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Assessment of Biomass Gasification: A Review of Basic Design Considerations

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Abstract The essence of a gasification process is the conversion of solid carbon fuels into carbon monoxide and hydrogen mainly; by a complex thermo chemical process. Other products of the biomass conversion are gases which contain carbon dioxide, methane and nitrogen. The history of gasification dates back to the seventeenth century. Since the conception of the idea, gasification has passed through several phases of development. Authors across the world have conducted studies and researches on the design of gasifiers, performed modeling and simulation of biomass gasification. Various energy crisis and technological advancements have influenced the development of gasifiers for different fuels, configurations and applications other than wood and charcoal. The economic success of a biomass gasification plant depend on the understanding of the basic principles involved, knowledge of the steps to be taken while designing and the hitch free running of the plant. This paper reviews the fundamentals and basic formulae adopted while designing a biomass gasifier for energy production. Aspects such as: the elemental composition, ash content and energy density of the biomass were considered. The gasification process physical and chemical characteristics were reviewed too. Design considerations were reviewed with special emphasis on the reactor and blower such as: the type of reactor, cross-sectional area of the reactor, height of the reactor, thickness of the fuel bed, fan airflow and pressure, insulation for the reactor, location of firing the fuel, size and location of the char chamber, intended uses as well as safety considerations.

Keywords: *biomass gasification, thermo-chemical conversion, sustainable energy, reactor, blower, design*

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1. Introduction

Biomass represents one of the largest sustainable energy resources in the world and has been perceived as an attractive source of power, fuels and other chemical products. However, the bulky and inconvenient form of biomass is a major barrier to its wide applications, and this provides a motivation for the conversion of solid biomass into liquid and/or gaseous fuels.

Gasification is the thermo-chemical conversion of solid fuel into the gas which contains mainly hydrogen, carbon monoxide, carbon dioxide, methane and nitrogen (H_2, CO, CO_2, H_2O, CH_4 and N_2). The product gas from the reactor also contains some contaminants like char particle, ash and some higher hydrocarbons or tar. The original chemical composition of the biomass feedstock and the operating conditions determine the amounts of contaminants with a typical concentration range of 1–150 g/Nm^3 for tars, 500–30 000 ppm for NH_3 and 20–200 ppm for H_2S [1].

The history of gasification dates back to the seventeenth century. Since the conception of the idea, gasification has passed through several phases of development. Various energy crisis and technology have influenced the development of gasifiers for different fuels, configurations and applications other than wood and charcoal [2]. Thus, the economic and technological successes of a biomass gasification plant depend on the understanding of the basic principles involved, knowledge of the steps to be taken and the required formulae.

According to Mc Kendry [3], most of the development work was carried out with common fuels such as coal, charcoal and wood. The key to a successful design of gasifier is to understand the properties and thermal behaviour of the fuel fed into the gasifier system. It was recognized that fuel properties such as surface area, size, shape as well as moisture content, volatile matter and carbon content affect gasification performance

Anjireddy and Sastry [4] reviewed various aspects of the research and development in biomass gasification in downdraft fixed bed reactors like advances in downdraft gasification systems, and the effect various parameters like equivalence ratio, operating temperature, moisture content, superficial velocity, gasifying agents, residence time on the composition of producer gas, yield and conversion. Deyong *et al.* [5] reviewed the numerical simulation on biomass gasification technology at home and abroad. At the same time, two commercial simulation softwares (Aspen Plus and Fluent) applied in chemical process was mainly introduced, and both of them were analysed and compared. Finally it was put forward that a better simulation result could be achieved for biomass gasification if applying Aspen Plus combined with Fluent. Simonyan and Fasina [6] reviewed the current status of biomass resources and their bioenergy potentials and the possibility of utilizing biomass to generate electricity in Nigeria. They evaluated various biomass energy conversion technologies and their applications to developing countries such as Nigeria. Ganesh and Chincholhat [7] reviewed the development and performance evaluation of various gasifier cook stoves that uses Rice Hush as fuel. The result showed that the Rice Husk gas stoves perform accordingly with the design which can satisfactorily produce a combustible gas. Yashwant [8] reviewed methanol production using producer gas in fuel cell and small scale irrigation systems for developing countries. Sanjay *et al.,* [9] reviewed downdraft gasification while designing and developing of a downdraft gasifier for running an air cooled, single cylinder, 4-stroke, direct injection diesel engine developing a power of 5 kW, on dual fuel mode at a rated speed of 1500 rpm. The emission and performance characteristics of the engine were studied for various gas flow rates at different loads condition. Sunil and Shukla [10] reviewed recent gasification methods for bio-methane production and the methods applied for the pre-treatment of biomass for cracking down the complex polymer structures.

Karthikeyan *et al.* [11] reviewed the critical factors that affect the integration of biomass gasification with syngas fermentation, such as carbon conversion efficiency, effect of trace gaseous species, H_2 to CO ratio requirements, and microbial preference of carbon substrate. Rahul *et al.* [12] reviewed the various research works on mathematical models, simulation models, heat integration, co-firing and enhancement which are contributing to the development of synthesis gas as an energy carrying clean fuel. Different type of mathematical and numerical model used in CFD analysis of biomass conversion process (gasification and combustion) using different type of computer application fluent, CFX and code modeling and investigated their computation result with the experimental result. They concluded that Mathematical models are necessary for the optimization purposes to find optimal operating conditions to obtain a better process performance. Mohandas et al., [13] reviewed the various aspects of research and modification in downdraft fixed bed gasifier system and parameters like equivalence ratio, operating temperature, moisture content, superficial velocity and residence time. The downdraft gasifiers were safer from environmental point of view. Applications like production of methanol, using of producer gas in fuel cell and irrigation system on small scale offers the great potential. It is one of the most attractive alternatives systems of energy. Mohd *et al.,* [14] reviewed biomass thermal gasification as well as the latest trends in gasification of biomass using downdraft gasification. The authors provided a full description of the process starting from basic understanding and ending by design of a gasification unit.

Authors across the world have conducted studies and researches on the design of gasifiers, performed modeling and simulation of biomass gasification [15-30]. Prince *et al.,* [31] constructed and analysed the performance of updraft gasifier using wood chips, sugarcane waste, and coconut shells as fuel. The experimental analysis for different biomass materials clearly show that the coconut shell having the greater temperature for all the zones as compared to the other two, when the air velocity increases. Maximum temperature of the different zones for coconut shell represents the optimum amount of combustion. The energy released will increase the rate of drying and pyrolysis. Optimum amount of biomass consumption rate is not only due to a higher combustion rate, but also due to the enhanced pyrolysis and drying rate. So, the coconut shell is best suitable material for the above constructed updraft biomass gasifier as compare to the other two.

