

A Comprehensive Literature Review of Thermochemical Conversion of Biomass for Syngas Production and Associated Challenges

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ABSTRACT

The interest in the thermochemical conversion of biomass for producer gas production since last decade has increased because of the growing attention to the application of sustainable energy resources. Application of biomass resources is a valid alternative to fossil fuels as it is a renewable energy source. The valuable gaseous product obtained through thermochemical conversion of organic material is syngas, whereas the solid product obtained is char. This review deals with the state of the art of biomass gasification technologies and the quality of syngas gathered through the application of different gasifiers along with the effect of different operating parameters on the quality of producer gas. Main steps in gasification process including drying, oxidation, pyrolysis and reduction effects on syngas production and quality are presented in this review. An overview of various types of gasifiers used in lignocellulosic biomass gasification processes, fixed bed and fluidized bed and entrained flow gasifiers are discussed. The effects of various process parameters such as particle size, steam and biomass ratio, equivalence ratio, effects of temperature, pressure and gasifying agents are discussed. Depending on the priorities of several researchers, the optimum value of different anticipated productivities in the gasification process comprising better quality syngas production improved lower heating value, higher syngas production, improved cold gas efficiency, carbon conversion efficiency, production of char and tar have been reviewed.

Key Words: Biomass, Thermochemical, Gasification, Types of Gasifiers, Operating Parameters.

1. INTRODUCTION

Mounting trepidations about the ecological problems related to the fossil fuels usage, world energy strategy aims to the promotion and development of alternative energy resources for sustainable application along with less or

no environmental problems [1]. Various initiatives have been taken and multiple targets are set to meet stringent emission requirements like roadmap 2050 [2], the framework for climate change 2030 [3], particularly 20-20-20 targets as promoting up to 20% share of

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renewable energy in EU (European Union) countries, by reducing 20% GHG (Greenhouse Gas) emissions into environment and 20% rise in energy efficiency in 2020 [4]. Alternative energy resources include wind, solar, tidal geothermal and biomass etc. are renewable and environmental friendly as compared to the fossil fuels. Among numerous alternative energy sources, the application of biomass as an alternative resource bring about many social, economic and environmental improvements. The management of biomass inappropriate manner reduces net carbon dioxide emissions almost zero and offers economic wellbeing of rural and semi-urban areas [1]. Biomass resources are extensive and copiously available in the world. However, one-third of total energy is obtained from biomass in developing countries of Asia and Africa. As the thermochemical transformation of lignocellulosic biomass is attractive prospect meant for the recovery of gas, liquid and solid products. The gas produced through thermochemical conversion of biomass is called synthesis gas or syngas. The syngas produced by thermochemical conversion of biomass possesses a substantial quantity of energy. The syngas obtained may further be exploited for power production and biofuel synthesis. Char produced during the gasification of biomass is organic inert material mainly containing carbon and ash. This transformation shows a partial oxidation of the carbon available in untreated biomass, usually takes place in the presence of gasifying carriers such as steam, carbon dioxide, air or oxygen. The condensation of heavier hydrocarbons takes place in temperature ranging from 250-300°C. Various types of unwanted gases are also produced, H₂S (Hydrogen Sulfide), hydrochloric acid and inert gas N₂ (Nitrogen). The presence of undesirable gases heavily relies on the treatment of raw materials and operational

parameters of gasification unit. The composition of the syngas depends on the operating conditions, especially the amount of hydrocarbons and tar. Normally the LHV (Lower Heating Value) of syngas is observed from 4-13MJ/Nm³ [5]. The amount of char produced strongly rests on gasification method and operational parameters. The lower heating value of char is in between 25-30MJ/kg [6]. The heat required to carry on the reaction is generally provided at the oxidation stage through allothermal or auto-thermal method. In the auto-thermal method of gasification, takes place through the internal heating of gasifier with partial combustion and in allothermal gasification process energy necessary to carry on the reaction is supplied externally. Thus the syngas produced has wide application for the synthesis of various chemicals including methanol, MTBE (Methyl Turt Butyl Ether) and DME (Dimethyl Ether). Syngas can be converted into liquid transportation fuel through Fischer-Tropsch synthesis methods depending on different H₂/CO ratios [7]. Further, in Integrated Gasification Combined Cycle both heat and power could be achieved. However, fossil fuels consumption produces a large amount of greenhouse gases [8], it is important to reduce the environmental impact caused by the non-renewable sources. As from numerous renewable energy means biomass is utmost significant environmental friendly resource widely available around the world for the generation of syngas and electricity [9]. Moreover, raw biomass when compared with coal has low utilization efficiency because raw biomass possesses ahigh quantity of moisture, high hydrogen to carbon ratio as well as high oxygen to carbon ratio. The main stages in gasification are, drying (endothermic stage, heat is absorbed), oxidation (an exothermic stage, heat is evolved), pyrolysis, and reduction both are endothermic stages in gasification. The additional steps

may be tar decomposition, in order to consider the creation of light hydrocarbons because of the disintegration of larger tar molecules [10]. Main steps in gasification processes are shown in Fig. 1 and are discussed in subsequent sections below. However, the overall energy structure consumes enormous quantities of natural resources and the most of the energy produced is derived from fossil fuels, which possesses serious environmental and health hazards. The more production of greenhouse gases results in severe global warming, which damages the ozone layer. Due to the high demand of energy, the number of fossil fuel power plants are installed that results in more production of carbon dioxide during fuel combustion, which is increased from $0-22 \times 10^{12}$ kg/year in between 1890-2009. Considering fossil fuels limitations, and the environmental glitches related to their application in the world is so far from attaining a sustainable energy future. Instead, we are strongly dependent on the non-renewable energy sources [11].

