**Gasification of Biomass for Sustainable Energy: Process, Technologies, and Applications**

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**Abstract**

Gasification is one of the thermo-chemical conversion technologies of biomass energy. It is the process by which solid biomass is converted into gaseous fuel (syngas). This chapter gives a brief information about the gasification process, reaction chemistry, different types of gasification technologies (fixed bed & fluidized bed) and producer gas. This chapter includes the discussion of the advantages and drawbacks of the various gasifiers and their uses & concludes with the brief about producer gas and its application.

**Keywords:** Gasification, pyrolysis, producer gas, biomass, gasifier

**1.Introduction**

Concerns about climate change and global warming lead to efforts that promote more renewable energy sources and improve energy efficiency in order to lower CO2 greenhouse gas emissions. In addition to solar and wind power, one of the primary sustainable energy sources is biomass. When wind and solar energy supplies are limited, biomass energy may be employed as an adjustable, controllable energy source that will be given in greater quantities. This is possible with the renewable energy combination that includes solar, wind, and biomass energy [1]. Biomass energy is one among the developing renewable energy resources that has become most emerging fuel resource because of its wide availability and characteristics [2].

Biomass is referred as the biodegradable portion of biologically derived products, wastes, and residues from industries like forestry, fisheries, aquaculture, agriculture (including plant and animal materials), and the biodegradable portion of municipal and industrial wastes [3]. The major conversion technologies used for biomass conversion are 1. Physical conversion, 2. Bio-chemical and 3. Thermo-chemical conversion [4]. Thermochemical conversion is a remarkable and the most important pathway for biofuel production, due to various benefits such as less reaction time, efficient nutrient recovery, small footprint and ability to handle several kinds of blends. Combustion, gasification, pyrolysis & torrefaction are the major thermo-chemical conversion technologies [5]. Among the thermochemical conversion processes, gasification has gained significant attention due to its superior combustion efficiency [6].

**2.Gasification**

The process of "biomass gasification" involves the conversion of carbonaceous biomass into combustible gases (such as H2, CO, CO2, and CH4) at particular heating values in presence of limited supply of oxygen [7]. Gasification is similar to combustion when air or oxygen is supplied, however it is known as a partial combustion process because combustion mainly focuses on heat generation whereas, the goal of gasification is to produce valuable gaseous products that may be stored for later use or utilised immediately for burning. Moreover, because gasification releases less harmful gases into the atmosphere and makes better use of the solid leftovers, it is seen to be a more environmentally friendly process [8].

The gas produced is referred as the producer gas. Producer gas mainly a combination of carbon monoxide, hydrogen and methane, together with carbon dioxide and nitrogen. Compared to the original solid biomass, the producer gas is more flexible as it can either be burnt to create steam and process heat or utilised in gas turbines to generate power [9]. Comparatively with other thermochemical processes, gasification offers greater potential for direct commercial use. The major advantages of gasification over direct combustion are: improved energy application flexibility, improved cost-effectiveness, thermodynamic efficiency at lower scales, and even reduced environmental effect when combined with gas purification and upgrading technologies

**3.Gasification process and reaction chemistry**

The gasification process consists of the following four stages: pyrolysis, reduction, oxidation, and drying.

**3.1Drying**

The biomass feed used for the gasification is usually sun dried and having moisture content 10-15%. Sometimes partially dried biomass is also used having moisture content up to 25%. Drying is the process of removal of moisture content of biomass feedstock completely to bone-dry. The temperature of the drying stage ranges from 100 -180 ℃. There will be no thermal decomposition of biomass in this stage.

