and operation conditions, the data listed in Tab. 6.2 can be used for reference purposes only.

Tab. 6.2: Biomass gas composition.

		Gas composition/ %						
		H_2	**CO**	**CH_4**	**CO_2**	**C_mH_n**	**N_2**	**O_2**
Pyrolysis	600 °C	24–25	26–28	15–17	23–26	6.3–6.9	0.5–1.1	0.05–0.8
	800 °C	34–37	19–25	17–19	17–19	4.4–6.3	0.7–0.9	0.2–0.3
Updraft gasification		6.2–10	25–31	4.0–5.2	3.6–4.6	0.3–0.6	46–60	1.0–2.2
Downdraft gasification		11–14	14–23	1.0–3.0	11–16	0.1–0.4	45–58	0.8–2.0
Two-step gasification		13–30	13–20	1.2–4.5	16–19	0.4–1.0	35–48	0.1
Bubbling fluidized bed		4.0–8.0	13–16	3.0–7.0	10–14	1.5–2.9	45–55	0.8–2.0
Circulating fluidized bed		4.0–8.0	14–23	4.0–10	7.0–15	1.0–2.5	45–60	0.8–2.0
Double fluidized bed		18–22	44–45	15–16	11–12	1.0–5.0	0.7–4.0	–

It can be concluded from Tab. 6.2 that the gas produced by pyrolysis in a double fluidized bed has higher quality than that from other gasification devices, because low nitrogen content is introduced into the system. Nonetheless, for other gasification devices, the air used as gasification agent contains 45–60 % nitrogen, which significantly decreases the calorie. Moreover, the CH_4 concentration produced by updraft, downdraft, and two-step fixed-bed gasifiers is low because of the high temperature; however, it increases significantly in a fluidized-bed gasifier with low temperature.

The product gas obtained by air gasification is of low heating value (4,200–7,560 kJ N^{-1} m^{-3}). In contrast, when the same amount of pure oxygen is used as gasification agent, the nitrogen dilution effect is not observed, thus the reaction rate and temperature increase, which can decrease the reactor volume and improve thermal efficiency. Therefore, the gas calorie can increase to 10,000–15,000 kJ N^{-1} m^{-3}. When steam is used as gasification agent, the gasification reactions not only include reduction reaction between steam and carbon, but also the shift reaction between CO and steam, methanation reactions, and biomass pyrolysis reactions. The typical gas composition produced by steam gasification is as follows: 20–26 % H_2, 28–42 % CO, 16–23 % CO_2, 10–20 % CH_4, 2–4 % C_2H_2, 1 % C_2H_6, and 2–3 % C_3, and the calorie is about 17–21 MJ Nm^{-3}. If the steam is mixed with some amount of hydrogen, the gas calorie can reach up to 22,260–26,040 kJ Nm^{-3}. Table 6.3 lists the properties of biomass gas produced by air as gasification agent.

In different gasification units, the content of tar and dust varies a lot. In general, the content of tar and dust of downdraft fixed-bed gasifiers is the lowest. The content of tar and dust of updraft fixed-bed gasifiers and fluidized-bed gasifiers are generally

Tab. 6.3: Properties of biomass gas.

		Density ($kg\ m^{-3}$)	Relative density	High calorific value ($MJ\ m^{-3}$)	Low calorific value ($MJ\ m^{-3}$)
Pyrolysis	600 °C	1.02–1.10	0.79–0.85	17–18	15–16
	800 °C	0.83–0.92	0.64–0.71	17–19	15–17
Updraft gasification unit		1.07–1.25	0.83–0.97	6.1–7.3	5.8–6.9
Downdraft gasification unit		1.07–1.31	0.83–1.02	4.1–5.8	3.8–5.5
Two-step gasification		1.01–1.23	0.78–0.95	5.0–6.2	4.5–5.6
Bubbling fluidized bed		1.04–1.23	0.80–0.95	4.8–6.4	4.5–6.0
Circulating fluidized bed		1.04–1.37	0.81–1.06	5.0–6.5	4.8–6.0
Double fluidized bed		0.95–1.03	0.73–0.79	14–17	13–16

higher than those of downdraft gasifiers. Further, dust content of fluidized-bed gasifiers is the largest and that of updraft fixed-bed gasifiers is the lowest.

6.2.5.2.1 Gasification efficiency

The gasification efficiency of a biomass gasification unit refers to the ratio of calorific value of output gas to the calorific value of used materials.

$$\eta = \frac{V_m H_m}{H} \times 100\,\% \tag{6.10}$$

where η is gasification efficiency; V_m is output gas per kg material ($Nm^3\ kg^{-1}$); H_m is low calorific value of gas ($kJ\ Nm^{-3}$); H is low calorific value of material ($kJ\ kg^{-1}$).

The η of a domestic fixed-bed gasifier is about 75–80 % and the highest η of a fluidized-bed gasifier has surpassed 80 % [112].

6.2.5.3 Air requirement

The calculation of the required air volume for biomass gasification, should be based on the calculation of the theoretical air requirement of complete combustion. Then according to the air equivalence ratio, the actual requirement is calculated. The following formula is used to calculate the theoretical air volume:

$$V = \frac{1}{0.21}(1.866\mathrm{C} + 5.55\mathrm{H} + 0.7\mathrm{S} + 0.7\mathrm{O}) \tag{6.11}$$

where V is the required theoretical air volume of complete combustion ($m^3\ kg^{-1}$); C is carbon content of material (%); H is hydrogen content of material (%); S is sulfur content of material (%); O is oxygen content of material (%).

The air equivalent ratio refers to the ratio of actual air consumption to theoretical air requirement in complete combustion. The air equivalence ratio is dependent on the material type and gasification unit type. When the value of ϕ lies in the range 0.25–0.33, the gas composition is relatively ideal. When the moisture content of material is higher or the content of volatile is lower, the air equivalent ratio should take the upper limit. Therefore, the required air volume of biomass gasification is as follows:

$$\mathrm{VL} = \Phi \mathrm{V} \tag{6.12}$$

where VL is actual required volume of air ($m^3\ kg^{-1}$); V is theoretical air requirement in combustion ($m^3\ kg^{-1}$); ϕ is air equivalence ratio.

6.2.5.4 Output capacity of a gasification unit

The production capacity of a gasification unit is related to its type and structure size. If the cross sectional area of the gasifier is larger, the production capacity is better. At present, the maximum output power of domestic fixed-bed biomass gasification devices has reached 7 MW and that of fluidized-bed biomass gasification devices has exceeded 25 MW.

6.3 Biomass gas purification

The crude gases at the outlet of a biomass gasification unit not only include the light gases such as H_2, CO, CO_2, and CH_4, but also contain impurities such as tar, moisture, and ash content. The presence of impurities can affect the stable operation of the downstream equipment. Therefore, purification of the crude gas is definitely required.

6.3.1 Impurities in biomass fuel gas

Impurities in biomass fuel gas can be divided into solid and liquid impurities. Solid impurities refer to the particulates in the stream of fuel gas, while liquid impurities mainly refer to tar and water condensed at room temperature.