The conversion of biomass into energy through different conversion routes is shown in Fig. 2. In this study,

thermochemical conversion technologies for biomass into syngas its technical challenges, operating parameters and their effect on the syngas quality are reviewed.

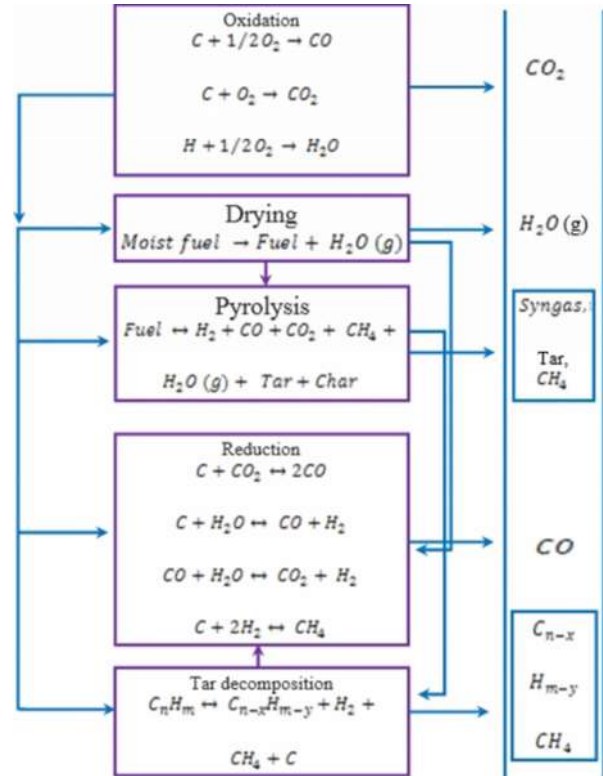


FIG. 1. MAIN STAGES IN GASIFICATION PROCESS [10]

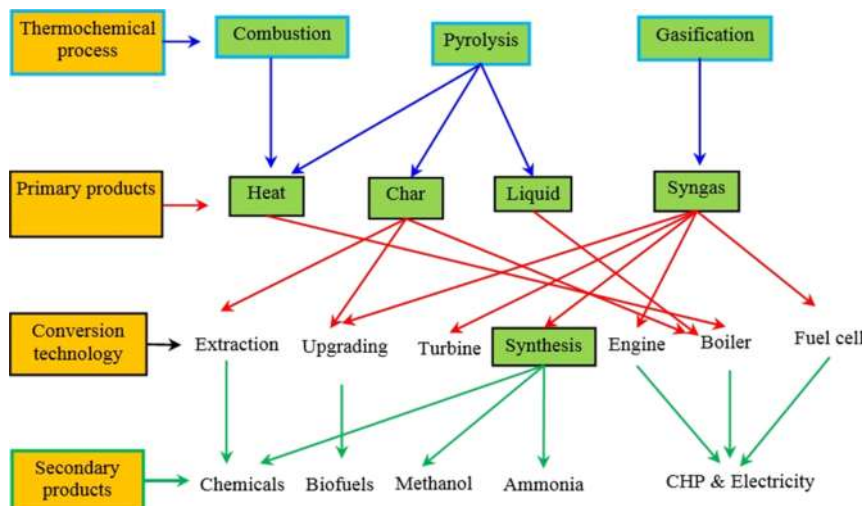
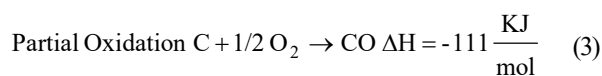
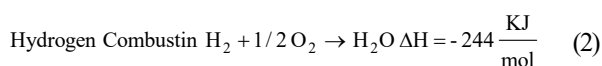
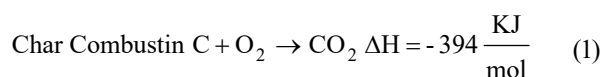


FIG. 2. THERMOCHEMICAL CONVERSION ROUTES FOR ENERGY PRODUCTION MAIN STEPS DURING GASIFICATION

1.1 Oxidation

In gasification process, the oxidation of biomass is performed to attain and sustain the thermal energy required to carry out endothermic processes at the desired level. In oxidation stage, restricted supply of oxygen is maintained in order to attain the stoichiometric ratio to oxidize the only portion of the material. Regardless of fractional oxidation involve entire carbonaceous types including tars; it is probably to make sure that only chars and hydrogen present in syngas take part in the partial oxidation process. During oxidation processes the main reactions take place are listed as follow:



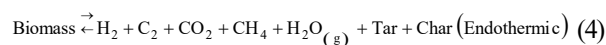
The thermal energy obtained in this step is required to maintain the whole process, whereas the combustion products are CO, CO₂ and water. When feedstock oxidation process is executed through the air the gas mixture may contain nitrogen, if only oxygen is used the nitrogen presence is practically absent in gas mixture.

1.2 Moisture Content and Drying of Biomass

The evaporation of moisture available in the feedstock is drying. The heat needed for the removal of moisture available in the feedstock is proportional to the moisture content within the biomass. In gasification generally, the heat needed for the removal of moisture is taken from the other stages of the gasification process. Drying is considered complete by increasing the temperature of biomass well above 150°C [12].