Lucia *et al.,* [32] investigated a suction downdraft gasifier coupled to engine-generator for small medium electrification using wood waste. The producer gas from the gasification method is combustible that can be employed to produce electricity. The diesel displacement rate gains 53.4% at 3 kW as a function of electrical power. The dual fuel mode engine efficiency reduced to 13.9% compared to diesel alone mode 23.1% at 3 kW, respectively. The concentration of the pollutions such as carbon monoxide (CO), Nitrogen Oxides (NO_x) was cautiously operationalized. Findings show that the emission level of CO augmented, while the NO_x reduced in dual fuel mode. Md Risat *et al.,* [33] made available the idea of electricity generation from Rice Husk in the rural areas. They concluded that power generation from Rice Husk is a better to alternative to the fossil based fuels. Elmer et al., [34] examined the technical performance of the Philrice updraft Rice Husk gasification system as a possible alternative source of energy for operation of single pass- rice milling factories. They also examined the current number and distribution of rice milling factories in central Luzan, discussed the potential benefit of introducing Updraft Rice Husk gasification systems to village rice milling factories. Produced gas could be used to power rice mills of small capacity.

Moriconia *et al.* [35] analysed the production of energy from biomasses on micro-scale from different perspectives: from the obtainment of producer gas from a gasifier to the cleaning of it removing tar in a scrubber filled with vegetable oils, to the use of producer gas in engine and Solid Oxide Fuel Cell (SOFC). Vaibhav [36] summarizes the research literature referred relative to the downdraft gasifier and found that the various factors which affects the down draft gasifier are throat diameter, throat inclination, nozzle inclination, length of reduction, nozzle diameter, number of nozzles, height of nozzle plane above the throat among others. Sreelal [37] designed, constructed and analysed the performance of low cost fixed bed biomass gasifier. The author determined the gasification performance parameters for different types of agricultural residues in order to build a compact and simple gasifier project that uses inexpensive feedstock that is available and almost free. Inayat *et al.* [38] investigated the effects of biomass blending ratio and biomass particle size on the syngas quality and performance of the co-gasification process. The results show that small particle size favours gas composition. The highest H_2 (10.91%), CO (25.60%), and CH_4 (2.79%) levels were obtained from the 5-10 mm particle size at 80/20, 50/50, and 20/80 blending ratios, respectively. Dhanak and Patel [39] gave the basic idea about gasification, its mechanisms, the types of gasifiers, characteristics of different biomass and finally concluded that biomass gasification strives against direct liquefaction, coal combustion and biochemical conversion (fermentation).

Shiriant *et al.,* [40] investigated the potentials and Eco-friendly way to electrify India; to provide an alternative solution to the depleting fossil fuels and greenhouse gas emissions. They are of the opinion that Rice Husk for power generation is a potential option to conventional energy source. Mena *et al.,* [41] carried out the modelling and simulation of an innovative combine heat and power (CHP) system composed of an updraft gasifier, an external combustion chamber and Organic Rankine Cycle (ORC) generator for the energetic valorisation of olive leaves. It is an innovative energy recovery system for high ash content biomass has been theoretically developed, representing a good opportunity to promote distributed generation systems. Senthil and Vevekanandan [42] conducted a statistical study on the effect of design and operating parameters such as bed temperature, pressure, equivalent ratio, feed rate and particle size on the performance of the gasification process of coconut shell as biomass in a continuous fixed bed updraft gasifier reactor. These parameters have an influence on the performance of the gasifier.

Husham [43] carried out a theoretical study by using three reactions for the wood burning analysis or (Wood Gasification).Results obtained were used in solving the multivariable non-linear equations by means of Newton-Raphson method. Matlab also was used in calculating the degree of equilibriums heat for the reactions absolute (946^{o}K, 763^{o}K, and 67^{o}K) and the thermodynamics functions for the reactions (ΔG, ΔH, K) with two ΔH+ (non- impulsive) and one ΔH-(impulsive).

Sonakar *et al.,* [44] analysed the performance evaluation of commercially available forced-graft Purti stove using different biomass fuels in order to determine the limitations in the design of the present model. They modified the existing design and improved the performance. Alberto *et al*., [45] assessed the efficiency of the gasification section in a large scale plant based on the experiences gained from the GoBiGas. Used the result obtained in the measurement campaign with full operation of the gasifier using wood pellets as a fuel. João *et al.,* [46] showed that gasification could be a more attractive way to convert biomass in energy, compared to using steam boilers, which in some cases can show a low efficiency. Gasification could be a cost-effective alternative for power production in Brazilian sugar cane plants with some additional advantages like the bagasse usage between the season and off-season periods to maintain a constant power generation throughout the entire year, higher energy availability and efficiency.

Shitab *et al.,* [47] determined the thermal characterization of Coal – Biomass. They studied and analysed the various blending ratios of three solid fuels by using the ultimate analysis technique. The results of emissions show that the Coal and BTW and their blends with coal have the advantages to utilize for co-processing regarding environmental concern. Abubakar *et al.,* [48] designed and developed a forward curved Blower for Downdraft Gasifier Reactor. The geometric parameters, operating conditions and the performance characteristics were determined. It was found that the blower can sufficiently supply air for a gasifier operation even at high temperature. Abubakar *et al.,* [49] tested and evaluated the performance of a forward curved blower for thermal applications. They determined the performance characteristics of the blower. A peak temperature of 891°C was recorded at 3111 rpm and an air velocity of 23.8 m/s. Major characteristics of the blower such as the power output were found to be 0.56 kW while the mechanical efficiency was varying between 55% and 62% respectively.

This paper reviews the fundamentals and basic formulae adopted while designing a biomass gasifier for energy production. Aspects such as: the elemental composition, ash content and energy density of the biomass were considered. The gasification process physical and chemical characteristics were reviewed too. Design considerations were reviewed with special emphasis on the reactor and blower.

2. Biomass Characteristics

2.1. Moisture Content

Moisture is of paramount importance in biomass gasification because it drains much of the deliverable energy from a gasification plant, as the energy used in evaporation is not recovered. It is the amount of water in the material, expressed as a percentage of the materials weight. This weight can be on a wet basis, on a dry basis, and on a dry-and-ash basis. [2].

2.2. Ash Content

This refers to the inorganic, residual component in biomass, usually obtained after combustion of the biomass. It is expressed in the same format as the moisture content. This property is especially important under high temperature gasification as melted ash may cause problems in the reactor [2].

2.3. Elemental Composition

The ash-free organic components of biomass are relatively uniform. The major components are carbon, oxygen, and hydrogen. Most biomass may also contain a small amount of nitrogen [2] as shown in Table 1 [50].

