

Biomass Gasification Processes in Downdraft Fixed Bed Reactors: A Review

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Abstract—Biomass Gasification is a chemical process that converts biomass into useful convenient gaseous fuels or chemical feedstock. It has emerged as a promising technology to fulfill the increasing energy demands of the world as well as to reduce significantly the volume of biomass waste generated in developing societies. In this paper, 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 are reviewed

Index Terms—Gasification, biomass, downdraft gasifier (DDG), equivalence ratio(ER), producer gas.

I. INTRODUCTION

Biomass is a non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms. This shall also include products, by-products, residues and waste from agriculture, forestry and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes. Biomass has high but variable moisture content and is made up of carbon, hydrogen, oxygen, nitrogen, sulphur and inorganic elements. The utilization of biomass is a very important source of energy in many parts of the world, especially for areas remote from supply of high-quality fossil fuels. Biomass power has also grown significantly in a number of European countries and in several developing countries, including China, India, Brazil, Costa Rica, Mexico, Tanzania, Thailand, and Uruguay. China's capacity rose 14 percent in 2009 to 3.2 Gigawatt (GW), and the country plans to install up to 30 GW by 2020. India generated 1.9 Terawatt-hours (TWh) of electricity with solid biomass in 2008. By the end of 2009, it had installed 835 Megawatt (MW) of solid biomass capacity fueled by agricultural residues (up about 130 MW in 2009) and more than 1.5 GW of bagasse cogeneration plants (up nearly 300 MW in 2009, including off-grid and distributed systems); it aimed for 1.7 GW of capacity by 2012. Brazil has over 4.8 GW of biomass cogeneration plants at sugar mills, which generated more than 14 TWh of electricity in 2009; nearly 6 TWh of this total was excess that was fed into the grid. As of 2007, the United States accounted for more than 34 percent of electricity from solid biomass generated in OECD (Organization for Economic Co-operation and Development) countries, with a

total of 42 Terawatt-hours (TWh). Japan was the OECD's second largest producer, at 16 TWh, and Germany ranked third, with 10 TWh. Although the U.S market is less developed than Europe's, by late 2009 some 80 operating biomass projects in 20 states provided approximately 8.5 GW of power capacity, making the United States the leading country for total capacity. Many U.S coal and gas fired power plants are undergoing partial or even full conversion to biomass by co-firing fuels in conventional power plants. Just over half of the electricity produced in the European Union from solid biomass in 2008 was generated in Germany, Finland, and Sweden. Biomass accounts for about 20 percent of Finland's electricity consumption, and Germany is Europe's top producer. Germany increased its generation of electricity with solid biomass 20-fold between 2002 and 2008. By early 2010, bioenergy accounted for 5.3 percent of Germany's electricity consumption, making it the country's second largest renewable generating source after wind power. The substitution of conventional fossil fuels with biomass for energy production results both in a net reduction of greenhouse gases emission and in the replacement of non-renewable energy sources [1]. Biomass energy conversion technologies especially pyrolysis and gasification have been substantially studied to promote renewable energy utilization and solving partially the environmental issues. Various types of gasification systems have been developed and some of them are commercialized. Yang et al. [2] concluded that fixed bed gasification is the most common technology for the energy use of biomass and solid municipal wastes. During the biomass gasification process, this renewable material undergoes different sub-processes. In a first step, biomass is dried up. Then, as the temperature increases, biomass is pyrolyzed and the lignin and cellulose are decomposed into volatile molecules such as hydrocarbons, hydrogen, carbon monoxide and water. Finally, the remaining solid fraction, which is called vegetal char, is oxidized when an excess of oxygen is available (combustion). When combustion developed with less oxygen than the stoichiometric, vegetal char is gasified by the pyrolysis and oxidation gases. This process is governed by the chemical reduction of hydrogen, carbon dioxide and water by char. The inorganic components in the biomass are not volatilized and remain in solid state as ash. However, at present, generating energy from biomass is rather expensive due to technological limits related to lower conversion efficiency [3]. Zainal et al. [4] performed experimental study on a downdraft biomass gasifier using wood chips and charcoal, varied the equivalence ratio from 0.259 to 0.46. It is found that the calorific value increases with equivalence ratio and reaches a peak value of 0.388, for which the calorific

