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Biomass Gasification: An Overview of Technological Barriers and Socio-Environmental Impact

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<http://dx.doi.org/10.5772/intechopen.74191>

Abstract

Biomass gasification has been regarded as a promising technology to utilize bioenergy sustainably. However, further exploitation of biomass gasification still needs to overcome a significant number of technological and logistic challenges. In this chapter, the current development status of biomass gasification, especially for the activities in China, has been presented. The biomass characters and the challenges associated with biomass collection and transportation are covered and it is believed that biomass gasification coupled with distributed power generation will be more competitive in some small communities with large amount of local biomass materials. The technical part of biomass gasification is detailed by introducing different types of gasifiers as well as investigating the minimization methods of tar, which have become more and more important. In fact, applying biomass gasification also needs to deal with other socio-environmental barriers, such as health concerns, environmental issues and public fears. However, an objective financial return can actually accelerate the commercialization of biomass gasification for power and heat generation, and in the meantime, it will also contribute to other technical breakthroughs.

Keywords: biomass gasification, gasifiers, tar removal, socio-environmental impact

1. Introduction

Fossil fuel is on the verge of depletion in this century. Scientists and governments around world are looking for new energy resources which could be used safely and efficiently with enough amount for deployment and security. Bioenergy is a renewable energy, which

is stored in the organic form in the chemical state and supports human beings' daily life since our ancestor apes knew how to use fire to cook. In these millions of years, bioenergy was mostly used in small scale like household cooking. Now, people have realized that efficient exploitation of biomass resource can actually reduce their dependency over fossil fuel. Biomass gasification has been regarded as an effective pathway to utilization of bioresource. It takes biomass as raw materials and employs pyrolysis or thermal cracking under anoxic conditions. This is an energy conversion process including a group of complex chemical reactions that large organic molecules degrade into carbon monoxide, methane and hydrogen and other flammable gases in accordance with chemical bonding theory. Biomass feedstock with the gasification agent is heated inside an integrated gasifier. With temperature increase, biomass goes through dehydration, volatilization and decomposition. Eventually, the produced gases are used for central gas supply and power generation. This technology has already been developed over several decades and progressively achieved commercialization all over the world, especially in Sweden, Germany, Canada, the United States, India and China. In the early stage, downdraft gasifier had been implemented at a large scale in China and India due to its relatively low tar production. Recently, the development of circulating fluidized bed (CFB) gasifier makes it adaptable for both biomass quality and the raw particle size. Besides, CFB is also easy for scale-up and ash cleaning.

China, as a large agricultural country, produces a large number of crop straw, poultry manure, agricultural by-products and other plant biomass every year. Thus, research and development on key technologies and integrated peripherals of biomass gasification become very necessary. China has already developed various gasifiers, the size of which range from 400 KW to 10 MW. However, compared with fossil fuel, biomass has lower bulk density and energy density, which make it uneconomic for collection and transportation. Therefore, biomass gasification coupled with distributed power generation in small communities with abundant biomass resource would be the way out in future [1].

In recent years in China, the yield of domestic waste has increased every year and exceeds 400 million tonnes per year. Chinese government's 13th five-year plan proposed that the proportion of waste harmless treatment should be no less than 70% by 2020. But waste landfill is still the primary method used to deal with waste in rural areas. Compared with landfill, gasification has advantages of lower environmental impacts and does not consume land resource. When contrasting gasification with incineration, the gasification technology has better quality of gaseous emissions with much lower capital input, which makes gasification more suitable for distributed deployment in rural area. Therefore, there will be a great demand for deployment of waste gasification treatment plants in Chinese rural areas, and more and more people are now focusing on the development of more efficient small-scale gasifiers with capacity under 300 tonne/day. The relevant equipment has also been deployed in Iran, Thailand, Burma and Laos. However, several technical barriers are still there such as effective removal of tar with low cost, environmental influence, accuracy control of gasifier inner temperature, solidification of fly ash and so on.

Therefore, this chapter introduces both technological and logistics challenges of biomass gasification via introducing biomass characters and gasifier technologies. The details of tar minimization and socio-environmental impacts of biomass gasification are also presented as main contents to help understand the primary barriers for the deployment of biomass gasification.

2. Biomass characteristics and general conversion

2.1. Composition of biomass and its common characteristics

Biomass includes all the living or recently living organisms, like land plants, grasses, water-based vegetation and manures [2], and these organisms consist of a number of major elements such as C, H, O, N, P and S. The classification of biomass into different categories is based on their properties. One feasible way is based on the appearances and the growth environment of biomass: woody plants, herbaceous plants/grasses, aquatic plants, manures and wastes [2]. Biomass could also be divided into two types: low moisture content and high moisture content. The low moisture content biomass can be used in thermo-chemical processes (i.e., gasification, combustion and pyrolysis), while the high moisture content plants are more suitable to be used in some wet processing technologies (i.e., fermentation and anaerobic digestion) [3]. Such high moisture contents would consume a large amount of energy for the drying process if employed as resources for thermo-chemical processing.