Table 1. Elemental Composition of Typical Biomass as derived from Ultimate Analyses [50]

Element	Symbol	Weight percent(dry and ash-free bases)
Carbon	C	44 – 51
Hydrogen	H	5.5 – 6.7
Oxygen	O	41 – 50
Nitrogen	N	0.12 – 0.60
Sulphur	S	0 – 0.2

2.4. Volatile Matter Content

The part of the biomass that is released when the biomass is heated is referred to as the volatile matter. Biomass feedstock contains a very high proportion of volatile organic material; 70 to 90% for wood [51].

2.5. Energy Density

The energy density refers to the potential energy available per unit volume of the biomass. It is dependent on the feedstock heating value and bulk density. In general, the energy density of biomass is about one-tenth of that of fossil fuels [2].

During the combustion process the organic matter in the husks (carbohydrate and carbonaceous fractions) is converted to carbon dioxide and water. During the combustion process very minor quantities of carbon monoxide, nitrogen oxides and volatile organic compounds are generated which leave the furnace with the flue gases. Table 2 lists the heating value of some biomass sources and their corresponding moisture and ash contents.

Table 2. Typical Characteristics of Different Biomass Fuel Types [2,52]

Biomass Type	Lower Heating Value (kJ/kg)	Moisture Content (%)	Ash Content (dry) (%)
Bagasse	7,700 - 8,000	40 – 60	1.7 – 3.8
Rice husk	14,000	9	19
Wood	8,400 – 17,000	10 – 60	0.25 – 1.7
Gin trash	14,000	9	12
Stalks	16,000	10 – 20	0.1
Coffee husk	16,400	5.9	11.4
Bamboo	15,000 – 18,000	Not measured	3.41
Prosopies	18,000 – 23,000	5.7	1.4
Eucalyptus	16,000 – 18,000	3.9	2.2

3. Gasification Process

The essence of a gasification process is the conversion of solid carbon fuels into carbon monoxide and hydrogen mainly, by a complex thermo chemical process [53] as shown in the general formula (Equation 1).

$$\begin{aligned} &\text{Biomass} + O_2\left(\text{or} H_2O\right) \\ &\to CO, CO_2, H_2O, H_2, CH_4 + \text{other hydrocabons} \\ &\to \text{Tar} + \text{Char} + \text{Ash} \\ &\to HCN + NH_3 + HCL + H_2S + \text{other sulfur gases.} \end{aligned} \tag{1}$$

Splitting of a gasifier into strictly separate zones is not realistic, but it is conceptually essential. Gasification is made up for five discrete thermal processes: Drying, Pyrolysis, Combustion, Cracking, *and* Reduction. All of these processes are naturally present in the flame seen while burning off a match, though they mix in a manner that renders them invisible to eyes not yet initiated into the mysteries of gasification. Gasification is merely the technology to pull apart and isolate these separate processes, so that the “fire” might be interrupted and pipe the resulting gases elsewhere. The processes of gasification are as illustrated in Figure 1 [54].

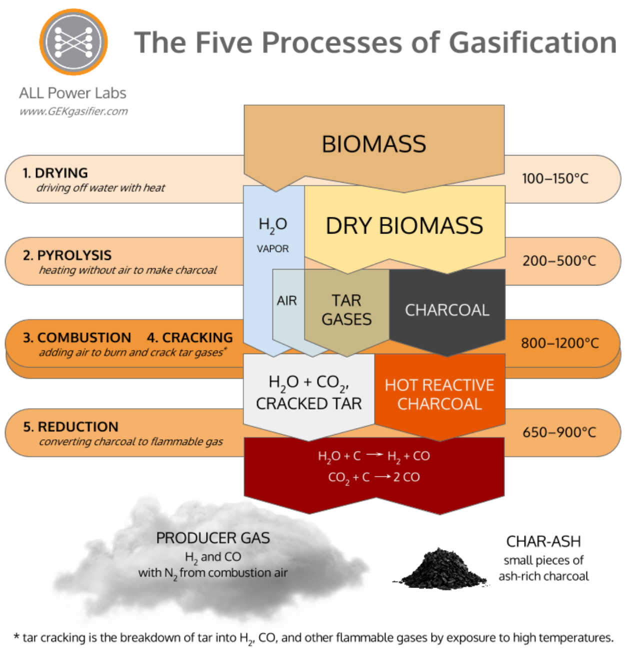

Figure 1. Reaction zones in a Downdraft Gasifier [54]

3.1. Drying

At temperatures between 100-200°C, water (moisture content within the biomass) is removed and converted into steam. In the drying zone, fuels do not experience any kind of decomposition. The resulting water vapour together with water vapour formed in the combustion zone partly lead to production of hydrogen and remaining is going with producer gas [55]. Drying is what removes the moisture in the biomass before it enters Pyrolysis. All the moisture needs to be (or will be) removed from the fuel before any above 100°C processes happen. All of the water in the biomass will get vaporized out of the fuel at some point in the higher temp processes. Where and how this happens is one of the major issues that has to be solved for successful gasification. High moisture content fuel, and/or poor handling of the moisture internally, is one of the most common reasons for failure to produce clean gas.

3.2. Pyrolysis

Pyrolysis is the application of heat to raw biomass, in an absence of air, so as to break it down into charcoal and various tar gasses and liquids. It is essentially the process of charring.

Biomass begins to rapidly decompose with heat once its temperature rises above around 240°C. The biomass breaks down into a combination of solids, liquids and gasses. The products of biomass pyrolysis have three states: solid charcoal, liquid wood tar and pyroligneous liquor, and combustible gas. Pyrolyzing at different temperatures may produce products with different contents. The higher the temperature is, the greater the amount of combustible gas and liquids, and the less the amount of solid charcoal. The reaction is influenced by the chemical composition of biomass fuels and the operating conditions. Charcoal obtained from pyrolysis zone is further reacted in the reduction zone to yield syngas. Tar and pyroligneous liquor produced in pyrolysis is a liquid containing more than 200 components, like acetic acid, methanol, acetic aldehyde, acetone, ethyl acetate, etc. These pyrolysis products can be further reacted in the subsequent reaction zones as well.

It is noted that no matter how a gasifier is built, there will always be a low temperature zone where pyrolysis takes place, generating condensable hydrocarbons [56]. The gasses and liquids produced during lower temp pyrolysis are simply fragments of the original biomass that break off with heat. These fragments are the more complicated H, C and O molecules in the biomass that are collectively referred to as volatiles. As the name suggests, volatiles are reactive. Or more accurately, they are less strongly bonded in the biomass than the fixed carbon, which is the direct C to C bond.

Both hydrogen and carbon monoxide are burnable fuel gasses. We do not usually think of carbon monoxide as a fuel gas, but it actually has very good combustion characteristics (despite its poor characteristics when interacting with human hemoglobin). Carbon monoxide and hydrogen have about the same energy density by volume. Both are very clean burning as they only need to take on one oxygen atom, in one simple step, to arrive at the proper end states of combustion, CO_2 and H_2O.