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value is reported to be 5.34 MJ/Nm³. It is also observed that complete conversion of carbon to gaseous fuel has not taken place even for the optimum equivalence ratio. J. F. Perez et al [5] has been developed a steady, one-dimensional model of the biomass gasification process, which has been validated with biomass of different size and varying the air superficial velocity. This model allows evaluating the effect of the physical, chemical and energy properties of biomass (size, density, proximate and ultimate analysis, and heating value) on the gasification process. Moreover, it enables the study of the gasifier geometry, the heat exchange and the different injection points of the gasifying agent. Dogru et al. [6] carried out gasification studies using hazelnut shell as a biomass. Jayah et al. [7] investigated the gasification of chips of rubber wood of varying moisture content (12.5–18.5 %) and chip size (3.3–5.5 cm) in an 80 kW downdraft throated gasifier, which was double walled with an air gap in between. B.V. Babu et al [8] varied the range of air-to-fuel ratio 1.37–1.64 Nm³/kg and that of equivalence ratio varied is 0.262–0.314 and reported that optimum operation of the gasifier is found to be between 1.44 and 1.47 Nm³/kg of air-to-fuel ratios at the values of 4.06 and 4.48 kg/h of wet feed rate, which produces the producer gas with a calorific value of about 5 MJ/m³. H. Olgun et al [9] designed and constructed a small scale fixed bed downdraft gasifier system which uses agricultural and forestry residues as feed. The air to fuel ratio is adjusted to produce a gas with acceptably high heating value and low pollutants. Heating values above 4 MJ/Nm³ are achieved in less than 10 min with hazelnut shells and similar quality gas is obtained for about 45 min. With wood chips, 15min are required to reach 4MJ/Nm³ and the delivery of this quality gas is limited to 30 min. The obtained heating values are acceptable. The Equivalence Ratio resulting in the highest heating value product gas has been found as 0.35 for both biomass species investigated in this study.

II. GASIFICATION OF BIOMASS

Gasification is basically a thermo-chemical process which converts biomass materials into gaseous component. The results of gasification are the producer gas, containing carbon monoxide, hydrogen, methane and some other inert gases.

A. Types of Biomass

Biomass may also be divided into two broad groups: (a) Virgin biomass (b) Waste. Primary or virgin biomass comes directly from plants or animals. Waste or derived biomass comes from different biomass-derived products. Table. I, list a range of biomass types, grouping them as virgin or waste. Energy crops [10], a virgin biomass are grown especially for the purpose of producing energy encompassing short-rotation or energy plantations: they comprise herbaceous energy crops, woody energy crops, industrial crops, agricultural crops, and aquatic crops. Typical examples are eucalyptus, willows, poplars, assorghum, sugar cane, soya beans, sunflowers, cotton etc. These crops are suitable to be used in combustion, pyrolysis, and gasification for the production of biofuels, synthesis gas and hydrogen. Large quantities of agricultural plant residues are produced

annually worldwide and are vastly underutilized. The most common agricultural residue is the rice husk, which makes up 25% of rice by mass [11].

TABLE I. MAJOR GROUPS OF BIOMASS AND THEIR SUB CLASSIFICATION.

Virgin	Terrestrial biomass	Forest biomass, Grasses, Energy crops, Cultivated crops
	Aquatic biomass	Algae, Water plant
Waste	Municipal waste	Municipal solid waste Biosolids, sewage, Landfill gas
	Agricultural solid waste	Livestock and manures, Agricultural crop residue
	Forestry residues	Bark, leaves, floor residues
	Industrial wastes	Black liquor, Demolition wood Waste oil or fat

B. Components of Biomass

Cellulose, hemicellulose and lignin and extractives are found to be the major components of biomass. Raveendran et al. [12] has reported the composition of biomass in terms of these components. Table.II reproduces these results for different biomasses. Woody plant species are typically characterized by slow growth and are composed of tightly bound fibers, giving a hard external surface, whereas herbaceous plants are usually perennial, with more loosely bound fibers, indicating a lower proportion of lignin, which binds together the cellulosic fibers. The relative proportions of cellulose and lignin are two of the determining factors in identifying the suitability of plant species for subsequent processing as energy crops.

TABLE II. TYPICAL COMPONENTS OF DIFFERENT TYPES OF BIOMASS.

Plant	Lignin (wt. %)	Cellulose (wt. %)	Hemicellulose (wt. %)	Ash (wt. %)
Subabul wood	24.7	39.8	24.0	0.9
Wheat straw	16.4	30.5	28.9	11.2
Bagasse	18.3	41.3	22.6	2.9
Corn cob	16.6	40.3	28.7	2.8
Groundnut shell	30.2	35.7	18.7	5.9
Coconut shell	28.7	36.3	25.1	0.7
Millet husk	14.0	33.3	26.9	18.1
Rice husk	14.3	31.3	24.3	23.5

C. Composition of Biomass

Every biomass type has carbon, hydrogen, and oxygen as major chemical constitutive elements. These element fractions can be quantified with the ultimate analysis. Ultimate analyses are reported using the C_xH_yO_z formula where x, y, and z represents the elemental fractions of C, H, and O, respectively. To fully describe biomass characteristics, it is customary to provide the proximate analysis. Proximate analysis gives the composition of the biomass in terms of gross components such as moisture (M), volatile matter (VM), ash (ASH), and fixed carbon (FC). It is a relatively simple and inexpensive process. The ultimate analyses and proximate analysis of various biomass feed stocks are reported in Table.III, Table.IV respectively. Ultimate analysis is relatively difficult and expensive compared to proximate analysis.