1.3 Pyrolysis

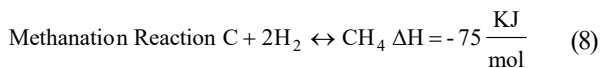
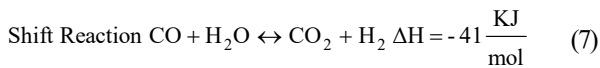
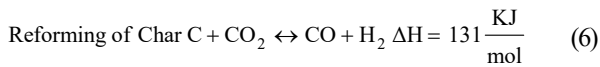
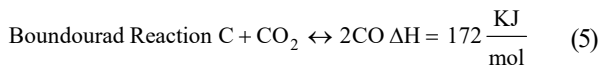
In this part of the gasification, thermochemical decomposition of feed takes place particularly, the breakdown of chemical bonds into smaller molecules having lower molecular weight are formed during pyrolysis phase. Pyrolysis products are mainly solids, liquids and gaseous fractions. The solid fractions obtained in this phase ranges from 5-10 weight percent for fluidized bed gasifier and 20-25 weight percent for fixed bed gasifier [13-14], is characterized by high heating value and high carbon content. The liquid fraction obtained in the form of tars fluctuates depending upon the type of gasifier used, the liquid tar content nearly 1% for downdraft gasifier, 1-5% for bubbling fluidized bed gasifier and 10-20% for updraft gasifier. The tars are complex organic material, which may be condensed at lower temperature ranges. The gases obtained in pyrolysis phase vary 70-90 weight percent of the feed material. Gas produced at pyrolysis stage is called pyrolysis gas primarily consisting of CO, CO₂, H₂ and light hydrocarbons, CH₄ and insignificant parts of acid or inert gases that may not be condensed at ambient temperature. The temperatures are maintained from 250-700°C to carry out pyrolysis reactions. In pyrolysis reactions, heat is absorbed which is directed from oxidation stage of the gasification process. The overall pyrolysis reaction is given below [15].



When biomass feedstock used for gasification contains cellulosic material nearly 50% of the weight, in such type of reactions the feed material is specified using the formula of cellulose C₆H₁₀O₆. In pyrolysis reaction various complex processes are observed such as heat transfer, product diffusion from biomass pores towards gas phase reactions occurring in series, high temperatures are maintained for cellulosic materials at pyrolysis stage from 600-700°C.

1.4 Reduction

In reduction reactions, the product obtained react with homogenous and heterogeneous gasification reactions to form syngas. Reactions taking place at reduction stage are mainly.



Both boudouard and char reforming reactions absorb heat and are well known as endothermic reactions during reduction stage [16], whereas, both water gas shift and methanation reactions are exothermic reactions. Reactions (4 and 7 are) chemical equilibrium reactions. According to thermodynamic equilibrium law in reactions 4 and 7 both product and reactants can coexist and maintain their concentration. The variations in temperature have a significant effect on the final gas composition. Lower temperature causes lower heating values of syngas and produces more tar, while higher temperatures upswing the oxidation of char and decrease the presence of tar in the syngas. The temperature effects are summarized in Fig. 3.

The effects of temperature on syngas production have guided to various technological solutions, producing syngas and a solid residue of different composition. The various temperatures at which gasification can be carried out at commercial level ranges from 800-1100°C. When gasification is performed using oxygen the temperatures are maintained in the range of 500-1600°C.

2. TYPES OF GASIFIERS

Gasifiers are generally of three types, as classified into fixed bed gasifiers, entrained flow gasifiers and fluidized bed gasifiers. Fixed bed gasifiers are further categorized as downdraft gasifiers, updraft gasifiers, cross draft gasifiers and open core gasifiers [17]. Whereas fluidized bed gasifiers are classified as bubbling fluidized bed gasifiers, circulating fluidized bed gasifiers and dual fluidized bed gasifiers [18-20]. Fixed bed gasifiers are less efficient and produce low heating value syngas, these gasifiers are appropriate for small and medium scale operations. Subsequently in fixed bed gasifiers mixing of feed does not take place, therefore to achieve a uniform temperature within the reactor is very difficult. As fluidized bed gasifiers have limited application when coal is used as a raw material for gasification due to low carbon conversion efficiency caused due to low bed temperature ranging from 800-1000°C. Fluidized bed gasifiers are best suited for lignocellulosic materials as lignocellulosic materials gasifying at lower temperatures as compared to that of the coal. Problems associated with the operation of updraft and downdraft gasifiers are also obviated in fluidized bed gasifiers. Fluidized bed gasifiers have got impetus over fixed bed gasifiers, currently, the major focus is kept on fluidized bed gasifier development on a

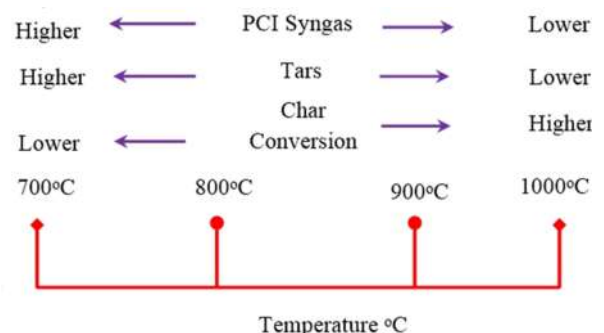


FIG. 3. TEMPERATURE VARIATIONS EFFECT ON SYNGAS CHARACTERISTICS

commercial scale. A number of technologies have been explored regarding fluidized bed gasifiers involving in biomass gasification, among these technologies, two types are commonly employed for this purpose circulating fluidized beds and bubbling fluidized beds [21]. In this study fixed bed gasifiers, entrained flow gasifiers and fluidized bed gasifiers are discussed in subsequent sections (Fig. 4).