Thus in review, pyrolysis is the application of heat to biomass in the absence of air/oxygen. The volatiles in the biomass are evaporated off as tar gases, and the fixed carbon-to-carbon chains are what remains- otherwise known as charcoal. The main process of thermal decomposition of biomass can be represented by Equation 2:

$$C_6H_{10}O_5 + \text{Heat} \rightarrow yC_xH_z + qC_xH_nO_k + CO + C. \quad (2)$$

3.3. Combustion

Combustion is the only net exothermic process of the Five Processes of Gasification; ultimately, all of the heat that drives drying, pyrolysis, and reduction comes either directly from combustion, or is recovered indirectly from combustion by heat exchange processes in a gasifier. Combustion can be fueled by either the tar gasses or char from Pyrolysis. Different reactor types use one or the other or both. In a downdraft gasifier, the tar gasses from pyrolysis are burnt to generate heat to run reduction, as well as the CO_2 and H_2O to reduce in reduction. The goal in combustion in a downdraft gasifier is to get good mixing and high temps so that all the tars are either burned or cracked, and thus will not be present in the outgoing gas. The char bed and reduction contribute a relatively little to the conversion of messy tars to useful fuel gasses. Solving the tar problem is mostly an issue of tar cracking in the combustion zone.

3.4. Cracking

Cracking is the process of breaking down large complex molecules such as tar into lighter gases by exposure to heat. This process is crucial for the production of clean gas that is compatible with an internal combustion engine because tar gases condense into sticky tar that will rapidly foul the valves of an engine. Cracking is also necessary to ensure proper combustion because complete combustion only occurs when combustible gases thoroughly mix with oxygen. In the course of combustion, the high temperatures produced decompose the large tar molecules that pass through the combustion zone.

The principal reactions are as shown in Equations (3, 4, 5 & 6) [57] (Wei, 2005):

$$C + O_2 \rightarrow CO + \text{Heat} \quad (3)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Heat} \quad (4)$$

$$COCH + \frac{1}{2}O_2 \rightarrow CO_2 + \text{Heat} \quad (5)$$

$$CH + \frac{3}{2}O_2 \rightarrow CO + 2H_2O \quad (6)$$

3.5. Reduction

In the reduction zone, several high temperature chemical reactions take place in the absence of oxygen. Reduction in a gasifier is accomplished by passing carbon dioxide (CO_2) or water vapor (H_2O) across a bed of red hot charcoal (C). The carbon in the hot charcoal is highly reactive with oxygen; it has such a high oxygen affinity that it strips the oxygen off water vapor and carbon dioxide, and redistributes it to as many single bond sites as possible. The oxygen is more attracted to the bond site on the C than to itself, thus no free oxygen can survive in its usual diatomic O_2 form. All available oxygen will bond to available C sites as individual O until all the oxygen is gone. When all the available oxygen is redistributed as single atoms, reduction stops [54].

Through this process, CO_2 is reduced by carbon to produce two CO molecules, and H_2O is reduced by carbon to produce H_2 and CO. The principal reactions that take place in the reduction zone are described by Equations (7, 8 & 9):

$$CO_2 + C + \text{Heat} \rightarrow CO_2 \quad (7)$$

$$C + H_2O + \text{Heat} \rightarrow CO + H_2 \quad (8)$$

$$CO + H_2O + \text{Heat} \rightarrow CO_2 + H_2 \quad (9)$$

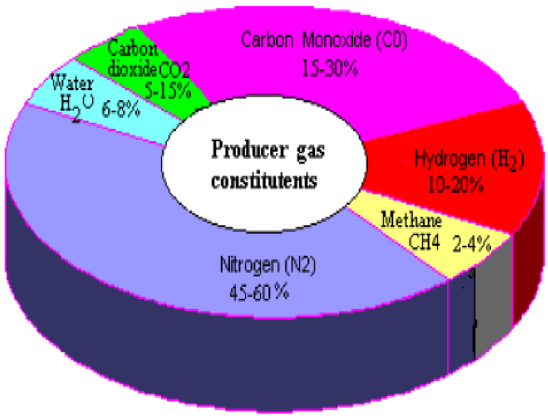

Figure 2. Syngas yields from gasification process [57]

The main reactions show that heat is required during the reduction process. Hence, the temperature of gas goes down during this stage. If a complete gasification takes place, all the carbon is burned or reduced to carbon monoxide and some other mineral matter are vaporized. The remaining are ash and some char [unburned carbon]. The synthesis gas (syngas) or producer gas is the mixture of combustible and non-combustible gases. The quantity of gas constituents depends upon the types of fuels and operating conditions. Typical producer gas constituents are shown in Figure 2. The heating value of producer gas usually varies from 4.5 to 6 MJ/m^3 (standard conditions) depending upon the quantity of its constituents [58,59].

4. Gasification Systems

Various gasification technologies have been under investigation for converting biomass into a gaseous fuel. A characteristic of the various gasifiers is the way in which the fuel is brought into contact at the gasification stage. In general, gasification technology is selected on the basis of available fuel quality, capacity range, and gas quality conditions. Table 3 shows the thermal capacity of different gasifier designs.

Table 3. Thermal capacity of different gasifier designs [52]

Design Type	Capacity
Downdraft gasifier	1 kW -1 MW
Updraft gasifier	1.1 MW -12 MW
Fluidized-bed gasifier	1 MW -50 MW
Cross draft gasifiers	W -200 MW

Larger capacity gasifiers are preferable for treatment of municipality solid waste as a feedstock and gasifier type; because they allow for variable fuel feed, uniform process temperatures due to highly turbulent flow through the bed, good interaction between gases and solids, and high levels of carbon conversion [52]. The gasifiers can be characterized based on the gas and stock flow path and illustrated in Table 4.

Table 4. Gasifiers Characterization [52]

Down draft		Updraft	Cross draft
Closed top	Open top		
- Old design - Reasonably dry wood - Good quality gas - For engine and thermal use	- Recent development - Reasonably moist biomass - Much better gas quality - For engine and thermal use	- High tar - For thermal use - Better gas quality - For better thermal use	-High moisture biomass - High tar - For thermal use

5. Gasifier Classifications

5.1. Fixed Bed Gasifiers

Fixed bed gasifiers have grates built in to support the feedstock and maintain a stationary reaction bed. They are relatively easy to design and operate but have limited capacity. Therefore, fixed bed gasifiers are preferred for small to medium scale applications with thermal requirements up to 1MW [60]. Fixed bed gasifiers can be classified as either updraft or downdraft depending on the method of air introduction.