Biomass is derived from solar energy via photosynthesis. Under a good illumination condition, carbon dioxide in the atmosphere can be converted into organic materials or, in another way, the solar energy is stored as chemical energy, which existed as chemical bonds in the organisms [4]. The said chemical energy is released when these bonds are broken either via thermo-chemical or wet processing. This is an ongoing energy transfer from the sun and hence the sustainability of biomass resource could be ensured. As we have known, the total energy captured annually in biomass is more than that of the annual energy consumption globally [5]. On the other hand, biomass is clean as it is carbon neutral. On the view of carbon network, the net emission of carbon dioxide into the environment during the harvesting of energy from biomass is zero. The final products of conversion of biomass (CO_2 and H_2O) are originally absorbed into the plants from the atmosphere during photosynthesis. The conversion of biomass also has less harmful releases such as NO_x and SO_x compared with fossil fuels [6].

However, the characters of biomass also create many barriers during its actual application. On the aspect of species diversity, biomass usually does not behave as steady as fossil fuels, which causes a lot of difficulty during project planning stage including gasifier type, plant size and the way of energy output. On the other hand, the varieties of biomass resource also lead to different heating values and moisture contents. Compared with other energy carriers, biomass has much lower heating values. Taking wood and wheat straw as examples, their lower heating values are only 18.6 and 17.3 MJ/kg, respectively, while the lower heating value of coal is as high as 23–28 MJ/kg [2, 7]. The reason for this disparity is that the oxygen content of biomass carbohydrates is very high while the combustible elements such as C and H are low. In addition, the intrinsic moisture content in biomass is also very high, which requires more energy for drying before further processes take place [3]. Hence, use of biomass requires the complexity in material handling, pre-treatment and the design of processing facilities [3]. For the purpose of transportation and collection, biomass is unlike any other renewable resources (solar, wind, hydropower) where it is able to be stored directly and transported somewhere else. However, biomass is highly dispersed in regional distribution and the low volumetric of biomass makes it a bit more difficult for the collection and transportation. Therefore, small-scale gasification unit operated in small communities with abundant biomass resource or domestic waste would be the way out in future.

2.2. General conversion technologies of biomass except gasification

For the utilization purpose, the conversion technologies of biomass could be classified in three categories: mechanical extraction; thermo-chemical conversion; and biological conversion, as illustrated in **Figure 1** [3, 8]. Among them, direct combustion, gasification and pyrolysis are considered as the thermo-chemical processes; fermentation and anaerobic digestion are regarded as biological conversion.

2.2.1. Direct combustion

The direct combustion of biomass is widely applied in small-scale cooking and domestic heating by converting chemical energy stored in biomass into heat [9]. In modern industrial technology, combustion is also employed in large-scale applications to produce mechanical power and electricity with the aid of boilers, steam turbines and turbo-generators. The temperature range of biomass combustion is within 800–1000 °C. Materials with the moisture content higher than 50 wt% are not suitable for combustion processes [3]. The net efficiency of electricity generation from biomass combustion varies between 20 and 40% [8]. The efficiency could be improved either by scaling up the system to over 100 MWe or co-firing with coal (<10 wt% by weight) [10].

2.2.2. Pyrolysis

Pyrolysis is a thermo-chemical process, in which biomass decomposes into fuel gas, bio-oil and solid char in the absence of oxygen. The selectivity leading to different types of products could be controlled by manipulating the operating conditions (temperature and residence time). Low temperatures (<500°C) and long residence time favor the production of solid char