According to different materials and the gasification process, the amount, size, and composition of solid and liquid impurities are also different. Wood materials always contain low ash content, which is commonly 5–10 g m^{-3}. However, straw materials contain higher ash content. The pyrolytic carbon is always weak and light, and it is easy to be carried by the gas. Thus ash content in the gas may be in the order of magnitude of tens of grams per cubic meter. The tar content of the downdraft fixed-bed gasification furnace is low, which is only 0.5–1 g m^{-3}, but the air flows through the ash layer, resulting in more ash content. The fuel gas of the updraft fixed-bed gasification furnace is filtered by the upper material layer, leading to less ash content. However, the tar and water during the drying and pyrolysis process are directly discharged without high temperature pyrolysis, so the tar content is higher, usually up to 50 g m^{-3}. The fluidized-bed gasification furnace has low temperature and high air velocity. Therefore, the tar content in the gas is at the level of 10 g m^{-3}.

6.3.2 Characteristics of biomass tar

Tar is a complex mixture of condensed hydrocarbons. Milne et al. (National Renewable Energy Laboratory, the United States) provided the following definition of tar: any organic materials produced during the heating or partial oxidation (gasification) of the organic matter can be known as tars, which are mainly aromatic hydrocarbons [113].

When biomass material is heated, its molecular bonds break. The smallest molecules are gases, and the larger molecules are called primary tar. Primary tar is usually some fragments of the original biomass structure. Moreover, primary tar under the conditions of gasification is not stable, and it becomes secondary tar in the further reaction. If the temperature is further increased, parts of the tar get converted to third-level tar. The following pathway of tar formation and evolution was illustrated by Elliott [114]:

$$\begin{aligned}\text{Mixed oxygen-containing compounds (400 °C)} &\rightarrow \text{phenol ether (500 °C)}\\ &\rightarrow \text{alkyl phenols (600 °C)}\\ &\rightarrow \text{different cyclic ether (700 °C)}\\ &\rightarrow \text{PAH (800 °C)}\\ &\rightarrow \text{greater PAH (900 °C)}\end{aligned} \tag{6.13}$$

The composition of tar is very complicated, containing more than 200 types of molecules as indicated by analysis with the main ingredients no less than 20 types. The quantity of tar produced by biomass gasification is related to reaction temperature, heating rate, and residence time in the gasification process. The tar yield is highest at about 500 °C. With the extension of residence time tar cracks completely, thus the amount becomes less.

As a by-product of the gasification process, tar has adverse impact on the gasification system and gas equipment. The production of tar reduces gasification efficiency, and the energy contained in tar is difficult to use, thus most of the tar is wasted. Tar is carried by the gas and gradually condenses in the conveying process. It forms a thick liquid, gets easily mixed with water and carbon grains, which can easily get attached to the pipe wall and equipment. It can block pipelines and valves, and lead to corrosive on metals, posing a threat to the safe operation of the system. Tar condensed into tiny droplets is more difficult to burn completely than gas. The incomplete combustion of tar can lead to the production of polycyclic aromatic hydrocarbons (PAHs) and the production of coke which can lead to wear and corrosion problems, and cause pollution and damage to gas utilization equipment. The large content of PAHs in tar leads to high toxicity. Tar and its smell after burning pose a health threat to persons who come into contact with the gasification system [115].

6.3.3 Gas cleaning: method and equipment

Biomass gas purification methods can be divided into the following two categories: physical and thermal chemical methods. The physical method involves the transfer of the impurity from the gas phase, thus achieving the purpose of gas purification, including mechanical separation, electrostatic separation, washing purification, filtration purification, and so forth. The impurities separated by the physical method cannot be directly used, which easily leads to secondary pollution and also results in the waste of energy. The thermal chemical method mainly involves high temperature in the furnace or addition of catalyst for further pyrolysis of tar, resulting in generation of permanent gases containing small molecules, thus reducing the tar production, avoiding secondary pollution, and improving the efficiency of gasification. The dust in gas can be removed through a simple physical separation process, after tar removal.

6.3.3.1 Mechanical separation and purification

Purification by mechanical separation includes cyclone and inertial separators. A cyclone separator is usually used as the first level of gas purification equipment, which is used for removing most of the solid impurities in gas. The gas enters the cyclone and produces a strong rotation around the inner barrel. The dust is separated from the air under the action of centrifugal force and falls into the hopper along the cone, while the gas with the dust removed is discharged into the inner barrel, as shown in Fig. 6.18. The cyclone device is simple, and the removal efficiency for dust particles of more than 10 microns is high. However, the flow resistance is large, so the design should be based on a comprehensive consideration of biomass gas dust properties and the pressure that the gas conveyor can provide.

Inside the inertial separator, particles of larger mass are affected by the inertial force when gas flow direction varies before finally getting separated. The dust removal efficiency of an inertial separator is not so high, usually under 70 %, due to its much simple structure [116].

6.3.3.2 Purification by electrostatic precipitator

An electrostatic precipitator, consisting of a precipitator and a power transformer rectifier unit, is a type of purification equipment that can separate dust from gas using electric field. The electrostatic precipitator exhibits high efficiency and can capture fine dust with particle size smaller than 1 μm. However, the electrostatic precipitator has strict operation requirements regarding the content of oxygen and tar in the

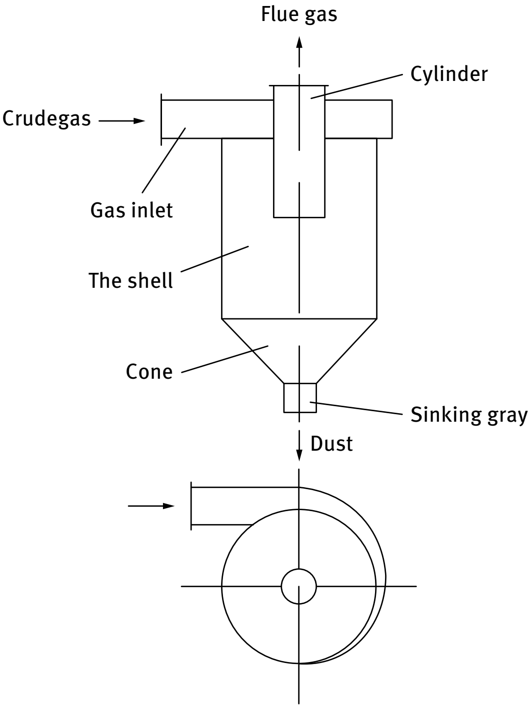


Fig. 6.18: Cyclone.

biomass fuel gas, because tar and dust can easily bind on the electrode and affect the stability and safe operation of the equipment.

6.3.3.3 Purification by wet separation

A spray scrubber can effectively remove dust and tar present in biomass fuel gas and has been widely used in industry. Biomass fuel gas comes into contact with spray droplets while rising in the tower. The solid particles and tar are mixed with water droplets, fall down to the bottom, and then get discharged. Further, the purified fuel gas leaves from the upper side. The spray scrubber can be single-layer or multi-layer according to the requirements for fuel gas purification. A spray scrubber can effectively capture particles with size greater than 1 μm with high efficiency. However, a large amount of water would be consumed; therefore, the wastewater should be purified to avoid secondary pollution.