TABLE III. PROXIMATE ANALYSIS OF VARIOUS TYPES OF BIOMASS.

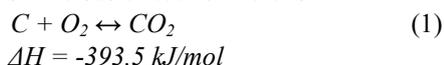
Biomass	VM (wt. %)	Ash (wt. %)	Fixed carbon (wt. %)
Bagasse	84.2	2.9	15.8
Coconut shell	80.2	0.7	19.8
Corn stalks	80.1	6.8	19.9
Groundnut shell	83.0	5.9	17.0
Rice husk	81.6	23.5	18.4
Subabul	85.6	0.9	14.4
Wheat straw	83.9	11.2	16.1

TABLE IV. ULTIMATE ANALYSES OF A DIVERSE VARIETY OF BIOMASS COMPOSITIONS (IN WT. %).

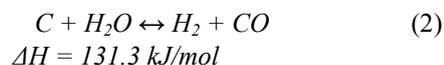
	Rice straw/husk	Sawdust	Sewage sludge	MSW	Animal waste
C (%)	39.2/38.5	47.2	29.2	47.6	42.7
H (%)	5.1/5.7	6.5	3.8	6.0	5.5
N (%)	0.6/0.5	0	4.1	1.2	2.4
O (%)	35.8/39.8	45.4	19.9	32.9	31.3
S (%)	0.1/0	0	0.7	0.3	0.3
Ash (%)	19.2/15.5	1.0	42.1	12.0	17.8

D. Chemistry of Gasification

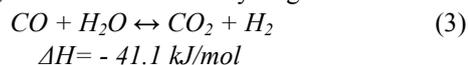
In a gasifier, the carbonaceous material undergoes several different processes like drying, pyrolysis, combustion, gasification processes. The dehydration or drying process occurs at around 100°C. Typically the resulting steam is mixed into the gas flow and may be involved with subsequent chemical reactions, notably the water-gas reaction if the temperature is sufficiently high enough. Pyrolysis (or devolatilization) process occurs at around 200-300°C. Volatiles are released and char is produced, resulting in up to 70% weight loss for biomass. The process is dependent on the properties of the carbonaceous material and determines the structure and composition of the char, which will then undergo gasification reactions. Combustion process occurs as the volatile products and some of the char reacts with oxygen to primarily form carbon dioxide and small amounts of carbon monoxide, which provides heat for the subsequent gasification reactions. The basic reaction here is



Gasification process occurs as the char reacts with carbon and steam to produce carbon monoxide and hydrogen, via the reaction



In addition, the reversible gas phase water gas shift reaction reaches equilibrium very fast at the temperatures in a gasifier. This balances the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen.



In essence, a limited amount of oxygen or air is introduced into the reactor to allow some of the organic material to be burned to produce carbon monoxide and energy, which drives a second reaction that converts further organic material to hydrogen and additional carbon dioxide.

Further reactions occur when the formed carbon monoxide and residual water from the organic material react to form methane and excess carbon dioxide. This third reaction

occurs more abundantly in reactors that increase the residence time of the reactive gases and organic materials, as well as heat and pressure. The ternary diagram (Fig.2) is a tool for representing the biomass conversion processes. The three corners of the triangle represent pure carbon, oxygen, and hydrogen- that is, 100% concentration. Points within the triangle represent ternary mixtures of these three substances. The side opposite to a corner with a pure component (C, O, or H) represents zero concentration of that component. For example, the horizontal base in the diagram opposite to the hydrogen corner represents zero hydrogen that is, binary mixtures of C and O. A biomass fuel is closer to the hydrogen and oxygen corners compared to coal. This means that biomass contains more hydrogen and more oxygen than coal contains. Lignin would generally have lower oxygen and higher carbon compared to cellulose or hemicellulose. The diagram can also show the geological evolution of fossil fuels. With age the fuel moves further away from the hydrogen and oxygen corners and closer to the carbon corner.

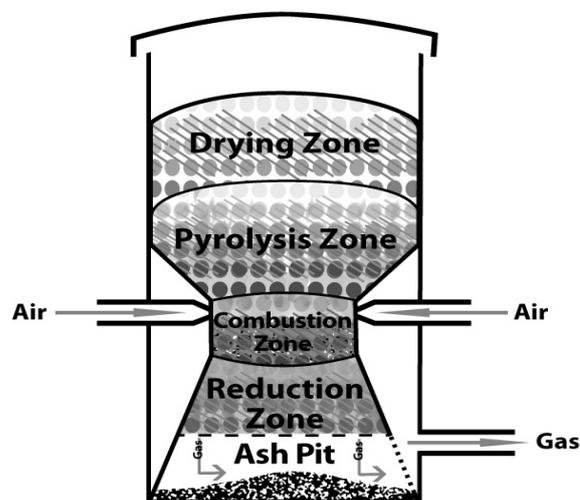


Fig. 1. Diagram showing the different zones in the process of gasification in downdraft gasifier.