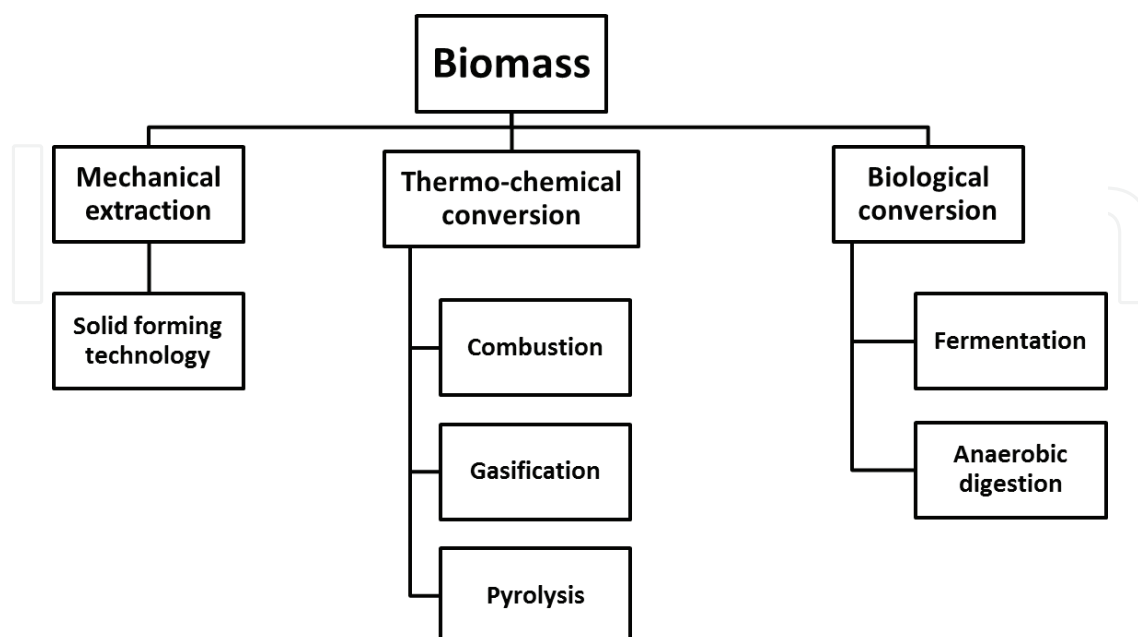


Figure 1. The main processes for the biomass conversion technologies [3].

(up to 35 wt% yield), while high temperatures (700–1100° C) and short reaction time favor the production of gases (up to 80 wt% yield) [11]. Bio-oil production is normally favored at 500° C, with very short retention time (<1 s) [12].

2.2.3. Fermentation

Fermentation is a bio-chemical process which is used for the production of about 80% of the world's ethanol [13]. The main process of fermentation involves using microorganisms to convert sugars into ethanol under a warm and wet environment. The sugar is typically obtained from the mechanical handling (crushing and mixing with water) of sugar-rich crops, such as sugar cane and sugar beet. However, the high cost of sugar-rich crops has diminished its proportion of utilization in fermentation. The starch-based biomass is also commonly used for ethanol production. However, it requires an extra step to convert starch into sugar by enzymatic reactions.

2.2.4. Anaerobic digestion

Anaerobic digestion involves using anaerobic microorganisms to convert biomass into biogas (CH₄ and CO₂ as the main gaseous products) by means of decomposition. Under the anaerobic environment, the organic material in biomass is decomposed into usable-sized molecules, such as sugar, as the first step. The sugar molecules is then converted into organic acids and further decomposed to CH₄ gas. This process has been proven as a commercially feasible technology and is widely applied in the rural areas of China.

3. Technologies of biomass gasification

Gasification process converts biomass, a low-energy density material, into a gaseous product (LHV at 4–11 MJ/N/m³), which is a mixture of CO, H₂, CH₄ and CO₂ [10]. Gasification is a partial oxidation process and it is commonly operated at 800–900° C for biomass gasification [2]. In some cases, steam is also used as the gasification agents. The gaseous products from the gasifier can be utilized in gas engines or gas turbines for the generation of electricity. In terms of economics, it has also been proven that the performance of a biomass gasification plant with a combined cycle gas turbine (CCGT) is comparable to that of a conventional coal power plant [7], if not better.

3.1. Types of gasifiers

The gasifier, as the principle component of a gasification plant, actually provides a space for biomass and gasification agent being mixed to a certain extent, in some cases with catalysts or additives [14]. The different selection of gasifiers is actually responsible for keeping steady the production of syngas regarding the variations of biomass. Literature shows that gasifiers could be categorized into three main types: fixed bed gasifiers, fluidized gasifiers and the entrained flow gasifiers [15].

3.1.1. Fixed bed gasifier

Fixed bed gasifiers is the traditional approach applied for biomass gasification and generally operated around 1000° C. An alternative name for the fixed bed gasifier is “moving bed reactor”. This is due to the movement of the biomass material in the main flow direction with very slow flowrate. The fixed bed gasifiers could be principally classified as updraft (countercurrent) and downdraft (co-current) due to the different airflow direction [14].

In an updraft gasifier (shown in **Figure 2**), the biomass material is fed from the top of the reactor, while the gasification agent enters from the bottom. The gasification agent flows through the bed of ash and biomass. The gas generated is exhausted through the top. For the reaction, the gasification agent meets the bottom char at first and achieves a complete combustion and raises temperature to c.a. 1000° C with production of H₂O and CO₂. This hot gas dries the incoming biomass near the top of the vessel and provides heat for pyrolysis of the descending biomass as well as percolates through the unreacted char bed to produce H₂ and CO [15]. In this gasification system, the product gas is withdrawn from the low temperature zone; thus, the product would be contaminated with significant amount of tars. If the product is used for further downstream applications like fuel in combustion engine electricity generator, a set of cleaning processes for tar removal is essential. However, the cleaning processes require intensive operation and establishment; therefore, the application of updraft gasification is not suitable for internal combustion engines [1].