The working principle of the impact (water bath) separator is as follows: the fuel gas passes the nozzle at a high speed and impacts on the relatively stationary aqueous layer below. As result, a part of the solid and liquid impurities in the fuel gas gets into the aqueous layer due to the inertia effect, and the other part is mixed with the splashing water droplets and air bubbles. Finally, the separated fuel gas can be discharged from the upper side. When the nozzle is above the liquid level, the main force is impact effect, which can efficiently separate large particles. When the nozzle is inserted into the liquid surface, better purification performance can be obtained due to the simultaneous occurrence of impact and shower.

The Venturi tube precipitator works on the principle of the Venturi tube. Small pores are installed in front of the throat to spray water. Water can be crushed into fine droplets after the dust-containing gas passes through the neck at high-speed. As result, the dust particles carried by the fuel gas are captured while the gas keeps on flowing around the droplet, thus achieving the purpose of purification. Venturi tube precipitators are efficient, simple, and can eliminate fine particles with size smaller than 1 μm. However, pressure loss is much higher in this process and a large amount of water is consumed, which may cause secondary pollution.

6.3.3.4 Purification by filter

A bag precipitator is typical of filtration purification equipment and has been widely used in the removal of industrial dust and recovery of small particles. Tiny dust particles larger than 0.1 μm can be effectively filtered and the efficiency is as high as 99 %. Pressure loss of the equipment is generally in the range 300–1,200 Pa, and increases with the running time. The dust on the surface of the fabric should be removed regularly by pulse air blowing or mechanical rapping. Materials for the filter bag should be resistant to high temperature and corrosion. Moreover, the bag precipitator should be suitable to run above 200 °C to prevent the adhesion of tar to the bag at low temperature.

The granular layer filter is another type of simple filtration purification equipment with only granular filtration material filled in the container. The filtration efficiency depends on the particle size, filtration velocity, and the thickness of the granular layer. Higher dust removal efficiency can be obtained with smaller-sized granular filtration material, higher filtration velocity, and thicker granular layer, but accompanied by a significant increase in pressure loss. The impurities in the filtration material have to be eliminated to ensure the normal running of the system, because the resistance increases with the precipitation and accumulation of impurities.

6.3.3.5 Tar removal by thermo-chemical conversion

6.3.3.5.1 Thermal tar cracking at high temperature

It is a simple route to reduce the tar content by gasification at high temperatures to convert tar into smaller noncondensable gases without employing any catalysts. However, an extremely high temperature is necessary to achieve high degree of cracking. As reported in the literature, at the selected residence time of 0.5 sec, the gas flow in a thermal tar cracking unit has to be heated to at least 1,250 °C to achieve sufficient tar cleaning. At 1,290 °C, the tar content is 12–15 mg m^{-3} [117]. To solve the problem of coking caused by local high temperature when tar directly cracks in the material bed, separation of the cracking reactor and the feeding device is required, such as in two-step gasification process, up–downdraft composite gasification process, and so on. Moreover, the content of ultrafine carbon particles in fuel gases increases after cracking at high temperature, which are very difficult to be eliminated.

6.3.3.5.2 Catalytic tar cracking

By using cracking catalyst, tar in the fuel gas can be converted into smaller noncondensable gases at 750–900 °C, realizing deep conversion at relatively low temperatures. Catalytic cracking has become a research focus to eliminate tar in the area of biomass gasification due to the involvement of relatively mild reaction temperature. Several materials including natural minerals, metal materials, and char can be explored as tar cracking catalysts. In particular, limestone, dolomite, olivine, zeolite, magnesite, nickel, molybdenum, iron, and alkali metals have been widely investigated and applied.

Dolomite is a mixture of $CaCO_3$ and $MgCO_3$ with the variation in composition based on its origin. In general, dolomites exhibit the best catalytic performance when the ratio of $CaCO_3/MgCO_3$ is 1–1.5 [115]. Other calcium-based carbonate materials, such as limestone, calcite, as well as magnesite are also low cost, easy to achieve, and highly valuable. As a catalyst for tar cracking, dolomite can be directly added in the gasifier or in the cracking reactor downstream. Dolomite can effectively destroy the phenolic primary and secondary tar, but exhibit limited ability for the conversion of PAHs. When dolomite is added in the gasifier, the tar conversion is mostly below 80 %; however, it increases up to 95 % when used in the secondary cracking reactor downstream. Nonetheless, dolomites show poor mechanical strength, poor thermal stability, lower resistance to attrition in fluidized beds, and the generated ultrafine particulates can be carried out by the gasification gas. Furthermore, sintering and coking occur at high temperature, resulting in damage to the porous structure and loss of activity.

Char is another potential catalyst for tar removal due to its large porosity and high surface area. Char is naturally produced during biomass gasification and mixed with ash, in which the alkaline metal also shows obvious catalytic activity in tar cracking.

Nickel-based catalysts are extensively applied in the petrochemical industry, and a wide variety of nickel-based catalysts are commercially available. Nickel-based catalysts exhibit higher catalytic activity than dolomites and char in tar cracking, and can lead to complete conversion of tar and methane even at 750 °C. Usually, nickel-based catalysts are employed in a cracking reactor downstream. However, nickel-based catalysts are expensive and sensitive to the composition of fuel gas, in which trace amounts of sulfur can poison the catalysts. Furthermore, catalysts also experience rapid deactivation due to carbon deposition.

In recent years, a variety of composite catalysts and monolithic catalysts have also been studied and developed. Composite catalyst combines the high performance of a metal catalyst with the low-cost of a natural mineral catalyst to overcome their individual deficiencies. Furthermore, the catalyst's performance can be significantly improved due to the interaction between the components, such as nickel/dolomite composite catalyst, nickel/magnesite composite catalyst, and so forth [118]. Monolithic catalyst, also named honeycomb catalyst, consisting of carriers, coatings, and the active components, is made up of narrow parallel channels. Monolithic catalyst is significantly different from the traditional granular catalyst, and shows lower bed pressure loss, higher mass transfer efficiency, smaller magnifying effect, as well as easier separation and regeneration [119].

Massive carbon is formed and gets accumulated on the surface of the catalyst in the process of tar catalytic cracking, which affects the catalytic activity. Therefore, water vapor is added in the process to reduce the accumulation of carbon on the surface of the catalyst to prolong the service life. At the same time, water vapor can also promote the steam reforming reaction of the lighter gases obtained from the cracking of tar, thus improving the quality of the fuel gas. For example, naphthalene reacts with water vapor as in following reactions:

$$C_{10}H_8 + 10H_2O \rightarrow 10CO + 14H_2 \tag{6.14}$$

$$C_{10}H_8 + 20H_2O \rightarrow 10CO_2 + 24H_2 \tag{6.15}$$

$$C_{10}H8 + 10H_2O \rightarrow 2CO + 4CO_2 + 6H_2 + 4CH_4 \tag{6.16}$$

6.3.4 Guideline for selecting a gas purification system

In a biomass gasification system, the content of impurities in the fuel gas generally has to be less than 20 mg m^{-3} [112]. The gas purification system is a very important part and directly related to the running stability of the terminal gas equipment. Therefore, designing a suitable gas purification system according to the impurities in the crude fuel gas is highly desirable. In general, the purification system is composed of many purification units to remove solid, liquid, and impurities with different particle sizes, respectively.

A mechanical separator has many advantages, such as being simple and less investment in equipment, reliable running and maintenance, as well as wide operating conditions. Consequently, it has been widely used in industries to remove solid impurities with particle diameter above 10 μm in the fuel gas. In order to reduce the load on subsequent devices, a mechanical separator is often used as the first stage device of gas purification.