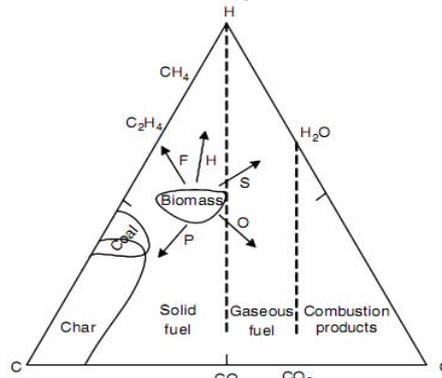


Fig. 2. C-H-O ternary diagram of biomass showing the gasification process. where, h-hydrogen s-steam o-oxygen p-slow pyrolysis f-fast pyrolysis l-lignin c-cellulose/hemicelluloses.

As mentioned above, the ternary diagram can depict the conversion process. For example, carbonization or slow pyrolysis moves the product toward carbon through the formation of solid char; fast pyrolysis moves it toward hydrogen and away from oxygen, which implies higher liquid product. Oxygen gasification moves the gas product toward the oxygen corner, while steam gasification takes the process away from the carbon corner. The hydrogenation

process increases the hydrogen and thus moves the product toward hydrogen.

III. DESIGN OF DOWNDRAFT GASIFIERS

Downdraft gasifiers are one among the fixed bed gasification systems. Downdraft gasification technology has an increased interest among researchers worldwide due to the possibility to produce mechanical and electrical power from biomass in small-scale to an affordable price. There exist mainly two designs for downdraft gasifiers: the Imbert gasifier (Throated or closed top gasifier) and the stratified gasifier (Throatless or open core gasifier). These gasifiers have been used for gasification of bark, wood blocks, chips and pellets, straw, maize cobs, refuse derived fuel (RDF), and waste pellets with various gasifying media like air, oxygen, Steam.

A. Imbert Downdraft Gasifiers

The Imbert downdraft gasifiers are suitable to handle biomass fuel having ash and moisture content less than 5% and 20% respectively [13]. This gasifier features a cocurrent flow of gases and solids through a descending packed bed, which is supported across a constriction or throat. The biomass fuel enters through the hopper and flows down, gets dried and pyrolysed before being partially combusted by the gasifying media entering at the nozzles. The throat allows maximum mixing of gases in high temperature region, which aids tar cracking. Below the constriction or throat the combustion gases along with tar pass through the hot char and are reduced to primarily CO and H₂. The imbert downdraft gasifier is generally used for gasification of woody biomass of uniform sizes and shapes as they flow smoothly through the constricted hearth. The producer gas from downdraft gasifier has lesser tar-oils (<1 %), higher temperature (around 700°C) and more particulate matter than that from an updraft gasifier. The gasifier has lower overall efficiency since a high amount of heat content is carried over by the hot gas [14, 15]. The physical limitations of biomass particle size limit the capacity of the imbert downdraft gasifiers to 500 kW.

B. Modifications in Imbert Downdraft Gasifiers

The throat of the imbert downdraft gasifier presents a hazard to low-density biomass fuels. The biomass in form of twigs, sticks or bars does not flow down smoothly causing bridging and channeling leading to increased tar production. The throated downdraft gasifier operation is very sensitive to feedstock size and quality. Modifications have been made in the gasifier to successfully gasify the low and medium density fuels like stalks, shells etc. Liinanki et al [16] introduced a rotating grate and a double conical hopper in a downdraft gasifier for gasification of coir dust, cotton stalk and wheat straw. The fuel had lower density and higher ash content compared to that of wood and was densified into briquettes. The double conical hopper in the gasifier created space for the fuel briquettes to expand when they were heated up to avoid the bridging problem in the pyrolysis zone. A rotating grate fed out the slag particles before their agglomeration in the gasifier. The distance between the

choke plate and the grate was also increased to increase the volume of the reduction zone to get better distribution of slag in the char bed. The gasification system consisted of a gasifier with a cyclone for coarse dust removal and a glass fiber-fabric for removal of fine material. The cold gas efficiency was 72-77 %. The tar content was below 1g/Nm³. Wheat straw pellets were also tested but due to small particle size, streams of cold gas passed between the throat and air nozzles resulting in incomplete tar cracking and in producer gas with high tar content.