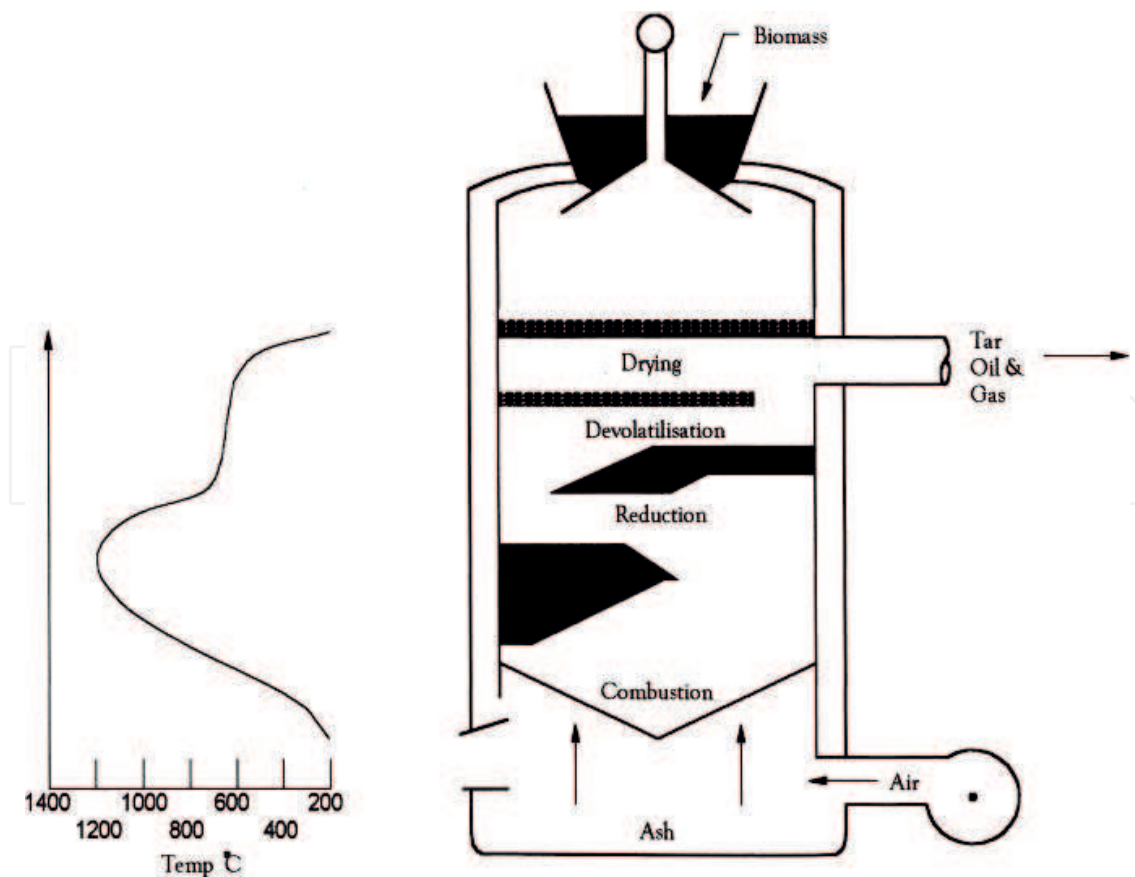


Figure 2. Schematic of updraft gasifier [16].

For the downdraft gasifier (shown in **Figure 3**), both biomass and gasification agent flow into the vessel from the top. At the “throated” area, where air or O_2 is fed into system with homogeneous distribution. The temperature could rise to around $1200\text{--}1400^\circ\text{C}$, which leads to both combustion and pyrolysis of the fuel. The produced hot gases will then be reduced to H_2 and CO as the main components after passing the hot char bed and will leave the gasifier unit at temperatures of about $900\text{--}1000^\circ\text{C}$. The tar content of the product gas is lower than that of the updraft gasifier, but the particulate content of the gas is higher [16]. Hence, the downdraft gasifier is suitable for downstream applications like internal combustion engines electricity generator. However, the product is withdrawn at a relatively high temperature; it needs to be cooled to acceptable range before further usage.

3.1.2. Fluidized gasifier

In the fluidized gasifier, the gasification agent enters the bed at a relatively fast rate from the bottom of the vessel and exits from the top. This kind of gasification features uniform temperature distribution in the bed zone. The consistency of temperature is obtained by the application of air-fluidized bed material, which ensured the intimate mixing of fuel, hot combustion gas and bed material. Currently, three main types of fluidized gasifiers are widely used [15], bubbling fluidized bed (BFB), circulating fluidized bed (CFB) and dual fluidized bed (DFB).