**3.2Pyrolysis**

In this stage the biomass is heated at a high temperature ranging between 250 - 700 ℃ in the absence of air. This stage consists of thermochemical decomposition of the carbonaceous structural components especially, breakdown of chemical bonds and formation of smaller molecular weight molecules [10]. The biomass is thermally decomposed and converted into solid, liquid and gaseous fuel. The reaction that takes place in the pyrolysis stage is given below [11] [12]:

Biomass ↔ H2 + CO + CO2 + CH4 + H2O (water vapour) + Tar+ Char (Endothermic)

**3.3Oxidation**

Desired air for the partial combustion of biomass will be introduced in this stage. The temperature of this stage varies between 700-1500 ℃. Various thermal reactions take place between the air and carbon produced in the pyrolysis zone. Most thermal reactions are exothermic in nature. Carbon reacts with the air to produce carbon dioxide and on the other hand heat reacts with hydrogen produces water vapour. The oxidation stage can be defined with the following reactions [13]:

C + $\frac{1}{2}$ O2 → CO (Partial oxidation reaction)

C + O2 → CO2 (Char combustion reaction)

H2 + $\frac{1}{2}$ O2 → H2O (Hydrogen combustion reaction)

**3.4Reduction**

In this stage all the thermo-chemical reactions will takes place in the absence of air. The reduction stage involves all the products of the previous stages of pyrolysis and oxidation; the gas mixture and the char react with each other resulting in the formation of the final syngas. The reduction temperature is a significant aspect of the whole process, influencing the characteristics of the solid residue and syngas. The main reactions take place in this stage are given below [12] [10]:

C + CO2 ↔ 2CO (Boudouard reaction)

C + H2O ↔ CO + H2 (Reforming of char reaction)

CO + H2O ↔ CO2 + H2 (Water gas shift reaction)

C + 2H2 ↔ CH4 (Methanation reaction)

**4.Classification of various Gasification technologies**

The gasification technology can be applied in a wide range of industrial applications, and numerous gasifier variants have been designed and tested. Many different configurations have been used in the construction and operation of gasifiers as shown in the figure.



**Fig.1: Classification of Gasifiers**

**4.1 Fixed bed gasifiers**

The three main types of gasifiers for fixed beds are the cross-draft, downdraft, and updraft models. Based on the fuel and air flow directions within the gasifier, these designations were assigned. Fixed bed gasifiers can operate on a small scale of up to 10 MW. For this reason, the majority of fixed bed gasifiers are utilised in decentralised biomass power production systems [14].

**4.1.1 Updraft gasifier**

 In the updraft gasifier the gasifying agent such as air or steam are introduced at the bottom section of the gasifier to interact with biomass which is fed from the top of the reactor. The generated fuel after gasification exists from the top side of the gasifier. Hence updraft gasifier is also known as the counter current type of gasifier [14]. These gasifiers have the highest thermal efficiency because of the low temperature of gases exiting the gasifier unit [15]. Apart from the high thermal efficiency these gasifiers have other advantages such as high methane content in producer gas, simple & low-cost process, smaller drop in pressure and a low tendency for slag formation [14][16]. However counter current type has some disadvantages such as low gas production, sensitivity to tar and moisture content of biomass, long startup time and poor reaction capability of the system [17].

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**Fig 2: Various zones of updraft gasifier** [14]

**4.1.2 Downdraft gasifier**

In these gasifiers the gasifying agent air or steam interacts with the biomass feedstock in the downward direction and the generated producer gas also flow downwards in the co-current direction and exits from the bottom side of the reactor. Hence the downdraft gasifier is also known as a co-current type gasifier [18]. The end products of the pyrolysis and drying zones are forced to pass through the oxidation zone of the reactor for thermal cracking which implies less tar yield in the final product. This gasifier is suitable for small scale decentralize power generation because of low tar and moisture content in the final product. However, downdraft gasifier has some drawbacks such as low thermal efficiency and high particulate matter [19].

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**Fig 3: Various zones of downdraft gasifier** [14]**.**

**4.1.3 Cross-draft gasifier**

It is one of the simplest types of gasifier design in which the biomass feedstock enters the reactor from the top and air is provided from the side of the reactor [14]. It has various advantages when compared to the other fixed bed gasifiers but it is not the ideal type. Less start time, compatible with dry air blast, flexible syngas production and fast response to the biomass fed into the reactor are some of the major advantages of the cross-draft gasifier. However, it has some drawbacks such as inability to handle high tar and ash contents, suitable only for small scale industries [17].