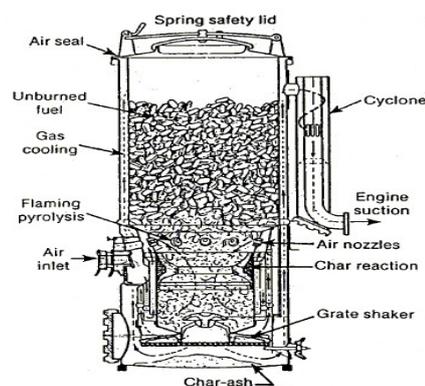


Fig. 3. Imbert type downdraft gasifier.

During the operation the gasifier was shaken to avoid bridging of fuel in throat. Small chips underwent faster char conversion increasing the conversion efficiency and therefore required smaller gasification zone length. Higher throat angle decreased temperature, reaction rate and conversion efficiency whereas smaller angles required a longer gasification zone length to reach optimum efficiency. For wood chip of moisture content 15 %, the optimum chip size was 5 cm, gasification zone length 22-33 cm, throat angle 61 degrees and conversion efficiency 56 %. The tar, water vapor and ash content were 7-9 % of the producer gas output. Sasidharan et al. [17] reported that downdraft gasifiers lined with ceramic material had greater life and lesser cost than downdraft gasifiers made of austenitic steel for biomass gasifier system below 500 kW. The gasifier made of steel failed at the throat and air nozzle region due to high temperature oxidation and corrosion mostly within 1500 hours of operation whereas the gasifier lined with ceramic material could withstand thermal shock. The composition of ceramic material was alumina (50-70 %), kaolin (16-20 %), feldspar (10-15 %) and talc (3-7 %). Warren et al. [18] reduced the grate spacing and increased the grate height so that it does not block with char in downdraft throated gasifier used for gasification of wood chips of coppice willow and poplar. The fine particles of the wood chips blocked the flow of air reducing the temperature in some areas of the throat. A fuel agitator was used to stir up the wood chip to allow free fuel flow but it was ineffective. The bridging of the fine fuel particles was not solved successfully so the fuel had to be removed of these particles prior to gasification.

C. Stratified Downdraft Gasifiers

The throatless (stratified or open top) downdraft gasifier was developed to overcome the problem of bridging and channeling in throated (Imbert) downdraft gasifiers. The

gasifier consists of a cylindrical vessel with a hearth at the bottom. During operation the air and biomass move downwards through the four zones in the reactor.

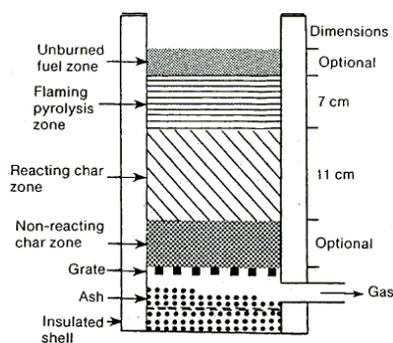


Fig. 4. Stratified downdraft gasifier.

The open top ensures uniform access of air and permits fuel to be fed easily and uniformly, which keeps the local temperatures in control [19]. The hot producer gas generated is drawn below the grate and up through the annulus of the reactor, where a part of the heat of the gas is transferred to the cold fuel entering the reactor, improving the thermal efficiency of the system. The pyrolysis components are cracked in the oxidation zone, as gas traverses a long uniformly arranged bed of hot char without any low temperature zones, therefore the tar generated is low 0.05 kg tar/kg gas. The open top throatless gasifier is suitable for small sized biomass having high ash content up to 20 % [20]-[23]. The gasifier is easy to construct and has good scale up properties.

D. Modifications in Stratified Downdraft Gasifiers

In order to improve the performance of throatless (stratified or open top) gasifier and use it for power and heat applications, changes were made in the design by allowing a varying air distribution in the gasifier, improving insulation of gasifier and re-circulating the gas within the gasifier. Mukunda, et al. [24] developed an open top gasifier consisting of a vertical tubular reactor with an open top and a water seal at the bottom. The lower two-thirds of the reactor was lined with a ceramic material to prevent high temperature corrosion. The upper part of the reactor was made of stainless steel with an annular jacket around it. The producer gas was drawn from below the grate and taken through an insulated pipe (re-circulating duct) to the upper annulus of the reactor where part of the sensible heat of the gas was transferred to the cold wood chips inside the reactor improving the thermal efficiency of the system. The entire reactor surface along with the re-circulating duct was insulated with aluminosilicate blankets. Dasappa et al. [25] developed an open top downdraft reburn reactor, a cylindrical vessel made of mild steel, with an inner lining of ceramic. Air nozzles were provided around the combustion zone. Uniform air distribution across the section was established by locating these nozzles at two different heights. The dual air entry from top and the nozzles favoured a high residence time for gases at elevated temperatures, thus eliminating the tar. The top of reactor helped in loading of fuel. The fuel bed was supported on an ash extraction screw. The screw was operated based on the ash content of biomass and / or the pressure drop across