5.1.1. Updraft or Countercurrent Gasifiers

In this type of reactor, air is taken in at the bottom, and the gas leaves at the top. The biomass moves counter to the gas flow and passes successively through drying, pyrolization, reduction, and hearth zones. In the drying zone, the biomass is dried. In the pyrolization zone, it is decomposed into volatile gases and solid char. The heat for pyrolization is mainly delivered by the upward-flowing producer gas and partly by radiation from the hearth zone. The advantages of this type of gasifier are its simplicity, relatively low gas-exit temperature, high thermal efficiency and as a result, biomass with high moisture content (up to 60% wb) [2] can be gasified without any pre-drying of the feed. Moreover, size specifications are not very critical for this gasifier [61]. Major drawbacks are the high amounts of tar produced.

5.1.2. Downdraft or Co-current Gasifiers

In the downdraft gasifier, air is introduced into downward flowing packed bed or solid fuels and gas is drawn off at the bottom. The zones are similar to those in the updraft gasifier; but the order is somewhat different [2,55]. A lower overall efficiency and difficulties in handling higher moisture and ash content are common problems in small downdraft gas producers. In addition to these drawbacks, it is important for downdraft gasifiers to maintain uniform high temperatures over a given cross-sectional area in the reaction chamber. These factors limit the use of downdraft gasifiers to a power range of less than 1 MW [55,61,62].

5.2. Fluidized Bed Gasification

Fluidized-bed gasification was initially developed to overcome operational problems of fixed-bed gasification of fuels with high ash content, but is suitable for large capacities (more than 10 M) in general [2]. The fuel is fed into a suspended (bubbling fluidized-bed) or circulating (circulating fluidized-bed) hot sand bed. The bed behaves like a fluid and is characterized by high turbulence. Major problems with fluidized bed gasification are the resulting high tar content (up to 500mg/Nm^3) (Wei, 2005), incomplete carbon combustion, and poor response to load changes. Problems with feeding, instability of the reaction bed, and fly-ash sintering in the gas channels can occur with some bio-fuels [61,62]. There are two principal types of fluidized bed gasifiers namely, bubbling fluidized bed (BFB) and circulating fluidized bed (CFB).

5.3. Entrained Flow Gasification

Entrained flow gasifier needs pulverized fuel and is operated above the ash melting point (>1000°C). Ash is removed as liquid phase and due to the high temperature tar content is very low. Two types of entrained flow gasifiers can be distinguished: slagging and non-slagging. In a slagging gasifier, the ash forming components melt in the gasifier, flow down the walls of the reactor and finally leave the reactor as a liquid slag. Generally, the slag mass flow should be at least 6% of the fuel flow to ensure proper operation. In a non-slagging gasifier, the walls are kept free of slag. This type of gasifier is suitable for fuels with only little ash.

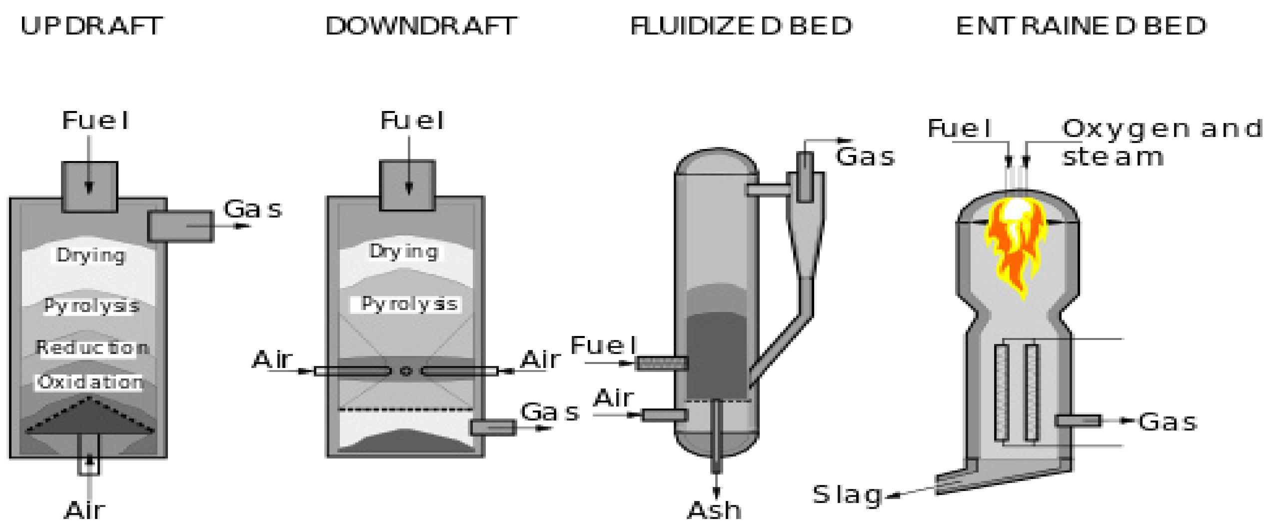

Figure 3. Main types of gasifier reactors [63]

Figure 3 shows the various schematics of Updraft, Downdraft, Fluidized Bed and Entrained Bed gasifiers [63].

5.4. Plasma Gasifier

In a plasma gasifier a high-voltage current is fed to a torch, creating a high-temperature arc. The inorganic residue is retrieved as a glass like substance [63].

6. Gas Quality and Characteristics

6.1. Gas Quality

The product gas formed from biomass gasification contains both combustible and noncombustible components. The generation of H_2S is of little importance in biomass gasification as long as the biomass contains less than 0.5% sulfur content. NH_3 is dependent on the nitrogen content of the biomass and biomass with less than 2% nitrogen is safe for gasification [56].

Table 5. Typical Characteristics of Fixed-Bed and Fluidized-Bed Gasifiers [2]

Characteristic	Fixed-bed downdraft	Fluidized-bed
Fuel size: (mm)	10 – 100	0 -20
Ash content (%)	<6	< 25
Operating temperature(°C)	800 – 1400	750 -950
Control	Simple	Average
Turn down	4	3
Capacity	<2.5	1 -50
Tar content(g/m^3)	<3	<5
LHV(MJ/m^3)	4.5	5.1

In gasification, tar is defined as a mixture of organic compounds in the product stream that are condensable in the gasifier or in downstream processing steps or conversion devices [64]. The gas quality indicates the extent to which the gas is suitable for end use equipment or process and is represented by several parameters including chemical composition, tar and particulate concentration, and Lower Heating Value (LHV) and is dependent upon the requirements of the end use itself. Typical Characteristics of Fixed-Bed and Fluidized-Bed Gasifiers are shown in Table 5.

6.2. Gasifier Fuel Characteristics

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. However the real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with 20 – 40% stoichiometric air but that a reliable gas producer can be made which can also be economically attractive to the customer. Towards this goal the fuel characteristics have to be evaluated & fuel processing done [65]. A gasifier is very fuel specific and it is tailored around a fuel rather than the other way round.