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**Fig 4: Various zones of cross-draft gasifier** [14]**.**

**4.2 Fluidized bed gasifier**

The performance of both updraft and downdraft gasifiers is affected by the physical, chemical and structural properties of the fuel. Reactor's severe pressure loss, slagging, and shortage of bunker flow are some common problems faced in these gasifiers. To overcome the above-mentioned problems fluidized bed gasifier is used. Unlike fixed bed gasifiers, different zones of gasification process of fluidized bed gasifiers are not evident at any particular location within the gasifier. In this type of gasifiers, the biomass feed stock is kept in suspended state by providing air velocity using a blower. For this system, the feedstock must be introduced into the reactor after being finely grounded into fine particles [14]. The bed is externally and after the sufficient temperature is acquired the biomass is introduced. The feedstock enters the gasifier at the bottom and quickly heated up to the bed temperature. As a result, the fuel is treated extremely quickly, pyrolyzing the component and mixing it with a lot of gaseous material. The distinct advantages of these type gasifiers are less tar production, greater carbon conversion rate, uniform & adjustable temperature and adaptability with respect to feed rate, particle size, moisture content, and utilisation of different types of fuels [14], [20]. For small to medium scale operations, fluidized bed gasifiers are effective. Fluidized bed gasifiers are classified into two categories discussed below.

**4.2.1 Bubbling fluidized bed gasifier**

It is the oldest gasifier among the other fluidized bed gasifiers [21]. The beds are usually made up of inert materials such sand, dolomite, etc and high-pressure fluidizing medium such as air, oxygen or steam being used. These types of gasifiers operate at low velocity of medium less than 1m/s. A cyclone separator is used at the end to collect the solid particles transported along with the gases. These gasifiers can operate at very high temperatures resulting in higher thermal cracking of feedstock to improve the production of syngas. Compared with circulating fluidized bed gasifiers, this type of gasifier has a lower carbon conversion efficiency.

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**Fig 5: Schematic view of Bubbling fluidized bed gasifier** [14]**.**

**4.2.3 Circulating fluidized bed gasifier**

Circulating fluidized bed is advanced and emerging technology as compared to fixed bed type of gasifiers. In this gasifier, the solid fuel flow outside the reactor and are re-introduced back into the reactor as a result the carbon conversion efficiency is increased. The fluidizing medium in this gasifier is high ranging from 3 m/s to 10 m/s [15]. The gas generated using circulating fluidized bed gasifier have low tar, ash and moderate gas temperature, finally reduced gas cooling load and improved overall conversion efficiency. Typically, circulating bed gasifiers are used in the power generating, boilers, cement kiln, and paper industries. etc.

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**Fig 6: Schematic view of circulating fluidized bed gasifier** [14]**.**

**5. Producer gas and its application**

Producer gas is the primary byproduct of the gasification process. It is the mixture of combustible and non-combustible gases. The nitrogen in the air remains same and dilutes the gas, so producer gas has a lower heating value 5800 KJ/m3. It is utilised near its point of application once the ash and sulphur compounds are removed. Gas turbines that are suitable for low calorific value are often powered by producer gas [22]. Various factors, including the type of feedstock, gasification temperature, pressure, bed material, residence time, and equivalence ratio, have a significant impact on the quality and quantity of the product gas. The various constituents of the producer gas are given in the table below.

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| --- | --- |
| Nitrogen (N2) | 45-60% |
| Carbon-monoxide (CO) | 15-30% |
| Hydrogen (H2) | 10-20% |
| Carbon-dioxide (CO2) | 5-15% |
| Water vapour (H2O) | 6-8% |
| Methane (CH4) | 2-4% |
| Calorific value | 4.5-6 MJ/m3 |

Table 1: Constituents of producer gas

Producer gas was generally utilised as an industrial fuel for the production of iron and steel, such as in blast furnaces and coke ovens, electricity generation, cement and ceramic kilns, and gas engines for mechanical power.