A scrubbing separator can effectively remove the tar and solid impurities with size greater than 1 μm present in the fuel gas, exhibiting high removal efficiency and reliability. However, wash water is polluted when the tar is eliminated and needs secondary purification, resulting in high cost.

Filter separator is efficient to remove the fine impurity particles from the fuel gas. Among different filters, bag filters show extremely good performance towards removing fine particles smaller than 1 μm and are used in the final stage of the biomass gas purification system.

Electrostatic separators can capture fine dust with particle size smaller than 1 μm, and with high efficiency. The electrode is sensitive to the content of oxygen and tar in the biomass fuel gas and it is generally used in large-scale fuel gas systems or for fuel gas with high required purity.

6.4 Applications of biomass gasification technology

The development and application of biomass gasification technology is closely related to the pattern of changes in electricity, gas, heat, and other different energy demands. Biomass gasification and its applications undergo continuous development under the above mentioned driving forces. Biomass technology has been applied in several fields, such as central gas supply, power, heating, fossil fuel substitution, chemical synthesis and so forth.

6.4.1 Biomass gasification and central gas supply

The traditional way of biomass used as cooking fuel was gradually abandoned in rural areas to improve living quality. Quality fuels such as natural gas and liquefied petroleum gas became more popular. However, these types of quality fuels were in short supply in rural areas and the prices were also. At the same time a large amount of waste biomass stalks were discarded and burned in the field, which led to environmental pollution and waste of resources. Therefore, gasifier using straw and low quality biomass feedstocks were developed by institutions like the Energy Research Institute of Shandong Academy of Sciences. Low calorific value gas transmission and distribution system and cooking appliances have also been developed. The technology for straw gasification for central gas supply has been developed and hundreds of projects have been established in China.

Biomass gasification and a central gas supply system (as shown in Fig. 6.19) including gasification system, gas purification system, and gas transmission and distribution system has been employed for villages. Downdraft gasifiers are mostly adopted for gasification, which use corn stalk, wheat straw, and other crop residues as feedstock. Gasification efficiency is generally 72–75 % and gas calorific value 4–5 MJ N^{-1} m^{-3}. Gas produced by the gasification unit is cooled down and purified through the cyclone separator, cooling scrubber, and filter. Then the gas is transported to the gas tank by blower (through a water sealer). The volume of the gas tank is decided based on the number of gas-using households and gas production capacity

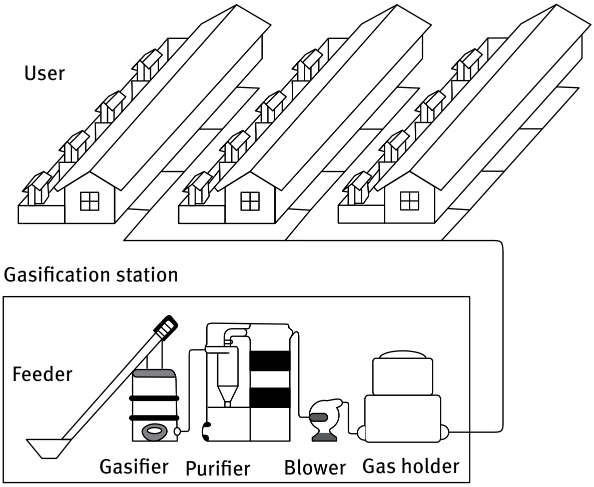


Fig. 6.19: Biomass gasification and central gas supply system.

of the gasification unit. The pressure of the gas tank is designed based on the pressure of the gas burner unit of the farthest user. The gas in the gas tank is transported with the aid of gas pressure and delivered to the final users through flame arrester and low pressure gas pipelines. The indoor system mainly includes the gas meter and the special gas burner for low calorie gas.

The need for cooking gas can be efficiently met by building a biomass gasification station in villages where families are concentrated. Biomass gasification and a central gas supply system have also encountered several problems that have restricted its development. (1) The producer gas contains a large amount of tar, which is difficult to purify. Wastewater produced from multistage filtration and washing should be handled properly to avoid secondary pollution. (2) Using producer gas as cooking gas only would result in intermittent operation of gasification equipments and low economic benefits. (3) Frequent opening and closing of the system would lead to high system failure rate, labor-intensity, and difficulties in maintenance as the tar would adhere to the devices and pipes. The above mentioned problems affect the application of biomass gasification and central gas supply. Therefore, biomass gasification and central gas supply for cogeneration has gradually become popular in rural areas. When gas demand for cooking has been fulfilled, gas can be used for power generation. At the same time the by-product hot water can be used to provide hot water and domestic heating to nearby residents. A typical small distribution energy supply system is formed this way, which can ensure continuous operation and improved economic performance.

6.4.2 Biomass gasification and power generation

Biomass gasification and power generation technology (as shown in Fig. 6.20) is one of the most efficient methods for large-scale utilization of biomass energy. Biomass is transformed into fuel gas. Ash, tar, and other impurities are removed from fuel gas after purification and cooling. Then the fuel gas is sent to the generator for power generation. Electricity can be sent to the power grid or directly supplied to surrounding electrical facilities.

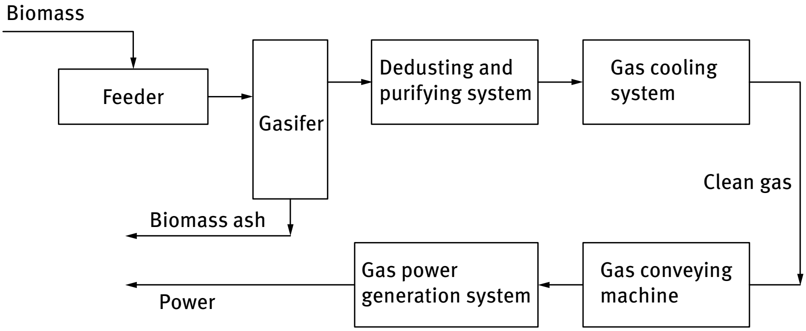


Fig. 6.20: Biomass gasification and power generation flowchart.

Biomass gasification and power generation technology exhibits following three typical characteristics: (1) The technology is flexible. An internal combustion engine or a gas turbine can be used as power generation equipment. Moreover, heat recovery boiler and steam generation systems can also be combined as power generation equipment. Therefore, selection of the appropriate generating set must depend on power generation scale to ensure reasonable power generation efficiency. (2) Compared with fossil fuel power plant, biomass belongs to renewable energy, thus CO_2, SO_2, and other greenhouse gases can be reduced effectively. (3) The economy of biomass gasification and power generation technology is good. Flexible power generation technology can guarantee that the technology is economic at a small scale. Simultaneously, the gas power generation does not involve any high-pressure process and the equipment for power generation is simple, thus investment in gas power generation is less than that in other renewable energy power generation processes. In terms of power generation scale, the system can be divided into small systems (power generation capacity is less than 500 kW), large systems (power generation capacity is more than 3,000 kW), and medium systems (power generation capacity is between 500 and 3,000 kW). The power generation efficiency of small and medium biomass gasification power generation systems is 12–30 %. However, for a cogeneration (CHP) system, the energy utilization rate is more than 60 % [120, 121].