the reactor. Two discharge outlets were provided for ash extraction. Altafini et al. [26] developed an open top stratified gasifier with internal gas recirculation, which could burn a part of the gas produced to raise the gasification temperature. The gasifier consisted of a cylinder with a cast iron grate fixed to a rotating shaft. Rods were fixed on the shaft to mix sawdust in the reduction zone and to extract the ash. In the center of the gasifier a device like a venturi aspirated part of the gases produced in it to be burnt in a chamber. The gasifier was used for gasification of 12 kg/h of sawdust of moisture content (9-11 %). With no recirculation of gases, the air / sawdust ratio had to be kept above 1.5 to get cold gas efficiency of 60 %, whereas with re-circulation of gases, the ratio was lower i.e. 1.1-1.4. Gas re-circulation raised the gasification reaction temperature, helped in burning a part of the tar and improved efficiency of gasifier. Strong mixing of sawdust was required to avoid bridging and channeling. The gasifier was used with a cyclone to remove particulate matter from producer gas. In another trial on the open core gasifier with gas re-circulation was conducted. The feed rate of sawdust, temperature and pressure in the gasifier was 11.34 kg/h, 800°C and 0.93 bar respectively. The moisture content of sawdust was varied from 0-30 %. It was observed that as the moisture content of the sawdust increased the air/dust ratio had to be increased to keep the temperature constant. The LHV of the producer gas reduced with the increasing moisture content of sawdust. Maximum cold gas efficiency (68 %) was achieved with sawdust having moisture content of 20 %. Barrio et al. [27] used a small-scale (30 kW) stratified downdraft gasifier to gasify wood pellets at a feed rate 5 kg/h. The design of the gasifier allowed for variation in the point of air injection along the length of gasifier. The grate was a perforated plate with a crank, which could be shaken manually. The equivalence ratio was lower (0.3) when air was taken in from the top (80 %) and sides (20 %) of the gasifier. It was 0.4-0.45 when 100 % air was taken in from the top (traditional open core). The gasifier produced 12 Nm³/h of producer gas with a calorific value of 5 MJ/Nm³ and CO and H₂ content of 20% each. The various downdraft gasifiers (Imbert Closed top and Stratified open top) with design modifications are shown in Fig.5.

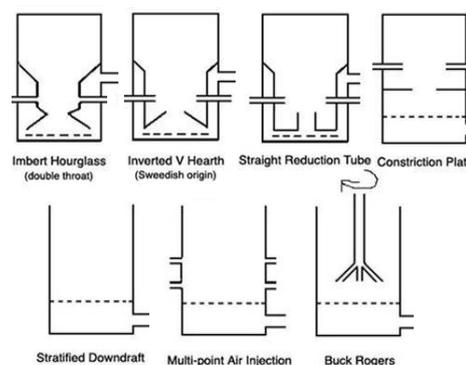


Fig. 5. The various downdraft reactor designs for gasification of biomass

IV. GASIFIER OPERATING CONDITIONS

A. Equivalence Ratio

The equivalence ratio (ER) is a key parameter that

considers the actual air/biomass ratio divided by the stoichiometric air/biomass ratio as

$$ER = (F_{\text{oxidant}}/F_{\text{biomass}})/(F_{\text{oxidant, stoichiometry}}/F_{\text{biomass}})$$

with stoichiometric oxidation or complete combustion taking place at $ER = 1$ [28]. The ER strongly influences the type of gasification products. This is very crucial because a high ER value results in a lower concentration of H_2 and CO as well as in a higher CO_2 content in the product gas. Thus, a higher ER decreases the heating value of the syngas. Increasing the ER also has a beneficial effect on reducing tar formation given the greater availability of oxygen to react with volatiles. This phenomenon is more significant at higher temperatures. On the other hand, an increase in the steam/biomass ratio is expected to produce a higher hydrogen fraction as a result of the water gas shift reaction. In addition, excess steam often drives the cracking of higher hydrocarbons and reforming reactions [29]. Lv et al. [30] divided biomass gasification into two stages based on the ER. In the first stage, the ER varied from 0.19 to 0.23. At this ER value, the gas yield increased from 2.13 to 2.37 $Nm^3 / (kg \text{ biomass})$ and the lower heating value (LHV) of the gas was augmented from 8817 to 8839 kJ/Nm^3 . In the second stage, the ER ranged from 0.23 to 0.27 and the heating value decreased as the ER increased, with this being the result of the influence of combustion in the gasification products. Garcia-Ibanez [31] reported that the maximum amount of H_2 (9.3 vol %) occurred at an ER of 0.59. When the ER range was between 0.59 and 0.73; this had a slight effect on the hydrocarbon content. However, according to Zhou et al. [32], ER does not significantly influence the concentration of nitrogen-containing products in biomass gasification. A slight increase in NH_3 was observed when the ER was increased from 0.25 to 0.37 at 800 °C in sawdust gasification. Nevertheless, the steam/biomass ratio provides an upper limit set by gasification stoichiometry. Exceeding this limit yields excess steam and H_2O in the product gas. The energy associated with excess steam and the enthalpy losses resulting from the unnecessary production of this steam need to be considered in the system energy balances. Such issues demonstrate the importance of selecting an optimal steam/biomass ratio in biomass steam gasification for achieving high process efficiency. Temperature, as described in Figure 6, is closely related to changes in ER and feeding rate. The bed temperature increased linearly with ER when the feeding rate was kept constant. On the other hand, higher feeding rates yielded a lower bed temperature at constant ERs. Typical values of ER for biomass gasification vary between 0.2 and 0.4. According to a number of studies, ER is one of the most important variables in the gasification process in fixed bed reactors [33], which affect the quality of syngas produced. In accordance with Garcia-Bacaicoa et al. [34], the amount of air fed into downdraft moving bed gasifiers controls the biomass consumption rate. The stoichiometric air/fuel ratio in cubic meters (at normal conditions) per kg of biomass can be expressed in terms of the chemical composition of the fuel and its typical value is between 5 and 6 Nm^3/kg when firewood is used. P. N. Sheth et al [35] in his studies reported that Molar fractions of N_2 and CO_2 decrease up to an equivalence ratio of 0.21. For larger values of ER