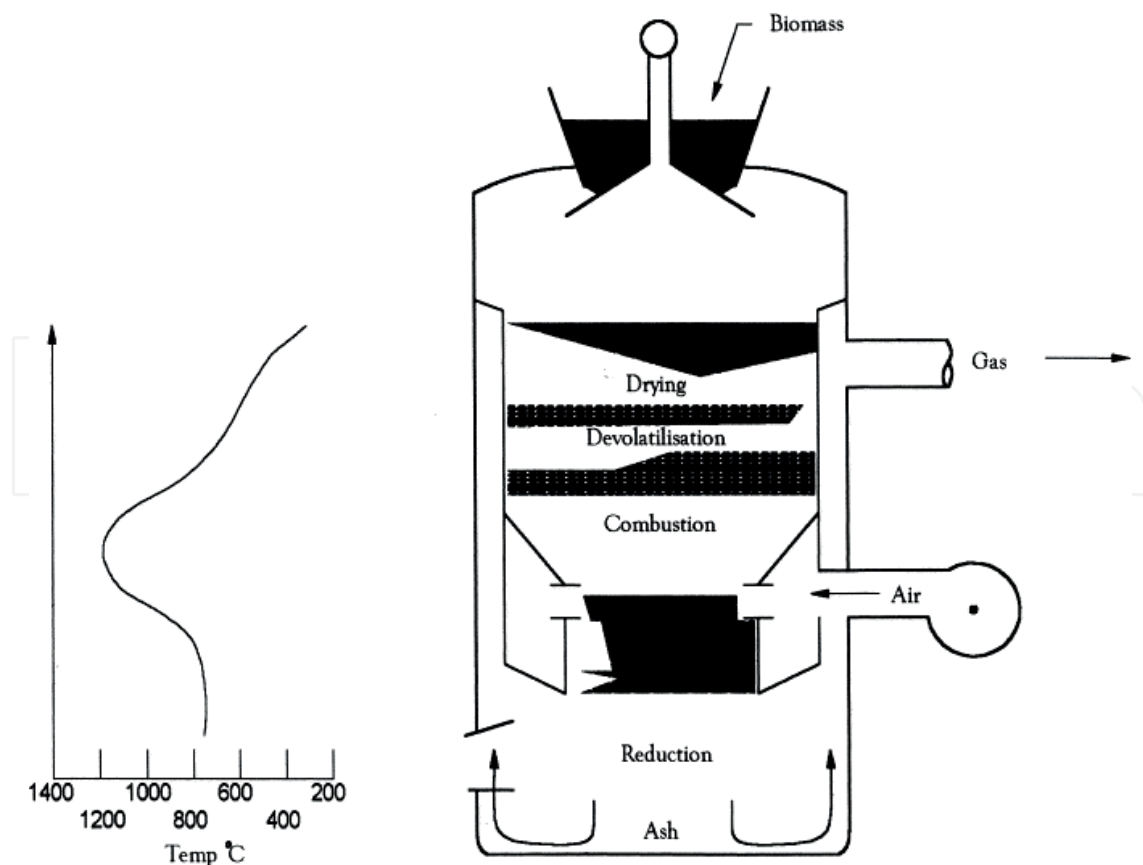


Figure 3. Schematic of downdraft gasifier [16].

BFB gasifier applies inlet from the bottom and moves the bed of fine-grained materials. The bed temperature is maintained at 700–900 °C by manipulating the ratio of fed biomass and gasification agent [16]. The flowrate of gasification agent is set to be slightly greater than the minimum velocity of fluidization of the bed material. The biomass is decomposed into char and gas products with a low tar percentage.

The CFB gasifier consists of two principle units: the gasifier unit and the circulation unit, as shown in **Figure 4**. The bed material and char in this type of gasifier is circulated between the reaction chamber and the cyclone separator, where ash and hot gas could be separated. The bed material is fully fluidized and leaves from the first unit, and then it is sent back by the second unit. The solids are moving in the solid circulation loop in greater extent of fluidization with higher residence time. Moreover, its operation pressure is also relatively higher.

Dual fluidized bed (DFB) gasifiers consist of two separated fluidized beds which are used for pyrolysis process and combustion process [14]. The first bed is operated as a pyrolysis reactor and it is heated by the second reactor with hot circulated bed material. The second reactor provides heat by burning char provided from the first reactor. The bed material plays an important role as a heat transfer medium, which prevents the dilution of the hot gas product.