Depending on the nature and type of reaction air blown gasifier comprises on four segments including drying, pyrolysis, combustion and reduction segments.

2.1 Updraft Gasifiers

Updraft gasifier is the oldest and simplest gasifier used for biomass gasification. In updraft gasifier air and necessary gasifying agents are introduced from the bottom of the gasifier. The supplied air moves upward of the gasifier as represented in Fig. 5, whereas feed is introduced from the top of the updraft gasifier and moves downward under the force of gravity creating countercurrent flow within gasifier. The drying segment is positioned at the top of the gasifier where biomass is introduced followed by pyrolysis, reduction and oxidation segments. Biomass first moves into the drying section where moisture is removed by maintaining the temperature above 100°C, during downward movement, biomass moves into pyrolysis section where biomass experiences

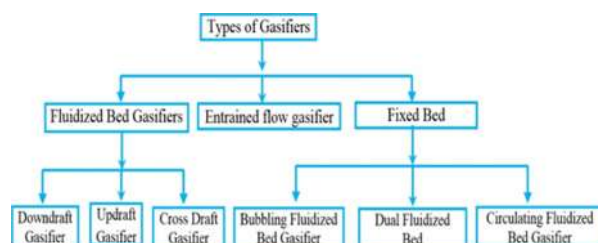


FIG. 4. TYPES OF GASIFIER USED IN BIOMASS GASIFICATION

disintegration and is changed into gases and char, followed by reduction zone, where, volatile gases and char produced are further changed to carbon monoxide and hydrogen. Finally, the unconverted char settles down in combustion zone, where solid charcoal is further combusted resulting in heat, and heat is effectively transferred to the solid particles moving downward to maintain pyrolysis and drying processes within the reactor.

In counter-current gasification, syngas is collected from the low-temperature zone located at top of the reactor resulting in the substantial amount of tar production as presented in Table 1. Countercurrent gasifier can accept higher moisture containing biomass up to 60% [23]. The major problem associated with updraft gasifier is high tar content. If the gas produced is to be introduced to internal combustion engines for power generation, it must go through the series of filtration steps to cut the tar concentration to a satisfactory level. The tar removal process further adds a financial burden on the investors and reduces the efficiency of the whole process. A considerable research has been done on the updraft gasifier over the last few years.

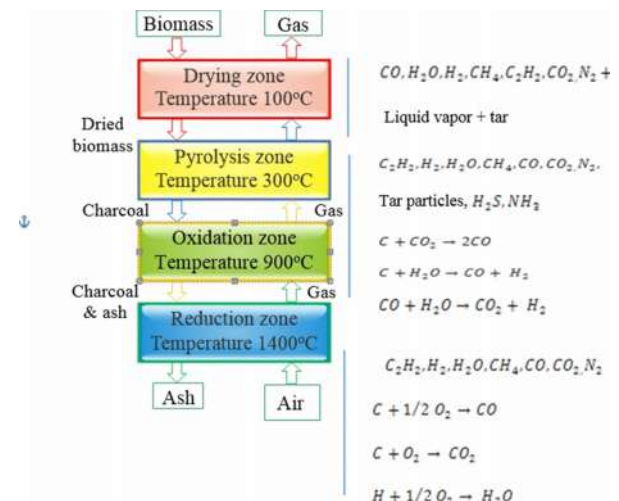


FIG. 5. THE ARRANGEMENT OF MULTIPLE STEPS IN UPDRAFT GASIFIER [22]

2.2 Downdraft Gasifier

In downdraft gasifier, feedstock and air are introduced from the top of the gasifier in drying zone. The feed material and air move downward co-currently from drying, pyrolysis, oxidation and reduction segments of downdraft gasifier. Diverse reactions are carried out in all section of the gasifier and are shown in Fig. 6. The gas produced during gasification process is drawn out from the bottom of the gasifier. In comparison to the updraft, downdraft gasifier produces less tar in product gas because of its thermal cracking in pyrolysis and reduction zones. As product gas passes from high-temperature oxidation and reduction zones, nearly the entire organic load is converted to form syngas. Downdraft gasifiers produce better quality syngas when compared with updraft gasifiers.

It is important to maintain the temperature of oxidation zone greater than 1000°C and the equal spreading of biomass and the gasifying agent is essential for smooth operation. The clean gas gathered from the gasifier is most appropriate for gas engines and gas turbines, since

the gas taken off from the downdraft gasifier possess relatively high temperature, needs cooling before downstream application [29]. The results obtained during the gasification of bagasse in downdraft gasifier reveal