At present, large-scale Biomass Integrated Gasification Combined Cycle (B/IGCC) system and the CHP system are becoming more popular, which mainly use circulating fluidized-bed gasifiers and gas turbines. The electrical efficiency and overall thermal efficiency of the system are both high. Wood and biomass pellet are used as fuel. The main drawbacks of B/IGCC technology include investment and generation costs, which has hindered the promotion of this technology. Small gasification power generation systems are mainly distributed in Southeast Asian countries and primarily use fixed-bed gasifiers and gas engines.

Most of the biomass gasification power generation systems in China are small and medium scale, ranging from kilowatts to megawatts. The generating equipment mainly uses internal-combustion engines. A gasification power generation system has the characteristics of low capital investment and good flexibility of fuel and scale. Power generation efficiency is generally about 20 % when the scale is less than 1 MW. Similarly, power generation efficiency is, in general, about 26–28 %, for projects whose scale is more than 5 MW. Some projects of power generation for biomass gasification are introduced in the following sections.

6.4.2.1 Four MW fixed-bed biomass gasification and power generation

A 4 MW power generation project using a fixed-bed gasifier has been built in Gaoyou, Jiangsu. Gas purification technologies employed in this system include the catalytic cracking of tar, electrostatic tar collector, phenol condensation water recovery, and desulfurization and dechlorination. Gas, electricity, and heat production units are combined in this project. Straw feedstock from rice, wheat, oilseed rape, corn, beans, and a variety of crops can be used as fuel and branches, reeds, and rice husk can also be used. The main technical parameters and economic indicators of the project are listed in Tab. 6.4.

Tab. 6.4: Technical data of a fixed-bed biomass gasification power generation project.

Item	Parameters
Feedstock	Biomass briquette fuel, density: 0.8–1.0, consumption: 3–3.5 million tons/year
Gas production of single furnace	5,000 $m^3\ h^{-1}$, equivalent to 1.76 $m^3\ kg^{-1}$ materials
Gas calorific value	7,100–7,500 $kJ\ m^{-3}$
Gasification efficiency	75–78 %
Content of tar	$< 10\ mg\ m^{-3}$
Content of H_2S	$< 50\ mg\ m^{-3}$
Power generation efficiency	30–33 %
Gas consumption	1.7 $m^3\ kWh^{-1}$, about 1–1.1 kg materials/kWh
Generated energy	30 million kWh/year

6.4.2.2 Rice husk power generation project

MW-level biomass gasification power generation technology and equipment have been successfully developed by organizations such as Guangzhou Institute for Energy Conversion of Chinese Academy of Sciences. Many domestic and foreign biomass gasification power generation projects have been designed. A rice husk gasification power generation project in Changxing, Zhejiang adopts an atmospheric fluidized-bed gasification unit and its power capacity is up to 1.2 MW with the annual energy output up to 4.8 million kWh. The power generation system of this project includes a cooling and purification system, internal combustion set/power transmission and transformation system, and tar washing wastewater/ash removal system. Most fly ash in the gas must be removed in hot state by an inertial duster and cyclone separator. Then the rest fly ash and tar are removed in two stages with a Venturi tube and a spray scrubbing tower. Simultaneously the gas must be cooled to room temperature. After purification, the gas enters into gas tank, and then sent into gas generator set which is composed of many internal combustion engines in parallel to produce power. Part of the ash is used as bed material because of the high content of rice husk ash and no other bed material is needed. The remaining ash is discharged by a spiral dry continuous ash system at the bottom of the gasification unit. Discharged rice husk ash is bagged for sale or used for casting insulation materials. Wastewater from the gasification system is treated by water treatment system and then recycled. The process is shown in Fig. 6.21 and technical parameters and technical indicators are listed in Tab. 6.5.

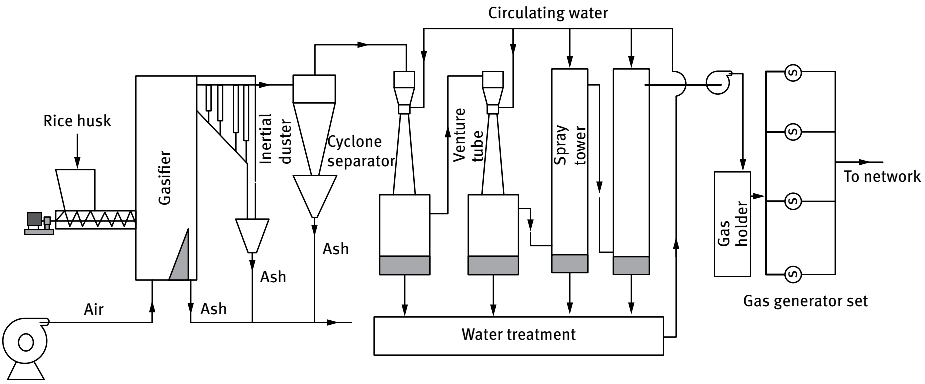


Fig. 6.21: Fluidized-bed gasification power generation scheme.

6.4.2.3 3 MW cone fluidized-bed biomass gasification power generation project

A 3 MW cone fluidized-bed biomass gasification generator has been developed by the Institute of Chemical Industry of Forest Products CAF. Biomass is separately sent to buffer storage bins of three gasification units. Then biomass feedstock is sent to the

Tab. 6.5: Technical data on a fluidized-bed biomass gasification power generation project.

Item	Parameters
Feedstock	Rice husk, moisture < 15 %, feed rate 400–1,500 kg h^{-1}
Gasifying agent	Air, hot fluidizing velocity 0.8–1.2 m s^{-1}
Gas production	500–3,000 Nm^3 h^{-1}
Operating temperature of gasification unit	700–800 °C
Gasification unit	Atmospheric fluidized bed
Gasquality	Calorific value 5,453–6,407 kJ Nm^{-3}
Power generation efficiency	18 %
Power generation equipment	Many 200 kW internal combustion engines in parallel, discharge temperature 500 °C

fluidized-bed gasifier by screw feeder at the bottom of the buffer storage bins with the feeding speed controlled by a frequency converter. A conical gas distributor is adopted for the fluidized-bed gasification furnace. The distribution of gasifying agent is uniform and maintenance is convenient. Combustible gas generated by the reaction first enters the cyclone separator for dust removal. Then it enters the spray scrubbing tower or other washing equipment for cooling. Finally, after further removal of tar and other impurities by the electrostatic precipitator, it enters the gas tank. Then the gas is transported to various internal combustion engines for power generation. The dust collected by the cyclone separator is pneumatically transported to the ash bin. The water from the spray tower can be recycled after cooling. A site picture of the project is shown in Fig. 6.22 and the technical indexes and parameters of the project are listed in Tab. 6.6.

Fig. 6.22: Site view of the Philippine biomass gasification power generation project.

Tab. 6.6: Technical indicators of the biomass gasification power generation project in the Philippines.