**6. Conclusion**

In the above chapter, gasification process and various gasification technologies were discussed. The process of converting solid biomass into gaseous fuels is known as gasification. The gasification process is completed in different reaction zones. It is observed that the construction of fixed bed gasifiers is simple and they are easy to operate. Fixed bed gasifiers consist of separate zones for different reaction zones. Downdraft gasifiers are utilised for both power generation and thermal applications as they produce less tar than updraft gasifiers, which are typically used for thermal applications. To overcome the problems faced in fixed bed gasifiers such as the reactor's severe pressure loss, slagging, and shortage of bunker flow fluidized bed gasifiers are used. However fluidized gasifier has its own advantages and drawbacks. Bubbling fluidized bed gasifier is simple in construction but its carbon conversion efficiency is low whereas, to improve the carbon conversion efficiency, the solid biomass is reintroduced into the reactor in circulating fluidized bed gasifier. Fluidized bed gasifiers used for large scale industrial purposes. There are no common criteria for selecting gasifiers. The main factors that go into identifying a gasifier are the type and availability of biomass, the downstream use of produced gas, and the required application level. Other elements, such as social acceptance, capital investment, and environmental restrictions, could also be very important.

**References**

[1] S. Heidenreich and P. U. Foscolo, “New concepts in biomass gasification,” *Prog. Energy Combust. Sci.*, vol. 46, pp. 72–95, Feb. 2015, doi: 10.1016/j.pecs.2014.06.002.

[2] Y. Li, A. Ahmed, I. Watson, and S. You, “Waste-to-biofuel and carbon footprints,” in *Waste Biorefinery*, Elsevier, 2020, pp. 579–597. doi: 10.1016/B978-0-12-818228-4.00021-6.

[3] M. Cortazar *et al.*, “A comprehensive review of primary strategies for tar removal in biomass gasification,” *Energy Convers. Manag.*, vol. 276, p. 116496, Jan. 2023, doi: 10.1016/j.enconman.2022.116496.

[4] P. Adams, T. Bridgwater, A. Lea-Langton, A. Ross, and I. Watson, “Biomass Conversion Technologies,” *Greenh. Gas Balanc. Bioenergy Syst.*, pp. 107–139, 2017, doi: 10.1016/B978-0-08-101036-5.00008-2.

[5] J. Zhang and X. Zhang, “The thermochemical conversion of biomass into biofuels,” *Biomass, Biopolym. Mater. Bioenergy Constr. Biomed. other Ind. Appl.*, pp. 327–368, 2019, doi: 10.1016/B978-0-08-102426-3.00015-1.

[6] B. Pandey, Y. K. Prajapati, and P. N. Sheth, “Recent progress in thermochemical techniques to produce hydrogen gas from biomass: A state of the art review,” *Int. J. Hydrogen Energy*, vol. 44, no. 47, pp. 25384–25415, 2019, doi: 10.1016/j.ijhydene.2019.08.031.

[7] T. Bhaskar, B. Bhavya, R. Singh, D. V. Naik, A. Kumar, and H. B. Goyal, “Thermochemical Conversion of Biomass to Biofuels,” *Biofuels Altern. Feed. Convers. Process.*, pp. 51–77, 2011, doi: 10.1016/B978-0-12-385099-7.00003-6.

[8] J. Rezaiyan and N. P. Cheremisinoff, “Gasification technologies: A primer for engineers and scientists,” *Gasif. Technol. A Prim. Eng. Sci.*, pp. 1–331, 2005.

[9] A. Demirbas, “Thermochemical Conversion Processes,” *Green Energy Technol.*, pp. 261–304, 2009, doi: 10.1007/978-1-84882-011-1\_6.