3.1.3. Entrained flow gasifier

Entrained flow gasifiers are generally classified into two types: top-fed gasifier and side-fed gasifier (shown in **Figure 5**), which is according to how and where the fuel and gasification agent is fed. This type of gasifier is suitable for integrated gasification combined cycle (IGCC) plants. It is extensively applied in large-scale gasification and is widely employed for coal, biomass and refinery residues. The gasification temperature of this kind of gasifier could reach 1400 °C with a pressure range of 20–70 bar [14]. This high temperature could accelerate tar cracking and mitigate severe tar issue of biomass gasification. However, this kind of high

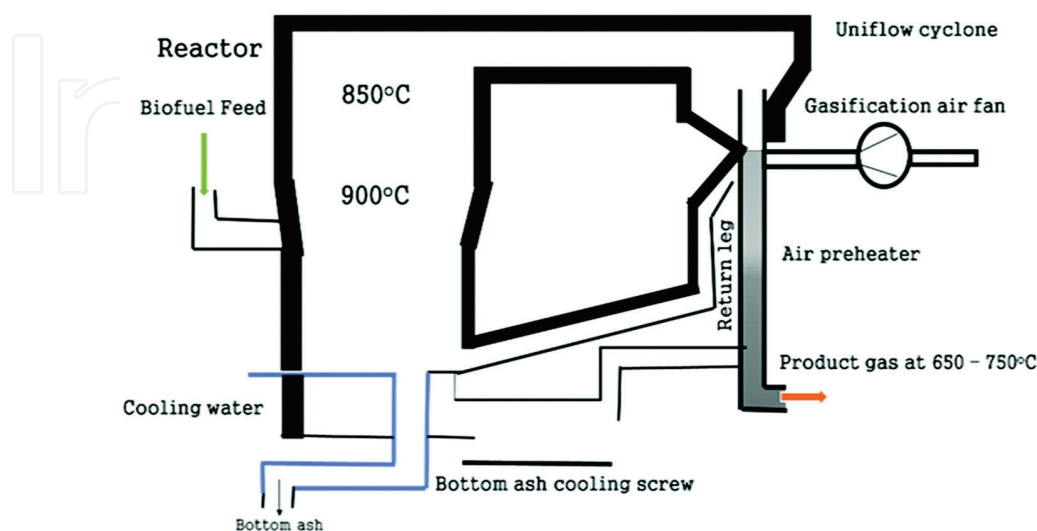


Figure 4. Schematic diagram of circulating fluidized bed gasifier (CFB) [17].

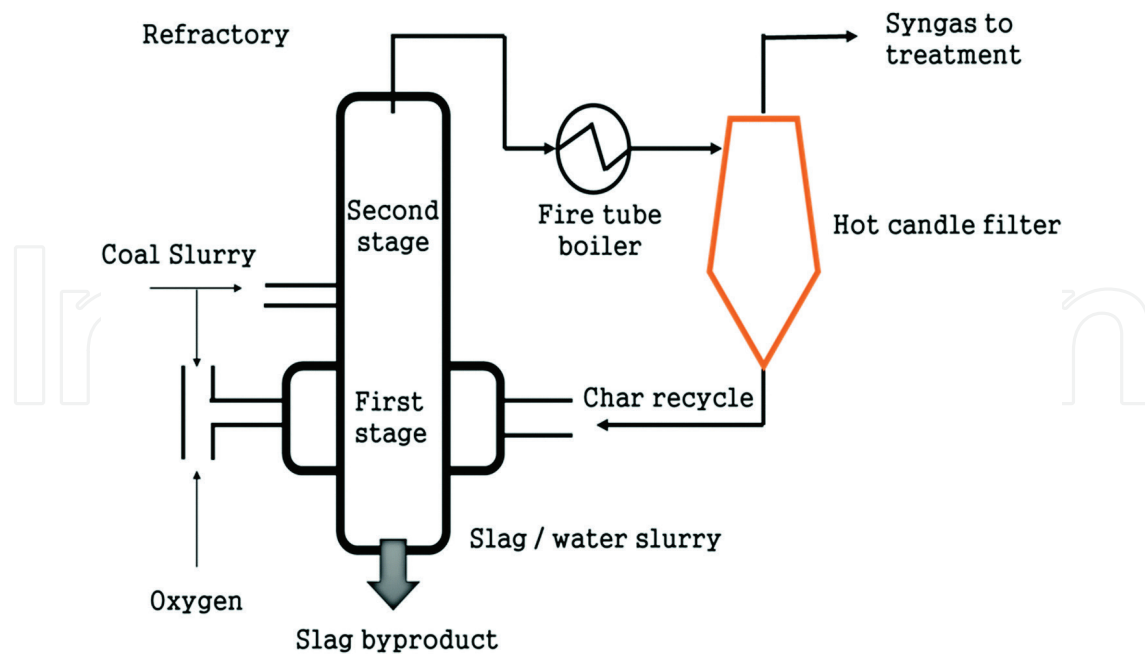


Figure 5. Schematic diagram of an entrained flow gasifier (side-fed) [17].

temperature gasification requires a finely fed biomass material (<0.1–0.4 mm), which makes this process unsuitable for most biomass materials (such as wood). Therefore, this process is not considered in detail.