7. Factors Influencing Gasification

7.1. Energy Content of Fuel

Fuel with high energy content provides better combustion. This is most especially obtained when using biomass that is freshly obtained. Deteriorated biomasses, such as those dumped on roadsides and along river banks for several months, were observed to be more difficult to gasify than the fresh ones. The choice of a fuel for gasification will be partly based on its heating value – the higher is the heating value (energy content) of the fuel, the higher is the efficiency of the gasifier. The method of determination of the fuel energy content will influence greatly on the efficiency estimation of the gasification system: fuel higher heating value determined experimentally using an adiabatic bomb calorimeter; fuel higher heating value on a moisture-free basis. Thus, the only realistic and most reliable way of presenting fuel heating value for gasification purposes is to adduce lower heating value (excluding the latent heat of water evaporation) [52].

7.2. Fuel Moisture Content

Biomass materials exhibit a wide range of moisture content and since this affects its value as a fuel source, it is important that the basis be stated whenever moisture content is measured [64]. If the moisture content is excessive, the combustion process may not be self-sustaining and supplemental fuel must be used which could defeat the objective of producing energy by biomass combustion [66]. Biomass with low moisture content can be properly gasified than that with high moisture content. Moisture content as an important input design parameter must be known for assessment of the cost of or energy penalty in drying the biomass. The moisture in biomass can remain in two forms: (i) free, or external; and (ii) inherent, or equilibrium. Free moisture is that above the equilibrium moisture content. It generally resides outside the cell walls. Inherent moisture, on the other hand, is absorbed within the cell walls. When the walls are completely saturated the biomass is said to have reached the fiber saturation point, or equilibrium moisture. Equilibrium moisture is a strong function of the relative humidity and weak function of air temperature. For example, the equilibrium moisture of wood increases from 3 to 27% when the relative humidity increases from 10 to 80%.Moisture content (M) is determined by the test method given in ASTM standards D-871-82 for wood, D-1348-94 for cellulose, D-1762-84 for wood charcoal, and E-949-88 for RDF (total moisture). For equilibrium moisture in coal one could use D-1412-[67]. In these methods, a weighed sample of the fuel is heated in an air oven at 103°C and weighed after cooling. To ensure complete drying of the sample, the process is repeated until its weight remains unchanged. The difference in weight between a dry and a fresh sample gives the moisture content in the fuel. Standard E-871-82 specifies that a 50 grams wood sample be dried at 103°C for 30 minutes. It is left in the oven at that temperature for 16 hours before it is removed and weighed. The weight loss gives the moisture (M) of the proximate analysis. Standard E-1358-06 provides an alternative means of measurement using microwave [4].

7.3. Dust Content

All gasifier fuels produce dust. This dust is a nuisance since it can clog the internal combustion engine and hence has to be removed. The gasifier design should be such that it should not produce more than 2 – 6g/m^3 of dust [65]. The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance.

7.4. Tar Content

Tar is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends upon temperature and heat rate and the appearance ranges from brown and watery (60% water) to black and highly viscous (7% water) [65]. There are approximately 200 chemical constituents that have been identified in tar so far. Very little research work has been done in the area of removing or burning tar in the gasifier so that relatively tar free gas comes out. Thus the major effort has been devoted to cleaning this tar by filters and coolers. A well-designed gasifier should put out less than 1 g/m^3 of tar [68]. Usually it is assumed that a downdraft gasifier produces less tar than other gasifiers [69]. However because of localized inefficient processes taking place in the throat of the downdraft gasifier it does not allow the complete dissociation of tar.

7.5. Ash and Slugging Characteristics

The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. The ash content of a fuel and the ash composition has a major impact on trouble free operation of gasifier. Biomass used for gasification usually contains10 to 12% moisture. For the biomass with high moisture content, drying should be done first before they are used as fuel for the gasifier [66].

7.6. Temperature within the Reactor

To achieve a high carbon conversion of the biomass and a low tar content, a high operating temperature (>800°C) in the gasifier is recommended. With the increase in temperature, combustible gas content, gas yield, hydrogen, and heating value all increased significantly, while the tar content decreased sharply. Although this showed that higher temperatures are favorable for biomass gasification, [70,71,72] from an overall process perspective, reduction of ash agglomeration requires lower temperatures. In practice, this may limit gasification temperatures up to 750°C [73]. Temperature affects not only the amount of tar formed but also the composition of tar by influencing the chemical reactions involved in the gasification network [74]. To produce a relatively clean gas by increasing temperature, several operational strategies are reported in the literature. Fagbemi *et al.* [75] showed that tar yields were increased first while temperature rose up to 600 °C and then dropped after the 600°C temperature was surpassed. At higher temperatures, primary C_nH_m were less significant and secondary reactions (i.e., tar cracking) prevailed. In the combustion zone of the gasifier, reactions between char and oxygen played a more dominant role, however [76]. Mae *et al.* [77] conducted experiments for treatment of biomass in nitrogen and air at 240-340°C in order to examine the low-temperature region in a downdraft gasifier by analyzing the treated precursors and product distribution. Gas-treated precursors were then pyrolyzed in flash mode at 764°C for further analysis. Overall, the tar yield decreased from approximately 50 wt % to less than 20 wt % upon oxidation of the sample at a very low heating rate to 260-300°C in air. Moreover, tar evolution was almost completely suppressed during the subsequent flash pyrolysis.

Temperature within the reactor during gasification also affects the production of flammable gas. There is a need to properly insulate the reactor so that during gasification, flammable gas can be produced. Biomass ash and refractory materials are good examples of materials effective in maintaining high temperature in the reactor for better gasification.

7.7. Reactivity

Reactivity of the fuel is a very important factor as it determines the rate of reduction reactions in the gasifier (from carbon dioxide to carbon monoxide). Reactivity depends on the type of the fuel (morphological characteristics, geological age) and can be improved through the stream treatment with activated carbon or with lime and sodium carbonate. Also the small quantities of potassium, sodium and zinc can act as catalysts and affect the rate of gasification.

8. Gasification Agents

Gasification agents are means of supplying oxygen in to the gasifier. They are mainly divided into:

a) Air gasification

Most common method of gasification is using air as gasification agent. This method is straight forward and very simple, requiring less capital and operating cost. However presence of inert Nitrogen in air dilutes the gas and hence lowers the calorific value per unit volume of gas.

b) Oxygen gasification

Oxygen gasification can be achieved by removing Nitrogen from air prior to supplying to the gasifier. This involves some additional cost, but avoids previously mentioned gas dilution problem and results in medium level of energy content of gas per unit volume.

c) Steam gasification

This is highly endothermic process. The heat needed should be supplied by external heat source or by partial oxidation of fuel. Partial oxidation of fuel is achieved by mixing steam with air or oxygen. This method produces gas with higher energy content compared to previous methods.

d) High temperature air/steam gasification

This novel method, with increase of physical enthalpy of gasification agent, ensures economic and environmental benefits over above all methods and attracts more attention nowadays. Average product gas composition (vol. %) with different gasification agents are given in Table 6.