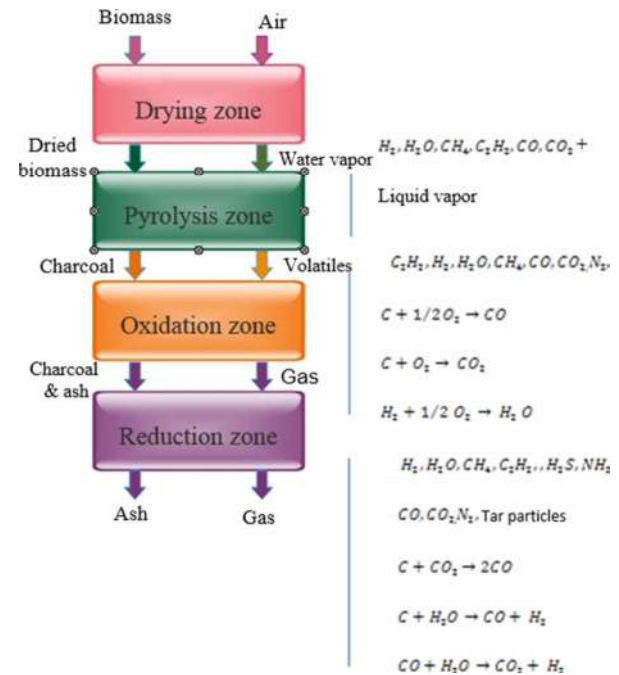


FIG. 6. THE ARRANGEMENT OF MULTIPLE STEPS IN DOWNDRAFT GASIFIER [22]

TABLE 1. GAS COMPOSITION IN PRODUCT GAS IN UPDRAFT GASIFIER UNDER DIFFERENT CONDITIONS

Biomass Type	Gasification Temperature (°C)	ER	Gas Composition (vol. %)	LHV (MJN/m ³)	HHV (MJ N/m ³)	Power (KW)	References
Cedar Wood	700-900	0-0.30	-	1-33.2	-	-	[24]
Cedar Wood	650-950	0-0.30	H ₂ (30-50), H ₂ S (35-39 ppmv), CO (22-53), CO ₂ (25-30), CH ₄ , (8-10), COS (< 2ppmv), N ₂ free	-	2.4-3.5	10	[25]
Mesquite Wood		2.7	CO (13-21), H ₂ (1.6-3), CO ₂ (11-25), N ₂ (60-64), CH ₄ (0.40-6),	-	2.4-3.5	10	[26]
Rice Straw	700-850	0.07-0.25	H ₂ (6-10), CH ₄ (4), CO ₂ (11-25), CO (10-18), NH ₃ (3100 ppmv), Cl ₂ (ppmv), N ₂ (46-63),	0.47-1.92	3.62-5.14	45	[27]
Juniper Wood	-	2.7	H ₂ (2.5-3.5), CH ₄ (1.50-1.8), CO (21-25), CO ₂ (14-19), N ₂ (58-61)	-	3.5-3.9	10	[26]
Wood chip Coconut Shell	700-900	0.3	H ₂ (22-27), CO(27-40), CO ₂ (39-42), CH ₄ (7-9),	-	17	15	[19]
Agro land Willow	800-820	0.35-0.39	H ₂ (30-45), CH ₄ (8-12), CO (20-25), CO ₂ (15-20), COS (200 ppmv), H ₂ S (2300 ppmv)	2-12	-	60	[28]

that CO, H₂, CO₂, CH₄ were 23, 13, 11, and 4% respectively with HHV of 5MJ N/m³, and during the gasification of hazelnut shells the carbon dioxide concentration was observed slightly low and the heat content of syngas enriched to 6.25MJ N/m³ [30]. With the application of two-stage downdraft gasifier heating value was observed at 6.50 MJ N/m³ having tar content of 0.0450gN/m³, whereas total combustible gases were more than 45% (Table 2) [31].

2.3 Entrained Flow Gasifiers

In EFG (Entrained Flow Gasifier) raw material and air supply passage in the same direction (co-currently), the reactions occur in a dense cloud fine particles ranging from (0.1-1mm) at a very high temperature and pressure changing in range of 19.70 and 69.10 atmosphere and the temperature is maintained well above 1000°C. Among the various types of gasifiers, entrained flow gasifier is a suitable choice for industrial scale operation. Entrained flow gasifier holds high efficiency for the production of syngas. The fabrication material required for entrained flow gasifier is of high quality because very high temperature and pressure are maintained within the gasifier. Feedstock required for gasification in entrained flow gasifier is of fine quality powder in order to achieve maximum conversion efficiency. Furthermore, the high temperature and pressure cause low tar formation during conversion process [33]. EFG offer constant temperature, higher heating rate and short residence time, currently, these are employed mainly in coal and liquid fuels, thus

have a little experience with biomass as a feedstock [34]. Several efforts have been carried out to maintain the required size of biomass to comply with gasifier requirements, but it adds to the economic burden of overall operational cost making it commercially unattractive option. Fuel particle size affects the entire successive steps such as fuel heating, reactants and syngas quality. Pre-treatment of feedstock is necessary to lessen the bulk density and moisture level available in biomass for the healthier operation of the process. Nevertheless, steam gasification upturns the hydrogen content of product gas, thereby increasing the lower heating value [22] (Fig. 7).

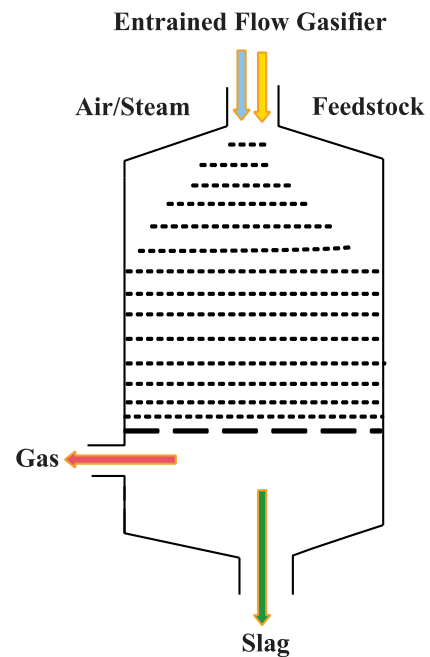


FIG. 7. THE ARRANGEMENT OF ENTRAINED FLOW GASIFIER.