ranging from 0.21 to 0.41, there is an increase in N_2 and CO_2 fractions. This is opposite to the trend observed for H_2 and CO molar fractions. The temperature of oxidation zone varies from 900°C to 1150°C and that of pyrolysis zone varies between 150°C and 400°C. At an equivalence ratio of 0.21, the oxidation zone temperature passes through maxima. The trend of calorific value, producer gas production rate and cold gas efficiency variation is similar to that of variation of CO and H_2 fractions with an increase in equivalence ratio. With an increase in the equivalence ratio, calorific value, producer gas production rate and the calorific value have maxima at an equivalence ratio of 0.21.

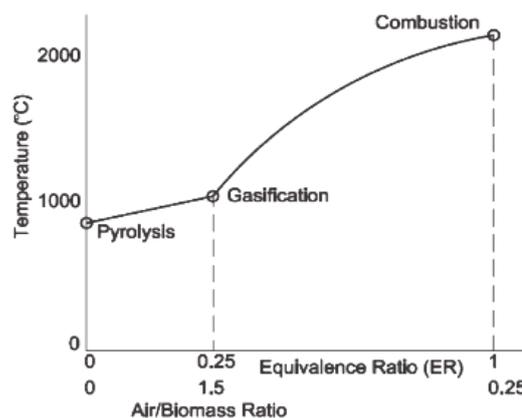


Fig. 6. Equivalence ratio and Air/fuel diagram.

B. Moisture Content

High moisture is a major characteristic of biomass. The root of a plant biomass absorbs moisture from the ground and pushes it into the sapwood. The moisture travels to the leaves through the capillary passages. Photosynthesis reactions in the leaves use some of it, and the rest is released to the atmosphere through transpiration. For this reason there is more moisture in the leaves than in the tree trunk. The total moisture content of some biomass can be as high as 90% (dry basis), as seen in Table . Moisture drains much of the deliverable energy from a gasification plant, as the energy used in evaporation is not recovered. This 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-1412-07. 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. However, this alternative represents only the physically bound moisture; moisture released through chemical reactions during pyrolysis constitutes volatile matter. The moisture content of some biomass fuels is given in Table.V. It is found that with an increase in the moisture content, the biomass consumption rate decreases. For higher moisture content of biomass, the energy requirement for drying increases and reduces the biomass pyrolysis. The biomass moisture content greatly effects both the operation of the gasifier and the quality of the product gas. The constraint of moisture content for gasifier fuels are dependent on type of gasifier used. Higher values of moisture content could be used in updraft systems but the upper limit acceptable for a downdraft reactor is generally considered to be around 40% on dry basis.

TABLE.V. MOISTURE CONTENT (MC) OF SOME BIOMASS FUELS USED IN THE GASIFICATION PROCESS.