Item	Parameters
Feedstock	Rice husk, consumption 1.70 kg kwh^{-1}
Gasification unit	3 cone fluidized beds
Gasifying agent	Air
Rate of gas production	1.63 m^3 kg^{-1}
Reaction temperature of gasification unit	700–850 °C
Power generation unit	8 internal combustion engines of 500 kw
Power generation efficiency	25 %
Efficiency of entire system	15 %

6.4.2.4 500 kW fixed-bed biomass gasification multi-energy cogeneration system

To improve the utilization of biomass energy, a combined cooling, heating, and power (CCHP) tri-generation system was applied as an important application for biomass producer gas. A 500 kW fixed-bed biomass gasification multi-energy cogeneration system (as shown in Fig. 6.23) has been designed by the Energy Research Institute of Shandong Academy of Sciences. The system is composed of gasifier, waste heat boiler, gas purification system, gas genset, and waste heat utilization system. Combined up- and downdraft fixed-bed is adopted for the gasifier. Moreover, the gas is heated to 1,000 °C by a high temperature regenerator and the tar in the gas is cracked into small

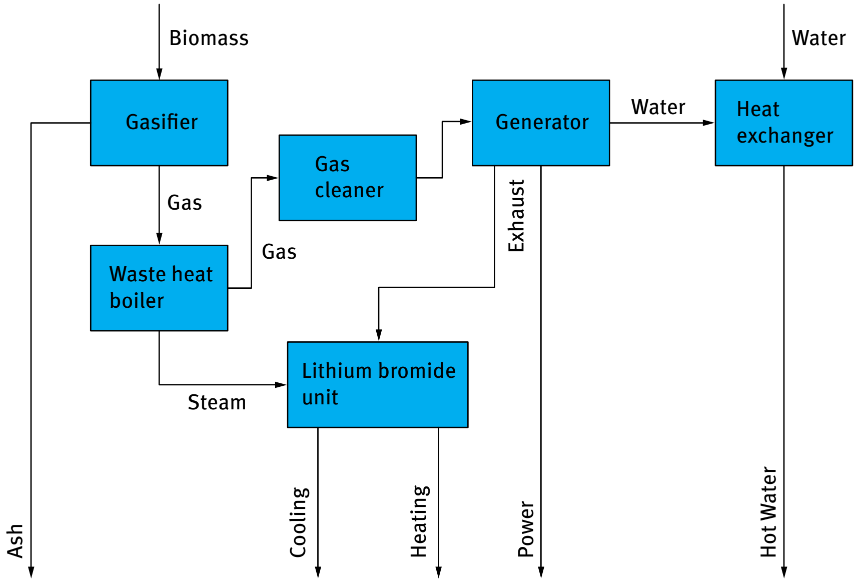


Fig. 6.23: Flow of biomass multi-energy cogeneration system.

molecule combustible gases under high temperature. After being discharged from the gasifier, high temperature gas enters into the waste heat boiler to exchange heat for steam production. After further purification and cooling, the gas is input to the internal combustion engine, and the genset is driven by the internal combustion engine to produce electricity for the grid. The high temperature gas discharged by the internal combustion engine and the steam produced by the waste heat boiler enter into a double-heat lithium bromide air conditioning unit. The high temperature gas and steam are used to generate heat in winter and cooling in summer. Hot water can also be provided to nearby buildings by using the heat which is brought by the internal combustion engine external circulation cooling water system. The gas generated by the system can also be transported by pipelines to nearby residents to be used as cooking gas. By the cascade utilization of waste heat, the system realizes the cogeneration and co-supply of cooling, heating, power, and gas. The overall energy utilization efficiency of the system is improved significantly.

6.4.3 Biomass gasification gas as substitutive fuel

Gas produced by gasification can be used to replace traditional fossil fuels as fuel for gas boilers or various industrial furnaces, producing hot water, steam, high temperature flue gas, and other types of heat sources that can be used in district heating or industrial applications. With biomass as a clean energy resource, the utilization of biomass gas as fuel gas can eliminate the pollution caused by fossil fuel burning.

In a centralized heating system powered by biomass gasification, fuel gas from a gasifier is sent to burners to provide heat to the end users. This system is relatively simple and provides high thermal efficiency. Biomass feedstock enters the updraft gasification unit through the feeding system. Gas produced by gasification is sent into gas-fired hot water boiler burners after dedusting. Feed water is heated by burning gasification gas and hot water is sent to the users through a water circulation system in order to fulfill the heat requirements. Better combustion can be obtained by using a gas-fired boiler furnace, reasonable air distribution, dedicated combustion arrangement. Compared to traditional solid biomass direct combustion, the burning of gasification gas has many advantages such as high thermal efficiency, complete combustion, and lower emissions of dust, poisonous and toxic gas, tar, and other harmful substances.

Presently, significantly larger biomass gasification units have been installed to implement the commercialization of biomass gasification gas for district-level heating. A centralized heating project in Lian Yungang has been demonstrated for heating the Flower Park. The project includes a set of biomass gasification units, a 500 m^3 dry gas tank, and a 1.4 MW biomass gas boiler, which can provide heat for 14,000 m^2 of greenhouse in winter.

The application of biomass gasification gas as a clean alternative energy in industrial boilers is popular worldwide [122, 123]. To reduce operating costs and emissions, oil-fired boilers with a specified evaporation rate of 8 t/h can be converted to use biomass gasification gas as fuel. The system of the project is mainly composed of feedstock storage, feeding devices, fixed-bed gasifier, gas purification and transportation systems, burner, and boiler. The chips (via feeder, bucket elevator, feed screw) enter the gasification unit from the top. The gasifying agent enters the gasification unit through the blower. The combustible gas is produced by chips in the gasifier, and then it is transported to the boiler burner by a fan after purification and dedusting by a cyclone separator. Further combustion of the gas provides heat for the boiler, and steam is produced. In the economizer, water is preheated by boiler exhaust gas, and then the boiler exhaust gas is discharged from the chimney. The process is shown in Fig. 6.24.

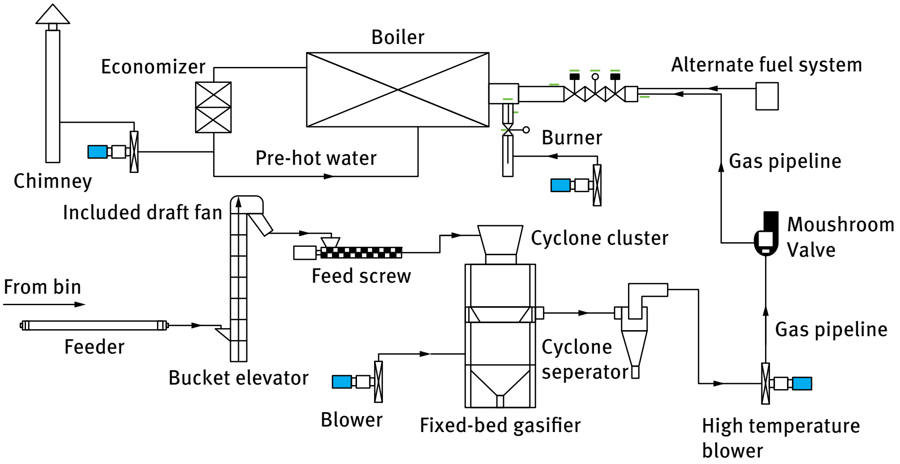


Fig. 6.24: The application of biomass gasification gas in a gas-fired boiler.

In this process, fuel oil can be used as standby fuel to ensure normal operating of boiler production when the biomass gasification equipment undergoes maintenance or in an emergency shutdown. After that retrofitting, the reduction in emissions of SO_2, dust, and CO_2 are 51.4, 10.0, and 13,500 tons, respectively, in this project. The technical parameters and indicators of the project are listed in Tab. 6.7.