TABLE 2. GAS COMPOSITION AND TAR CONTENT OF SYNGAS IN DOWN DRAFT GASIFIER

Biomass Type	Gasification Temperature (°C)	ER	Gas Composition (vol %)	Tar (gN/m ³)	HHV/LHV (MJ N/m ³)	Power (KW)	References
Bagasse	1040	-	-	0.367-.40	-	50	[29]
Hazelnut Shells	1000	0.351	H ₂ (13), CO (23), CO ₂ (11), CH ₄ , (4)	-	5.0	45	[32]
Wood Waste	900-1050	0.20-0.35	H ₂ (8-12), CO (15-22), CO ₂ (5-8), CH ₄ (1-3), N ₂ (60-70)	-	4.5-6.25	15	[30]

2.4 Bubbling Fluidized Bed Gasifiers

These gasifiers are simplest and low-cost gasifiers, used for continuous biomass gasification. BFB (Bubbling Fluidized Bed) gasifiers can be operated at a varied range of feedstocks with different particle amounts comprising powdered biomass. High heat transfer rate between bed material and fuel is achievable in BFB gasifier, besides that uniform temperature throughout the bed area can be maintained within gasifier. BFBs are effective to deliver uniform syngas production during operation. The syngas produced contains a lesser quantity of unconverted carbon and tar [35, 36]. BFB gasifiers are commonly used in biomass gasification operations, numerous investigations are reported in literature about the performance of BFBs nevertheless, the output varies in many inquiries regarding the desired quality of final product. It is difficult to attain the high solid conversion in BFB gasification due to the back mingling of particles. Even though higher mixing rates in BFBs enhances the product level. In BFBs mixing of partially and fully gasified constituents' effects on solid stream comprising partly gasified particles which decrease the conversion of solids within the gasifier. The oxygen diffusion rate is very slow in gasifier creating an oxidizing state in the reactor thus dropping the gasification efficiency. Above mentioned intrinsic restrictions of BFB gasification adversely affects the syngas production. These inherent limitations are overwhelmed in CFBs (Circulating Fluidized Beds) by providing extended solid residence time with the help of a solid circulating loop [37].

2.5 Circulating Fluidized Bed Gasifiers

In CFBs excessive rate of the fluid is maintained within the reactor in order to create a turbulent stream regime which entrains the bed particles and char in the gas stream. The entrained particles present in circulating streams are gathered from the top and moved to another unit for further

operations. However, in external CFB gasifiers, the solid particles are gathered into a cyclone, parted from the gas phase and recycled to the gasifier. The separation of particles continues throughout the operation period of the gasifier to enhance the residence time of solids [35]. The main problem associated with external (CBFs) is the addition of solid separation unit and the equipment required for the transportation of gathered solids recycled to the gasifier. The addition of solid separation equipment and solid return equipment further increase the installation cost along with causing difficulties in controlling of the process [38]. In recent years internal CFB gasifiers are considered as an attractive choice for gasification. Two separate chambers are provided in internal CFB gasifiers, these chambers function as a BFB bed gasifier and other chamber function as a pneumatic riser combustor. Bed material circulates between two chambers enabling the separation of tar and other residues which are further moved to the combustion chamber. Air is provided to carry out the char combustion, heat produced during the combustion of char is directed to combustion chamber which increases the temperature of particles available in the combustion chamber. The hot particles provide the heat necessary for endothermic steam gasification. They are sometimes termed as dual fluidized bed gasifiers as they comprise of BFB gasifier and CFB combustor, several studies are executed regarding CFBs and copious research originates in literature showing simulation and modelling of CFBs which may assist in the optimization of process parameters, design and scale-up of the gasifier. In CFB prolonged catalytic activity is achievable when compared with BFBs, whereas due to fouling in BFBs prolonged catalytic activity is difficult to maintain owing to deposition of carbon on a catalytic surface. The fouling of surface can be avoided in CFBs because of the burning of deposited carbon in the circulation process [39]. The operating parameters CFB gasifiers and their impact on syngas quality are discussed in subsequent sections.

3. MAIN FACTORS IN FLUIDIZED BEDS

For proper working of a biomass gasifier and the effect of different operating parameters on gasification performance requires a complete understanding of the process parameters. Lignocellulosic biomass possesses different properties such as morphological chemical and physical properties that may upset the overall process parameters, if not taken into consideration before the design and operation of the gasifier [40]. The selection of

biomass for gasification significantly depends on its heating value. Biomass materials possessing greater heat content improve the economy and performance of the plant. As fluidized beds provide effective heat transfer rates and can be operated at varying varieties of feedstocks [41]. The results of proximate and ultimate analysis of several feedstocks are shown in Table 3. For better syngas quality and minimizing the char and tar content in outlet streams, numerous researchers have been performed on different feedstocks in order to understand the kinetic characteristics before its gasification to happen.

TABLE 3. THE ULTIMATE AND PROXIMATE ANALYSIS OF BIOMASS.