3.2. Tar removal

Tar is a major inherent problem in biomass gasification; it can cause a lot of issues such as equipment blockages, lower system efficiency, poor quality gas output and increased maintenance. Tar consists of a group of very complicated mixtures with more than 200 components. Several key components include benzene, toluene, single-ring aromatic hydrocarbon, naphthalene and so on. The formation of tar was due to lower temperature of gasification. It was confirmed that increased temperature of gasification could reduce the content of tar in the outflow and it was believed that higher temperature can promote the cracking of tar [18]. Currently, there are a lot of methods that could be employed for tar minimization, and they can be divided into two categories depending on where the removal technology is applied.

Firstly, tar could be removed inside the gasifier by choosing an appropriate operation parameter or using a catalyst. Previous research indicates that both particle size and surface area-volume ratio of loading feedstock have a significant effect on tar yields [19, 20]. It showed that the gasification of pine saw dust only produced 0.4 wt% of tar at 700 °C when the particle size was smaller than 75 micron. While if particle size increased to the range of 600–1000 micron, the tar yield would be higher than 10 wt% even at 900 °C. From the view of thermal kinetics, the gasification of larger size of particles needs to overcome greater resistance of thermal conductivity; in other words, it needs more time to complete heat transfer and the devolatilization of biomass materials. On the other hand, small particle size also can contribute to a fast diffusion of the gasification agent and shorten time duration of the whole process. However,

the small size of feedstock particle required much more energy input during the biomass pre-preparation process. In addition, it is also effective by applying an optimal design of gasification reactor. A collaborative project between Switzerland and India demonstrated that an open-top fixed bed would produce much less tar and particulates than a closed-top fixed bed [15]. The reason behind this is that the open-top fixed bed could introduce dual air from the top and nozzles actually increase the residence time for degrading tar.

Secondly, in many processes, tar is removed as a downstream step after gasification, including mechanical method, thermal cracking and catalysis. The details of some common technologies have been listed in **Table 1**. Wet gas cleaning method has been accepted at an early stage. Its equipment investment is relatively low and the operation is also easy to handle. But this technology would also create a lot of waste water and bring serious environmental issues. Therefore, dry gas cleaning method becomes more widespread via various types of filters, rotating particle separators and dry cyclones. Although the dry method avoids waste water issues, its efficiency of tar removal is not good enough if compared with wet method. On the other hand, the replacement, renewal or disposal of filter materials reduces the financial effectiveness of the entire gasification system. This similar situation could also be applied to thermal cracking method and higher operation temperature requires much more energy input.

In the recent two decades, catalytic cracking has attracted more and more attention and has already become the central branch of research. Catalytic cracking is more like a downstream catalytic reforming unit and could easily degrade comparative stable tar to a significant extent. The previous research indicated that the catalytic cracking unit could promote gas yield by 10: 20 vol% and increase the heating value by c.a. 15% [23]. Ni-based catalyst is applied most widely and especially preferred for hydrogen or syngas production. Nickel has a very good catalytic activity and a preferable price advantage. While the application of Ni catalysts needs to avoid extremely high heavy-tar content flue gas, which will form a serious carbon deposition over the catalyst surface and lead to a quick deactivation. The other transition metal-based catalysts, such as Co, Fe and Cu, also have similar issues. Thus, some applications used the two-stage catalytic reforming process: the first stage used dolomite to

Method	Technique used	Details/examples
Wet gas cleaning [21]	Usage of mechanical device or equipment	Electrostatic precipitator, wet cyclone, wet scrubber
Dry gas cleaning [21]	Usage of mechanical device or equipment	Cyclone, rotary partial separator, fabric filter, ceramic filter, activated carbon adsorber, sand filter
Thermal cracking [21, 22]	Application of high temperature with long residence time	Maximum tar destruction was found at 1250 °C and 0.5 s
Catalytic cracking [21]	Usage of appropriate catalyst	Tar cracking catalysts are divided into five major groups, namely Ni-based, non-Ni-based, alkali metal-based, acid catalysts, basic catalysts and activated carbon-based catalysts

Table 1. Post-gasification tar removal methods [15].

reduce the concentration of tar to a certain level and then the second stage employed transition metal-based catalysts bed for near-completed removal of tar. But this kind of two-stage reforming process would increase operational cost clearly. In the research scale, some people applied noble metal catalysts and achieved highly catalytic activity as well as better carbon-resistant ability. However, high cost and low accessibility still restrain the wide utilization of noble metal-based catalysts before the technical breakthrough of catalyst regeneration. Alkali metal catalyst is an alternative with good catalytic performance and also exhibits outstanding coke resistance. It is due to this that alkali metal could suppress directly decomposition of hydrocarbon by avoiding quick adsorption of tar components. But alkali metal evaporates under high temperature gasification condition. In many practical process, biomass ash has been reused as an alkali catalyst because most biomass contains abundant alkali metal elements and it is believed that this type of natural catalyst with properties of low cost and disposability should attract special attention.