Table 6. Variation of gas composition with different gasification agents [78]

Gasification agent	H_2%	CO%	CO_2%	N_2%	CH_4%	H_2:CO
Air	15	20	15	48	2	0.75
Oxygen	40	40	20	0	0	1
Steam	40	25	25	2	8	1.6

9. Factors Affecting Gasifier Design

There are several factors to consider in designing a gasifier. Proper consideration of these factors will be of great help in order to come up with the desired design of the gasifier and its desired .performance. As given below, the different factors that need to be considered in designing a gasifier using biomass as fuel are:

9.1. Type of Reactor

The operating performance of the biomass gasifier basically depends on the type of the reactor used. Although there are several types of combustor that can be used, the top lit updraft (T-LUD) or the inverted downdraft (IDD) under the down-draft type gasifier was proven to work well with this waste material as compared with the traditional bottom-lit downdraft type, cross-draft type, or updraft-type reactors. Of the different types of reactor, T-LUD/IDD has better operating characteristics in terms of ease of starting the fuel, least smoke emitted, and tar produced during operation. In this type of reactor, smooth operation of producing gas can be achieved. However, it has one disadvantage: it is difficult to operate in a continuous mode. A cross-draft type reactor is more fitted for a continuous operation except that smoke emission and erratic burning of gas are experienced in this type. Combining these two types in one reactor would be a new approach in the design development of a biomass gasification stove in the future.

9.2. Cross-sectional Area of the Reactor

This is the area in which biomass is burned and this is where the fuel is gasified. The wider the cross-sectional area of the reactor, the stronger the power output. Uniform gasification can be achieved when the reactor is designed in circular rather than in square or in rectangular cross-section.

9.3. Height of the Reactor

The height of the reactor determines the time the gasifier can be operated continuously and the amount of gas that can be produced for a fixed column reactor. Usually, the combustion zone moves down the entire height of the gasifier reactor at a speed of 1 to 2 cm/min. The higher the reactor, however, the more pressure draft is needed to overcome the resistance exerted by the fan or by the blower.

9.4. Thickness of Fuel Bed

The thickness of the fuel bed is only considered when designing a cross-draft gasifier. It is the same as that of the height of the reactor in the down-draft gasifier. Similarly, the thicker the layer of fuel in the reactor, the greater is the resistance required for the air to pass through the fuel column. The only advantage in using a thicker column of biomass is that it slows down the downward movement of the combustion zone in the reactor, which can help in minimizing the erratic production of flammable gas during gasification.

9.5. Fan Airflow and Pressure

The fan provides the necessary airflow that is needed for the gasification of biomass. They are available in AC or DC. The fan to be used should be capable enough to overcome the pressure exerted by the biomass and, subsequently, by the char. A high pressure fan is usually ideal for down-draft type gasifier reactor, while low-pressure fan is used for cross-draft type reactor. The amount of airflow per unit mass of biomass is about 0.3 to 0.4 of the Stoichiometric air requirement of the fuel. A kilogram of biomass usually requires about 4.7 kg of air to completely burn the fuel. In case of unavailability of suitable longer fan size needed, two fans can be used which are positioned either in parallel or in series with each other. Multistaging of fan was proven to be effective in increasing the available pressure for the same airflow. Using blowers can overcome pressure in long reactors or those with thicker fuel column. However, the noise produced by its impeller can be destructive to the users.

9.6. Burner Type

The commonly used LPG type burner can be utilized for a biomass gasifier. However, there is a need to retrofit the burner design to allow proper combustion of fuel gas. Retrofitting includes enlarging of the inlet pipe of the burner and the provisions of a cone to induce secondary air, thereby making the gas properly ignited and burned. If the burner is to be designed and be fabricated for the biomass gasifier, burner holes of about 3/16 to 1/4 of an inch spaced at 1/8-in. apart were proven to work well with gasified biomass. The air for combustion should be introduced at the exhaust port of the burner rather than at the inlet port.

9.7. Insulation for the Reactor

The gasifier reactor needs to be properly insulated for two reasons: First, this will provide better conversion of biomass fuel into gas. Second, this will prevent burning of skin when they accidentally touch the reactor's surface. Biomass ash was found to be the cheapest and the most effective insulation material for biomass gasifier. Concrete mixed with biomass, at a proportion of 1:1 can also be used as an insulator. However, the reactor will become heavier and freight cost would be more expensive.

9.8. Location of Firing the Fuel

Biomass fuel can be fired in the stove in different ways. For fixed bed gasifiers, like the down-draft reactor, the fuel can be fired starting from the top (Top Lit) or from the bottom (Bottom Lit) of the reactor. So far, for an inverted down-draft type gasifier, firing the fuel on top is the best and easiest way. Firing the fuel in this manner minimizes smoke emission. However, reloading of fuel in between operation is not possible. Experience on the previous gasifier design revealed that reloading of fuel during operation is only possible when burning of fuel starts from the bottom of the reactor. The other advantage of firing from the bottom is that the total start-up time for the same height of the reactor can be extended, which cannot be done when firing the fuel from the top of the reactor.

9.9. Size and Location of the Char Chamber

The size of the chamber for carbonized biomass determines the frequency of unloading the char or the ash. Bigger chamber can accommodate larger amount of char and can allow longer time before the char is removed. In addition, designing a shorter chamber will give sufficient height for the gasifier reactor and the burner. If the desired by-product of gasification is char, the size of the chamber should not be too big so that it will only require a shorter time before it is discharged. The hot char discharged from the reactor undergoes further burning which will consequently convert the char into ash. To properly discharge the ash or the char from the reactor, the angle of friction at the bottom of the chamber hopper should be at 45 degrees. In the case of limited angle, scraper or scoop will be needed to properly discharge the ash or the char.

9.10. Pressure Draft of Fuel and Char

During gasification, the column of fuel and of char inside the reactor exerts pressure to the fan in moving the air. The amount of pressure exerted depends on the thickness of the column as well as the nature of the fuel and the char, at various superficial gas velocities. In order to overcome the resistance exerted by the char, a small percentage of about 10% should be added to the data obtained from the biomass.

10. Basic Design Formulae

In order to achieve the desired design of the gasifier, factors such as: Type of reactor, cross-sectional area of the reactor, height of the reactor, thickness of the fuel bed, fan airflow and pressure, insulation for the reactor, location of firing the fuel, size and location of the char chamber, intended uses and safety considerations; need to be taken into account.