In a steel bar production line in a steel enterprise in Guangdong, biomass gas is used in the heater before billet rolling to replace the original heavy oil fuel. Technical parameters and indexes of the project are listed in Tab. 6.8.

In a thermal power plant in Jingmen, Hubei, gas produced by biomass gasification is sent into a coal-fired boiler. Then the co-combustion of the mixed gas and pulverized coal replaces part of the coal load. After simple preprocessing, the biomass undergoes efficient gasification in the fluidized-bed gasifier. Further, after purification and de-

Tab. 6.7: Indicators for the biomass gasification and gas utilization project in Qingyuan.

Item	Parameters
Biomass	Chip consumption 2t/h
Gasifying agent	Air
Gasification temperature	700–900 °C
Gasification efficiency	> 80 %
Gas quality	Calorific value > 5,400 kJ Nm^{-3}, temperature > 350 °C
Efficiency of gas-fired boiler	> 99 %

Tab. 6.8: Technical indicators of biomass gas replacement project, Guangdong.

Item	Parameters
Feedstock	Biomass briquette fuel
Gasification unit	LQX fixed-bed gasifier
Gas production of single furnace	5,000 Nm^3 h^{-1}
Gas quality	Low calorific value 5,093 kJ Nm^{-3}
Gas consumption	22,090 m^3 h^{-1}
Form of the heating furnace	Regenerative

dusting, the gas produced by biomass gasification is directly sent into the large power station boilers. Then the gas and pulverized coal are burned to produce steam. Finally, high power generation can be achieved by using the original steam turbine generating system. The main technical parameters and process indicators of the project are listed in Tab. 6.9.

Tab. 6.9: Technical indicators for the biomass gas heat utilization project in Jingmen.

Item	Parameters
Feedstock	Calorific value 14.7 MJ kg^{-1}, consumption 8t/h
Gasification unit	Circulating fluidized-bed gasifier
Gas production	18,110 Nm^3 h^{-1}
Gas quality	Calorific value 5,000–6,000 kJ Nm^{-3}, temperature > 400 °C
Temperature of gasification unit	750–850 °C
Heat efficiency of gasification unit	> 90 %
Generated power	10.8 MW
Generation efficiency	> 33 %

6.4.4 Applications of biomass gasification in chemical synthesis

Gasification gas can be effectively utilized as a feed gas for chemical synthesis processes. Hydrocarbon fuel, alcohol chemicals, and ammonia for synthesis applications can be obtained by catalyzed synthesis technology. Directional gasification, gas cleaning, and conditioning have been applied for synthesis gas production [122, 124].

Unlike conventional gasification, the purpose of directional gasification is to produce chemical synthesis gas, in which the content of H_2 and CO needs to be improved for easing downstream molecular reorganization. In general, the following methods are adopted to realize directional gasification.

(1) Increasing the gasification temperature. Studies have shown that high gasification temperature favors the increase in H_2, CO, and CO_2 content with a decrease in hydrocarbons.
(2) Use of steam and oxygen as gasifying agents. Reforming, water-gas shift reaction, and other reactions can occur between steam and hydrocarbons, resulting in improved content of H_2 and CO. As a gasification agent, O_2 not only improves the gasification, but also avoids dilution by N_2.
(3) Prolonging the reaction time: With longer reaction time, the cracking of tar and other macromolecules in gas would be more prominent.

The gas conditioning process is mainly composed of purification, reforming, and water-gas shift reaction. The purpose of gas purification is to prevent the fine dust particles and microdroplets of tar in the gas from entering into subsequent processes. Ceramic filters can be used in gas purification. During gas reforming, hydrocarbon components and tar in the gas react with steam to generate H_2 and CO. Water-gas shift reaction leads to an increase in the H_2 content, during which the ratio of H_2/CO in the gas is adjusted to meet the final requirement of chemical synthesis process. For example, the optimal ratio for $H_2/(2CO + 3CO_2)$ in methanol synthesis is about 1.05.

6.4.4.1 Ammonia synthesis project in Finland

Ammonia obtained from gasification gas is used to produce fertilizers in a chemical plant in Finland, with peat being used as feedstock. The moisture content of crushed peat is decreased from 40 to 15 % before sending it to the gasifier where a mixture gas containing CO and H_2 is generated. Then the mixture gas and N_2 are used to synthesize ammonia. Further, ammonia is used to produce chemical fertilizers to meet agricultural needs. A mixture of peat and sawdust as fuel has also been proven to be feasible. The main technical parameters and process indicators of the project are listed in Tab. 6.10.

Tab. 6.10: Technical indicators for the biogas ammonia synthesis project in Finland.

Item	Parameters
Feedstock	Peat, consumption 23t/h
Gasification unit	Pressurized fluidized bed
Gasifying agent	O_2 290 Nm^3/t, steam 160 kg/t
Gasification temperature	750–950 °C
Gas components	CO 35 %, H_2 32 %, CH_4 6–8 %, CO_2 22 %
Gas production	Purified mixture of CO and H_2: 925 Nm^3/t
Carbon conversion of gasification	88 %

6.4.4.2 Hundred-ton pilot project for the synthesis of dimethyl ether

The test system for the project to produce 100 tons/year dimethyl ether (DME) was built in 2006 in Jinan by the Energy Research Institute of Shandong Academy of Sciences and Guangzhou Institute of Energy Conversion, CAS. In this system, a two-stage fixed-bed gasification process is adopted, with corncob as the feedstock and O_2-enriched air as gasifying agent. High-temperature bag filters and indirect water-cooling are applied for purifying the syngas. The syngas produced (after turbochargeing decarbonization, and deoxidation) is converted into DME through one step synthesis, and then a distillation system is adopted for product refining. The flowchart for the DME synthesis process is shown in Fig. 6.25. Fig. 6.26 provides the site view. The system's technical indicators and process parameters are listed in Tab. 6.11.

Tab. 6.11: Technical indicators for the biomass DME project in Jinan.

Item	Parameters
Gasification unit	Two-step fixed-bed gasifier
Main component of synthesis gas	H_2 25–38 vol. %, CO 25–38 vol. %, CO_2 16–25 vol. %
Synthesis temperature	260–270 °C
Synthesis pressure	4.2–4.4 MPa
Synthesis tower airspeed	650–1,000 h^{-1} and 1,200–1,500 h^{-1}
Single pass conversion rate of CO	82.00 % and 73.55 %
Selectivity of DME	73.95 % and 69.73 %

6.4.4.3 Thousand-ton cogeneration project of low-carbon mixed alcohol and DME

A demonstration project involving thousand-ton oxygenated liquid fuel production from biomass gasification has been built in Foshan by Guangzhou Institute of Energy Conversion, CAS, at the end of 2013. The system uses a biomass fluidized-bed gasifier to produce syngas and then oxygenated liquid fuel (cogeneration of low-carbon mixed alcohol and DME). After crushing and drying, biomass feedstock is sent into the fluidized-bed gasification unit to produce crude gas with low tar. Ash in the crude gas is removed by high temperature inorganic membrane filtering. The tar is con-