Biomass Type	Ultimate Analysis (Dry Basis, wt. %)					Proximate Analysis (% w/w)				LHV (MJ/kg)	References
	C	H	N	O	S	FC	M	VM	Ash		
Cedar wood	51.10	5.90	0.12	42.50	0.020	18-20	a	80-82	0.3	19.26	[42]
Olive oil residue	50.70	5.89	1.36	36.97	0.30	19.4	9.5	76	4.6	21.2	[43]
Wood sawdust	46.20	5.1	1.5	35.4	0.06	17.9	10.4	70.4	1.3	18.81	[44]
Rice straw	38.61	4.28	1.08	37.16	0.65	16.55	5.58	65.23	12.64	14.40	[45]
Risk husk	45.8	6.0	0.3	47.9	-	13.1	12.3	73.8	0.8	13.36	[46]
Spruce wood pellet	49.3	5.9	0.10	44.4	-	17.10	8.4	74.2	0.30	18.5	[47]
Pine sawdust	50.54	7.08	0.15	41.11	0.57	17.16	a	82.29	0.55	20.54	[14]
Coffee ground	52.97	6.51	2.8	36.62	0.05	16.7	10.5	71.8	1.00	22	[48]
Coffee husk	46.8	4.9	0.6	47.1	0.6	14.30	10.4	74.3	1.00	16.54	[46]
Grapevine pruning waste	46.97	5.8	0.67	44.49	0.01	19.78	a	78.16	2.06	17.91	[49]
Larch wood	44.18	6.38	0.12	49.32		14.86	8.16	76.86	0.12	19.45	[50]
Sugarcane Bagasse	48.58	5.79	0.2	38.94	0.050	28.7-30.7	a	67-70	1.26	19.05	[51]
Jute stick	49.79	6.02	0.19	41.37	0.050	21.4-23.4	a	76-78	0.62	19.66	[51]
Peach stone	51.95	5.76	0.79	40.7	0.01	18.10	8.53	81.3	0.65	21.6	[52]
Corn cob	40.22	4.11	0.39	42.56	0.04	16.11	9.71	71.21	2.97	16.65	[53]
Cotton stem	42.8	5.3	1.00	38.5	0.20	15.50	7.9	72.3	4.30	15.2	[54]
Wheat straw	46.10	5.6	0.5	41.7	0.08	18.1	a	75.8	6.10	17.2	[55]
Camphor wood	43.43	4.84	0.32	38.53	0.100	14.750	12.29	72.47	0.49	17.48	[56]
straw	36.57	4.91	0.57	40.70	0.14	17.910	8.5	64.98	8.61	14.6	[39]
Switch grass	47	5.3	0.5	41.4	0.10	17.10	20	58.4	4.6	18.7	[57]
Beech wood	48.27	6.36	0.14	45.2	-	18	a	81	0.8	19.2	[58]

FC: Fixed Carbon, a Dry basis, VM: Volatile Matter, M: Moisture,

3.1 Effect of Temperature

Bed temperature during the operational process of the gasifier affects the heating value and composition of the syngas produced. Based on Le Chatelier's principle, the variations in temperature affect the syngas composition based on the thermodynamic characteristics of the reaction. In endothermic reactions high-temperature increases syngas production, while in exothermic reactions high temperature favors reactants. The purpose of gasification is to produce a syngas enriched in CH_4 , CO and H_2 having medium to a high heating value that is appropriate for turbines and internal combustion engines [59]. Increase in temperature increases combustion rate producing additional amounts of CO_2 and H_2O production. It has been investigated that high temperature enhances carbon conversion efficiency, produce less tar and char quantities. Rice husk gasification was observed at 700-800°C, it was monitored that rise in temperature from 700-800°C, the concentration of H_2 (Hydrogen) increased from 5.370-7.460%. A research was done by varying temperature in the range of 650-850°C. The maximum carbon conversion efficiency was achieved 82% and energy efficiency of 96% at 850°C while increasing temperature from 650-850°C improved hydrogen content from 4-15% [60].

3.2 Effects of Gasifying Agent

Numerous researches have been done on biomass gasification through FBG (Fluidized Bed Gasifiers) using different gasifying agents such as oxygen, steam and air, as gasifying agents [61]. Biomass gasification systems using air as a gasifying agent have been used on an industrial scale in various countries, air as a gasifying agent upsurges the overall feasibility of the gasification unit. Nonetheless, the addition of air as a gasifying agent produces syngas highly diluted by nitrogen available in the air with having Lower Heating Value in the range of 4.0-6.0 MJ/m^3 and H_2 content in the range of 8-14 volume%,

which is effective for electricity generation [61-62]. When biomass gasification is performed using O_2 enriched air gasification systems produce syngas having medium heating value, this system involves oxygen production equipment, which results in a rise in installation and operational cost of the process. Whereas steam-based gasification units produce syngas having heating value in the range of 10-16 MJ/m^3 and H_2 in range of 30-60 volume% while endothermic reactions reduce the temperature of the bed, supplementary equipment is necessary to maintain the temperature of the bed above 700°C [63]. In gasification systems using steam- oxygen as a gasifying agent, the heat required is directed from partial oxidation reactions. The syngas formed in steam-oxygen gasification has a high H_2 content and dilution with nitrogen is not favorable whereas, the cost incurred on pure O_2 is high making the overall process unfavorable on an industrial scale. For distinct feedstock flow rate, two ratios are necessary to be controlled for the evaluation of the gasification plant. One is Equivalence ratio when air or oxygen gasification is used while for steam to biomass ratio when steam is used as a gasifying agent.