There is need to determine the overall amount of power needed. This can be estimated from the energy requirement, thus the amount of fuel to be supplied to the burner, to meet the energy required for cooking or boiling. From there on, compute the size of the combustion chamber of the gasifier in terms of diameter and height of the reactor.

Other parameters like thickness of insulation and sizes of materials can also be computed [52]. Computing the amount of air and the pressure draft needed to gasify biomass. These are important information in the selection of the fan or blower needed for the reactor.

The energy demand, which refers to the amount of heat that needs to be supplied by the gasifier, can be determined based on the amount of food to be cooked and /or water to be boiled and their corresponding specific heat energy (i.e. if coking or water boiling is the main task) as shown in Table 7.

Table 7. Energy Requirement for Cooking Food and for Boiling Water [51]

Food	Specific Heat (kcal/kg-°C)	Total Energy needed (kcal/kg)
Rice	0.42-0.44	79.3
Meat	0.48-0.93	56.5
Vegetables	0.93	74.5
Water	1.0	72

The quantity of energy needed can be evaluated using the formula [51,52].

$$Q_n = \frac{M_f \times E_s}{T} \quad (10)$$

where:
Q_n - energy needed, kcal/hr
M_f - mass of food, kg
E_s - specific energy, kcal/kg
T – Cooking time, hr

The energy input in terms of fuel in the gasifier [51].

$$FCR = \frac{Q_n}{HV_f \times \xi_g} \quad (11)$$

where:
FCR - fuel consumption rate, kg/hr
Q_n - heat energy needed, kcal/hr
HV_f - heating value of fuel, kcal/kg
ξ_g - gasifier burner efficiency, %.

Gasifier burner efficiency assumed to be 17%. [50].

The reactor diameter is thus [51,52]:

$$D = \left(\frac{1.27FCR}{SGR}\right)^{0.5} \quad (12)$$

where:
D - Diameter of reactor, m
FCR - fuel consumption rate, kg/hr
SGR - specific gasification rate of biomass.

The height of the reactor would be [51,52]:

$$H = \frac{SGRxT}{\rho_{rh}} \quad (13)$$

where:
H - Length of the reactor, m
SGR - specific gasification rate of biomass, kg/m^2-hr
T - Time required to consume biomass, hr
$\rho_{biomass}$ – density of biomass considered, kg/m^3

The time to consume the biomass [51,52]:

$$T = \frac{\rho_{biomass} \times Vr}{FCR} \quad (14)$$

where:
T - time required to consume biomass, hr
V_r - volume of the reactor, m^3
$P_{biomass}$ – density of biomass considered, kg/m^3
FCR - rate of consumption of biomass, kg/hr.

If the proposed gasifier is circular, for the amount of air needed for gasification [52], it is very important to determine the size of the fan or of the blower needed for the reactor. This can be simply determined using the rate of consumption of biomass fuel (FCR), the Stoichiometric air of biomass (SA), and the recommended equivalence ratio (ε) for gasifying rice husk of 0.3 to 0.4 [51].

$$AFR = \frac{\varepsilon xFCRxSA}{\rho_a} \quad (15)$$

where:
AFR - air flow rate, m
ε - Equivalence ratio, 0.3 to 0.4 [51]
FCR - rate of consumption of biomass, kg/hr
SA - Stoichiometric air of biomass
ρ_{ra} - air density, 1.25 kg/m^3.

The superficial air velocity, which refers to the speed of the air flow in the fuel bed, is [52]:

$$Vs = \frac{4AFR}{\pi(D)^2} \quad (16)$$

where:
Vs - Superficial gas velocity, m/s
AFR - air flow rate, m^3/hr
D - Diameter of reactor, m

The total resistance to air flow [52]:

$$R_f = T_{f \times} S_r \quad (17)$$

where:
R_f - Resistance of fuel, cm of H_2O
T_f - thickness of fuel column, m
S_r - specific resistance, cm of water/m of fuel.

10.1. Blower Technical Characteristics

The blower technical characteristics are determined using formulas as suggested by Vibhakar & Chaniwala [79].

1.) Air density (ρ):

$$1.325 \times \left(\frac{P_b}{T_a}\right). \quad (18)$$

2.) Air velocity ($V_{(i.o)}$):

$$1.096.2 \times \sqrt{\frac{P_{v(i,o)}}{\rho}} \quad (19)$$

3.) Duct cross sectional Area ($A_{(i,o)}$):

$$\frac{\pi \times d_{(i,0)}^2}{4} \quad (20)$$

4.) Volumetric flow rate ($Q_{(i,o)}$):

$$V_{(i,o)} \times A_{(i,o)} \quad (21)$$

5.) Avg. Volumetric Flow Rate (Q_{avg})

$$\frac{Q_i + Q_0}{2} \quad (22)$$

6.) Power Output of Fan (W_o)

$$\frac{Q_{avg} x\Delta P_s xK_p}{6362} x \frac{0.746kw}{1hp} \quad (23)$$

7.) Mechanical Efficiency of Fan (η_f)

$$\frac{W_o}{W_i} \quad (24)$$

Where:
P_b = Barometric pressure, Pa
T_a= Absolute temperature, °C
P_v = inlet and outlet dynamic pressure, P
ρ = Density, kg/m^3
d= Duct diameter, m
$V_{(i.o)}$ =inlet and outlet velocity, m/
$A_{(i,o)}$ = Duct cross sectional Area, m^3

Q_i = inlet volumetric flow rate, m^3/s
Q_o = outlet volumetric flow rate, m^3/s
ΔP_s= static differential pressure, Pa
K_p=Air compressibility factor
W_o = power output of blower, kW
W_i= power input to blower driver shaft, kW.

10.2. Gasification Efficiency

The gasification efficiency (Equation 25) [80] is a very complex but crucial criteria in determining the performance of any designed gasifier. It depends on the fuel used to raise the temperature of the feed material before stimulating the production of the gas. Depending on the nature and calorific value of the feed, the gasification efficiency varies between 70 -85% [81]. In order to determine this parameter, major tests of importance are; the determination of the elemental chemical components of the gas produced through proximate and ultimate analyses and/or a thermal test to determine the calorific value of the produce gas using a bomb calorimeter.

$$\eta_g = \frac{\text{Heating value of gas} \times \text{gas flowrate}}{\text{Heating value of fuel} \times \text{fuel consumption rate}} \quad (25)$$

Where: η_g= the gasification efficiency.

11. Conclusion

At the end of the review, the following conclusions were drawn:

1. Biomass gasification has received tremendous attention throughout the world.
2. Biomass as a renewable source has the potential to contribute to sustainable energy across the world due to its advantage in providing a continuous feedstock supply.
3. The thermo-chemical and physical characteristics of the biomass and together with the optimum design of the gasifier are parameters of crucial importance.

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