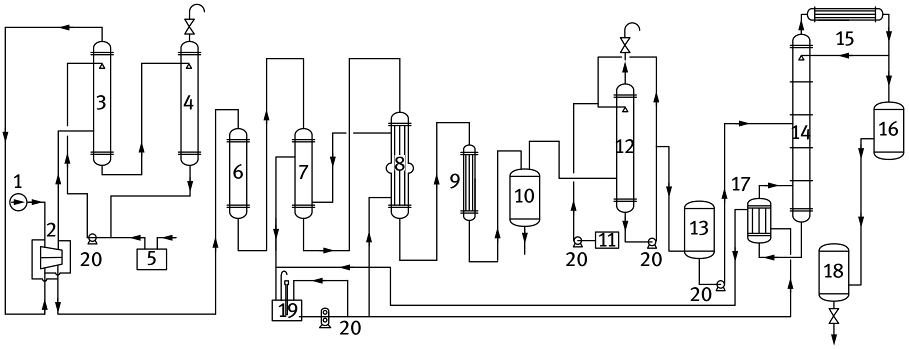


Fig. 6.25: One-step DME synthesis from biomass gas.
1. Synthesis gas inlet, 2. compressor, 3. decarbonization tower, 4. regeneration tower, 5. propylene carbonate storage tank, 6. adsorption tower, 7. deaeration tower, 8. converter, 9. condenser, 10. gas–liquid separator, 11. soft water flume, 12. absorption tower, 13. intermediate storage tank, 14. distillation column 15. overhead condenser, 16. overhead storage tank, 17. reboiler, 18. finished tank, 19. heat transfer oil stove, 20. circulating pump


(a) (b)

Fig. 6.26: Site view of hundred ton capacity biomass DME project.

verted by catalyst loading on the filter surface to adjust the ratio of H_2/CO. Deoxidation of biomass syngas produced by the gasification system can be completed after gas buffer storage. Then the syngas is sent into an oxygenated liquid fuel converter after compressor booster, decarburization, and deep purification. Oxygenated liquid fuel is separated from tail gas by condensation and soft water absorption. Part of the tail gas is recycled to the converter while the rest is sent into the internal combustion engine to provide power for compressors and other equipment. High alcohols and DME are obtained by simple distillation purification of oxygenated liquid fuel. Figs. 6.27 and 6.28 show the process of this project. The main technical parameters and indicators are listed in Tab. 6.12.

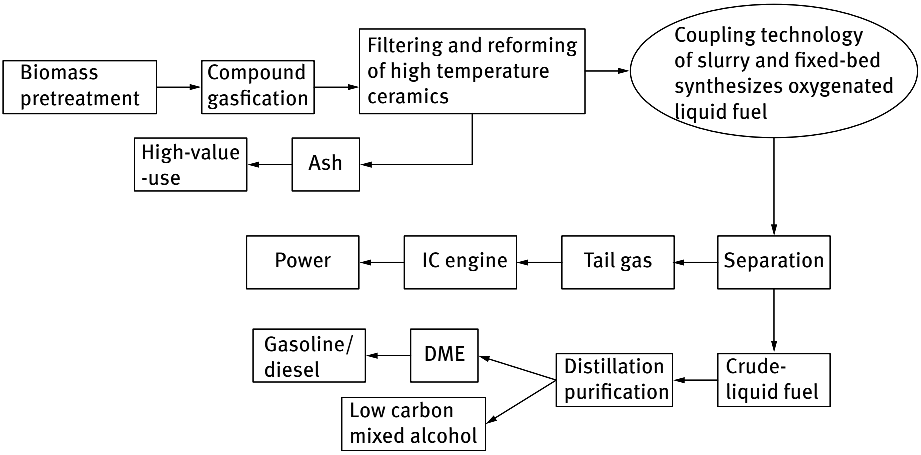


Fig. 6.27: Flow chart for biomass gasification for industrial synthesis.

Fig. 6.28: Demonstration system of biomass gasification for oxygenated liquid fuel synthesis.

Tab. 6.12: Technical indicators for the chemical synthesis project in Foshan.

Item	Parameters
Gasification unit	Fluidized-bed gasifier
Efficiency of gasification system	≥ 80%
Synthesis gas quality	Tar content ≤ 10 mg Nm^{-3}; ratio of $H_2/CO \geq 1.1$
Conversion of synthesis system	Single pass conversion of low carbon mixed alcohol CO > 50 %, C_2 of alcohol product + alcohol selectivity > 60 %
Total efficiency of system	> 38 %

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Index

Anaerobic digestion 146
automatic control system 265

Bag precipitator 317
bio-diesel 3
bio-ethanol 3
bio-gas 3
biodiesel 18
biofuel 11, 145
biogas 145
biogas projects 16
biogas storage cabinet 190
biomass 1
biomass carbon-based slow-release fertiliser 273
biomass combustion 101, 103–105, 107–115, 117, 131, 132, 135, 137, 140, 141
biomass energy plan 22
biomass gasification system 293
biomass molding fuel 19
biomass oven 117, 119, 120
biomass power generation 20
biomass resources 1
biomass utilization technologies 4
bubbling fluidized bed 303
Burning Heat Supply 281

Cellulosic ethanol 17
central gas supply 320
chemical synthesis 330
Chinese Biomass Energy Consumption 5
circulating fluidised bed boiler 267
circulating fluidized-bed 304
combustion 1
Concepts of biomass briquetting fuel 223

decarbonization 203
dehydrationprocess 201
deoxidation 212
desulphurization 194
dimethyl ether 331
Direct-fired boiler 267
down-draft 296, 300
Dry anaerobic digestion 179
dual fluidized bed 307

fermentation bacteria 149
Fixed-bed gasifier 297
fixed-bed gasifier 295
flat die extrusion briquetting technologies 245
Fluidized bed 296
fluidized-bed 302

Gas cleaning 315
gas cooking stove 272
Gas quality 310
gasification 289
Gasification intensity 310
gasification reaction 291
gasifier 295
Gasifying agent 290
gasifying, and burning devices 269
grate 297

Homoacetogenic bacteria 150
horizontal-draft 296

Industrial Production System 261

Liquid fuel 10
low-carbon mixed alcohol 331

Methanobacteriales 152
Methanococcales 153
Methanogenic bacteria 150
methanogenic pathway 146
Methanomicrobiales 153
Methanopyrales 154
Methanosarcinales 154
multi-energy cogeneration 326

power generation 322
pre-treatment 159
purification and upgrading 193

reactor 166
ring-die extrusion briquetting technology 237
rod-like fuel briquetting system 257

https://doi.org/10.1515/9783110344349-008

Scaled Production of Biomass 275
screw extrusion press 258
scrubber 316
segmented burning equipment 268
semi-gas cooking stove 272
storage and transportation 162
Substitutive Fuel 327

Tar 314
tar cracking 317
Trends for Biomass Briquetting Fuel 282
Two-phase anaerobic fermentation process 185
two-stagegasifier 301

up-draft 299
updraft 296

Venturi-tube precipitator 317

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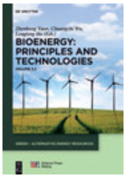

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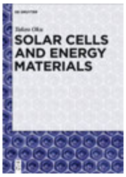

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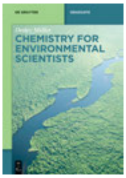

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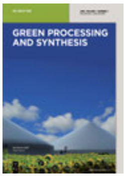

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