Biomass	Corn stalks	Wheat straw	Rice straw	Rice husk	Dairy cattle manure
MC (wt%, wet basis)	40-60	8-20	50-80	7-10	88
Biomass	Wood bark	Saw dust	Food waste	RDF pellets	Bagasse
MC (wt%, wet basis)	30-60	25-55	70	25-35	40-50

C. Superficial Velocity

A superficial velocity, SV, is defined as a ratio of the syngas production rate at normal conditions and the narrowest cross sectional area of the gasifier. A number of authors have indicated that SV influences the gas production rate, the gas energy content, the fuel consumption rate, the power output and char and tar production rates. It is independent of reactor dimensions, allowing a direct comparison of gasifiers with different power outputs. Yamazaki et al. [36] reported a case with a good performance of the gasifier when low tar content in producer gas and high efficiency were obtained for SV values of about 0.4 Nm/s. Low values of SV result in a relatively slow pyrolysis process with high yields of char and significant quantities of unburned tars. On the contrary, high values of SV cause a very fast pyrolysis process, formation of a reduced amount of char and very hot gases in the flaming zone. However, such high SV values may significantly decrease the gas residence time in the gasifier, resulting in lower efficiencies in the tar cracking processes. The lowest gravimetric tar yield of 0.7% was obtained at 0.4 m/s SV, and the highest was obtained at 0.7 m/s. High tar yields at high SV are attributed to short residence time and channeling. In the region of 0.4-0.6 m/s SV, which gave low tar yield, the gas composition was

suitable for operation of an IC engine [37].

D. Operating Temperature

Researchers have conducted extensive studies reviewing the influence of temperature on tar production during biomass gasification [38]. 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, [39], [40, 41] from an overall process perspective, reduction of ash agglomeration requires lower temperatures. In practice, this may limit gasification temperatures up to 750 °C. [42] Moreover, Mahishi and Goswami [43] reported that the hydrogen at chemical equilibrium initially increased with temperature, reached a maximum, and then gradually decreased at the highest temperatures. 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 [44]. To produce a relatively clean gas by increasing temperature, several operational strategies are reported in the literature. Fagbemi et al. [45] showed that tar yields were augmented first while temperature rose up to 600 °C and then dropped after this temperature was surpassed. At higher temperatures, primary CnHm were less significant and secondary reactions (i.e., tar cracking) prevailed. This led to considerable tar decomposition [46]. In the combustion zone of the gasifier, reactions between char and oxygen played a more dominant role, however [47]. Subramanian et.al [48] identified two temperature ranges above and below 500°C. Generally temperatures above 500°C are chosen for reduction of carbon dioxide by carbon to carbon monoxide. Therefore, pyrolysis of biomass is carried out at temperature less than 500°C for the maximum yield of char with inert medium flowing complete gasification is achieved at temperature above 500°C with air flowing. K. Mae et al. [49] 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. This indicates that the structure of the treated precursors was gradually changed to suppress tar release through cross-linking reactions and partial oxidation. From elemental analysis of the precursors treated with air, it was also estimated that dehydration and partial oxidation proceeded simultaneously. The results indicate that the release of tar products such as dimers can be partially suppressed by air treatment at low temperature. Therefore, several factors including tar content, gas composition determining gas heating value, and char conversion should all be taken into consideration and weighted carefully in the selection of the gasifier operating temperature.

E. Gasifying Agents

Gasification under different atmospheres such as air, steam, steam oxygen, and carbon dioxide has been reported in the literature. In general, the gasifier atmosphere determines the calorific value of the syngas produced. When one uses air as the gasifying agent, a syngas with low heating value is obtained. This is mainly due to the syngas dilution by the nitrogen contained in air [50, 51]. However, if one uses steam or a combination of steam and oxygen, a syngas with a medium calorific value is produced [52]. In addition, the combined use of steam and air gives much higher H₂ yields than with air alone. This also helps to reduce the energy required for the process, which is normally provided by combusting a fraction of the biomass.

F. Residence time

Residence time has a significant influence on the amount and composition of the produced tars. According to Kinoshita et al [53] the fraction of oxygen-containing compounds tends to decrease by increasing residence time. Furthermore, yields of one and two aromatic ring compounds (except benzene and naphthalene) decrease with residence time, where as those of three- and four-ring species increase. Olivares et.al [54] observed a decrease in the total tar content when the space time was augmented in biomass gasification with a bed of dolomite.

V. CONCLUSIONS

Biomass has high potential to contribute to world energy needs. The fixed bed gasifier is the most practical option for production of a low calorific value gas for use in small-scale power generation schemes or thermal applications. The physical and chemical characteristics of biomass, capacity of gasifier and its intended application decides the choice of gasification system. The downdraft gasifier is suitable for both thermal and engine applications. The gasification of low-density biomass such as rice husk presents fewer problems in a throatless downdraft gasifier. The tar content can be minimized by separating pyrolysis and gasification zones as in two-stage gasifier. The commercial installations for fixed bed gasification systems have come up in many countries. The standardization of design and operating parameters of gasifiers, fuel processing and gas cleaning systems needs to be taken up to popularize small scale fixed bed gasification systems for decentralized thermal and power applications. The development in efficient utilization of biomass to meet energy needs will have dual advantage of reducing our dependence on commercial energy and protecting our environment. Although gasification technologies have recently been successfully demonstrated at small scale by the researchers and several demonstration projects are under implementation they still face economic and other non-technical barriers when trying to compete in the energy markets. This can be achieved via economic development through biomass systems integration.

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