[10] A. Molino, S. Chianese, and D. Musmarra, “Biomass gasification technology: The state of the art overview,” *J. Energy Chem.*, vol. 25, no. 1, pp. 10–25, 2016, doi: 10.1016/j.jechem.2015.11.005.

[11] S. M. Atnaw, S. A. Sulaiman, and S. Yusup, “Biomass gasification,” *Waste Biomass Manag. - A Holist. Approach*, pp. 159–185, 2017, doi: 10.1007/978-3-319-49595-8\_8.

[12] M. Thakkar, P. Mohanty, M. Shah, and V. Singh, “An overview of biomass gasification,” *Recent Adv. Biofuels Bioenergy Util.*, pp. 147–156, 2018, doi: 10.1007/978-981-13-1307-3\_7.

[13] N. J. Rubinsin, N. A. Karim, S. N. Timmiati, K. L. Lim, W. N. R. W. Isahak, and M. Pudukudy, “An overview of the enhanced biomass gasification for hydrogen production,” *Int. J. Hydrogen Energy*, vol. 49, pp. 1139–1164, 2024, doi: 10.1016/j.ijhydene.2023.09.043.

[14] C. Loha, M. K. Karmakar, S. De, and P. K. Chatterjee, “Gasifiers: Types, Operational Principles, and Commercial Forms,” *Energy, Environ. Sustain.*, pp. 63–91, 2018, doi: 10.1007/978-981-10-7335-9\_3.

[15] S. K. Sansaniwal, K. Pal, M. A. Rosen, and S. K. Tyagi, “Recent advances in the development of biomass gasification technology: A comprehensive review,” *Renew. Sustain. Energy Rev.*, vol. 72, pp. 363–384, 2017, doi: 10.1016/j.rser.2017.01.038.

[16] P. Basu, “Biomass gasification, pyrolysis and torrefaction: Practical design and theory,” *Biomass Gasification, Pyrolysis Torrefaction Pract. Des. Theory*, pp. 1–564, 2018, doi: 10.1016/C2016-0-04056-1.

[17] S. Mishra and R. K. Upadhyay, “Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters,” *Mater. Sci. Energy Technol.*, vol. 4, pp. 329–340, 2021, doi: 10.1016/j.mset.2021.08.009.

[18] S. Pang, “Fuel flexible gas production: Biomass, coal and bio-solid wastes,” *Fuel Flex. Energy Gener. Solid, Liq. Gaseous Fuels*, pp. 241–269, 2016, doi: 10.1016/B978-1-78242-378-2.00009-2.

[19] R. Thomson, P. Kwong, E. Ahmad, and K. D. P. Nigam, “Clean syngas from small commercial biomass gasifiers; a review of gasifier development, recent advances and performance evaluation,” *Int. J. Hydrogen Energy*, vol. 45, no. 41, pp. 21087–21111, 2020, doi: 10.1016/j.ijhydene.2020.05.160.

[20] M. Siedlecki, W. de Jong, and A. H. M. Verkooijen, “Fluidized bed gasification as a mature and reliable technology for the production of bio-syngas and applied in the production of liquid transportation fuels-a review,” *Energies*, vol. 4, no. 3, pp. 389–434, 2011, doi: 10.3390/en4030389.

[21] J. M. Wheeldon and D. Thimsen, “Economic evaluation of circulating fluidized bed combustion (CFBC) power generation plants,” *Fluid. Bed Technol. Near-Zero Emiss. Combust. Gasif.*, pp. 620–638, 2013, doi: 10.1533/9780857098801.2.620.

[22] P. Grammelis, N. Margaritis, and E. Karampinis, “Solid fuel types for energy generation: Coal and fossil carbon-derivative solid fuels,” *Fuel Flex. Energy Gener. Solid, Liq. Gaseous Fuels*, pp. 29–58, 2016, doi: 10.1016/B978-1-78242-378-2.00002-X.