In the future, the development of novel and economic catalysts is still a promising option for tar elimination. At this stage, the biggest barrier for the catalyst development is the unclear mechanism of complex tar reformation. Therefore, employing model tar components for the study of coke formation mechanism is still very important and will be an effective way out. For the catalyst synthesis, composite catalysts with different components should be considered. It is also favored that if the developed catalyst could be applied under a low temperature condition (400–600° C), it will minimize cost effectively in a practical operation by using waste heat. In addition, the practical application of the catalyst also requires solving many scale-up issues, such as variation of temperature and pressure, impurities, fly ash and catalyst collapse.

4. Socio-environmental impact

Biomass gasification could exploit an abundant variety of waste materials as feedstock such as agricultural residues and food waste. It actually achieves resource recovery and mitigates CO₂ emission as an environmental benefit. However, power generation from biomass gasification poses several key hazards and socio-environmental impacts.

4.1. Health and safety hazard

One of the major risks is the potential emission of toxic producer gas and particulates. The production of CO, SO_x, NO_x and volatile organics involves incomplete combustion and oxidation of trace elements in feedstock [24]. As one of the most dangerous constituent, CO can permeate into human blood system and combine with hemoglobin to stop oxygen adsorption and distribution. Long-term exposure to CO causes asthma, lung inflammation, schizophrenia and cardiac defects. Toxic gases like SO_x, NO_x and volatile organics could also destruct inhalation, ingestion and dermal system of human [25]. Hence, the entire gasification process should prevent leakage and an efficient gas clean-up system is essential. In recent years, the hazard of particles emission (PM_{2.5}) attracts public attention increasingly, due to its carcinogenicity. PM_{2.5} particles can adsorb many soluble organic compounds including alkanes,

carboxylic acid and aromatic compounds, which will damage human organs like lung and liver [26]. For control of these particles' emission, an efficient gas clean-up system with conditioning unit is necessary, as well as avoiding insufficient combustion and gasification. In addition, ashes and condensate from biomass gasification also contribute to environmental problems if they are not disposed properly. Especially the toxic condensate with high content of tar is very difficult to deal with and has higher risk of hazards.

Besides the risk of health hazards and environment, gasification is also confronted with risk of fire and explosion. Because the gasification system is normally operated at relatively high temperature and pressure, it also produces flammable gas mixture with a great portion of hydrogen gas. However, explosion is not easy to be created even air leakage into the gasification system, which could raise a partial combustion. This will only lead to lower quality and higher temperature of producer gas [1], unless there is a large amount of air which enters with feedstock from the feeding system or massive leakage of flammable outlet gas occurs.

4.2. Social impact

The development of bioenergy will need a lot of land for energy-growing crops. This requirement will clash with other applications of farmland, like food and other cash crops. The competition with food agriculture must be intensive. The food shortage is still a big global issue nowadays. According to the data of World Hunger Education Service, the world's hungry population was 925 million in 2010. Besides this, the world population is still growing by rate of 1.2%. The natural disasters and climate change also affect agriculture. These three factors will decide that the demand of the farmland in the future will expand. Thus, transferring farmland for energy crop planting in a large scale would be difficult, especially in Europe.

4.3. Ethical issues

The bioethics report by Nuffield council points out that deployment of bioenergy should not violate the human right which is reflected in the Universal Declaration of Human Right (UDHR). In the UDHR, it states that every people can share and enjoy the protection of the moral and the any product from any scientific, literary or artistic which is owed by them. There are a lot of ethical issues referring bioenergy, like human rights, solidarity and sustainability. Biofuel production application will require land use, water supply and labor from local community. Destruction to the land and local ecosystem cannot be avoided. Also, land displaced for energy crops will not only bring food price increases; some local residents may face migration. All these could be regarded as the actions, which violate the human rights of citizens and non-citizens.

5. Conclusion

The commercialization of biomass gasification is still at the early stage of development and leaves a lot to be desired on the technology aspect. In particular, large-scale utilization of biomass still needs to overcome the challenge of biomass collection and transportation, due

to its low energy density. However, in some small communities, with large amount of local biomass materials, using biomass to replace polluting fossil fuels is a competitive way for providing reliable and clean power and heat.

This chapter provides the current technique status and development condition in China. It concludes that the gasification of biomass waste with distributed power generation would be a potential market. The properties of biomass feedstock have been analyzed and both advantage and disadvantage of biomass utilization were pointed out. Consequently, highly dispersed property and the low volumetric of biomass limit its large-scale application. Apart from that, this chapter also detailed some common types of gasifiers, except some emerging technologies, for meeting special requirements such as supercritical water gasification (SCWG) for wet biomass and plasma gasification for toxic organic waste. The tar issue, one of the most baffling problems in biomass gasification, is introduced briefly as well as its removal technologies. In our view, the socio-environmental impact is not the primary factor for restriction of biomass gasification development, while an objective financial return can actually attract investors and accelerate commercialization; in the meantime, it will also contribute to other technical breakthroughs.

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