3.3 Effect of Equivalence Ratio

In biomass gasification one of the most important parameters taken into consideration throughout the operation of the plant is ER (Equivalence Ratio). It is the amount of air to biomass weight ratio divided by stoichiometric air to biomass weight ratio required for complete burning of biomass [64]. It is noticed that maximum combustion happens at high ER when the higher quantity of air is supplied into the reactor, it increased char combustion to generate CO_2 , reducing the amount of combustible gases production such as H_2 , CH_4 , CO . Besides that increase in ER results decrease in the LHV of syngas as more ER encumbers the production of CH_4 and light hydrocarbons possessing fairly greater heating

values. At high ER ratio nitrogen available in air further, dilute the syngas reducing its energy content. Various studies carried out on ER have revealed that too small ER is also disparaging and adversely affect the gasification process as it causes the decrease in reactor temperature [14]. Hence, the appropriate value for equivalence ratio is from 0.20-0.40. ER value changes depending upon the required operating parameters and subsequent application of syngas [65]. Combustion of raw syngas in the downstream heating system, tar is not considered as a thoughtful concern, only product gas may possess high heating value, in this case, gasifier used can be supplied at minimum ER of nearly 0.20. When the temperature of the gasifier is maintained below 850°C tar yield increases, to control the tar formation ER should be increased to about 0.3-0.4 for better results [65]. Experimental results obtained by various researchers revealed that enhancing the ER above 0.4 decreased the quantity of CO, CH₄, H₂ and C₂H₂. The maximum concentration of 10% was observed at ER 0.260, besides that experimental results revealed that increasing the ER tar concentration lessened and at ER of 0.450 tar concentration further reduced to 2.0 g/m³. While LHV achieved was 5.20, and 3.50-4.50 MJ/m³ at ER of 0.250-0.450 respectively. It was observed from the gathered data that ER is in direct relationship with syngas yield.

3.4 Effect of Steam and Biomass Ratio

Steam and biomass ratio is the flow rate of steam divided by the biomass flow rate within the reactor for gasification of the biomass. Steam and biomass ratio in gasification is an important parameter taken into consideration during operation of gasifier. Lv et. al. [14] performed various experiments to investigate the significance of steam and biomass ratio on the quality of syngas by varying both ratios from 0.0-4.04, they

found that addition of steam to the gasifier enhanced the lower heating value of gas, carbon conversion efficiency and syngas production. According to their research steam to biomass ratio in the range of 1.35-4.040 is optimum at which, more steam reforming reactions of CO, CH₄ and C₂H₂ occurred due to the introduction of steam which produced more concentration of H₂ and CO. Qin et. al. [66] examined the outcome of steam and biomass ratio on the formation of tar and its properties by varying steam to biomass ratio in the range of 0.49-2.66 at 900°C, found that by increasing ratio, tar formation gradually decreased from 3.87-1.71%. At high steam and biomass ratio aromaticity of tar further reduced. The effect of steam-oxygen gasification on product distribution was analyzed by various researchers and observed by varying steam to oxygen ratio and steam, oxygen to biomass ratios from 2.0-3.0 mole/mole and 0.60-1.60 kg/kg correspondingly. The H₂ content of the syngas was 14-30 volume percent the decrease in H₂ was noticed as the steam to biomass ratio was improved or the steam to oxygen ratio was steadily lessened. However, when the quantity of O₂ was increased more quantity of H₂ was combusted in the gasifier, the alike tendency was found for CO, by changing the ratios and its concentration in the syngas was from 30-50 volume percent. As the gasifying agent to biomass ratio increased to a value above 1, it decreased the char yield to about 10%. Using steam in gasification process produce more H₂. Efforts are made to increase the production of syngas with a high concentration of H₂ and at the meantime capturing of CO₂ to increase the process performance. Limestone (CAO) is commonly used as a bed material to capture CO₂ in steam gasification process [50].

3.5 Effect of Biomass Size

Biomass size significantly affects the gasification efficiency, the smaller particle size of biomass raises

the overall efficiency of gasification unit, however, the smaller size of biomass increases the operational amount of the unit. A plant having 5-10 MW generation capacity, nearly 10% of the amount of energy produced is necessary to reduce the size of biomass [67]. While larger particle size decreases the initial treatment rate of biomass and increases devolatilization time. It is necessary to maintain balance by examining the outcome of biomass particle size on the overall efficiency of the process. Ly et. al. [14] experimented about the influence of particle size on the quality of syngas in four different assortments of 0.2-0.3, 0.45-0.6, 0.3-0.45 and 0.5-0.9mm. They investigated and concluded that lesser size of particles produced more C_2H_4 , CO, CH_4 and less quantity of CO_2 in contrast to larger particle size. With the application of small biomass gasification particle size, syngas yield, LHV, and carbon conversion efficiency increased. Small biomass particle size offers more surface area and greater heat transfer rate. Smaller particle size served in the production of more light gases and less quantity of condensate and char. In terms of cost comparison gasification of coal and biomass through thermochemical conversion process is one of the most economical and simple technology among the various renewable energy technologies. The biomass-based and coal power generation plants can be in the 1-20MW capacity range or higher. The smaller size of the plant is supported, where the biomass resources are available. Through the installation of the smaller size of power plants in biomass zones will reduce the transportation cost of the raw material [68]. The capital cost of energy produced using biomass and coal is lower when compared with wind energy and considerably lower than the electricity generated using diesel as a fuel. Therefore, the best option among various energy conversion technologies is thermochemical conversion of feedstock for energy production.

3.6 Effect of Catalyst

In biomass and coal gasification different types of catalysts are used in order to enhance the syngas composition in terms of CH_4 , CO and H_2 production. The most common catalysts normally used include MgO , Al_2O_3 , SiO_2 , TiO_2 , Fe/CaO catalysts. However, the order of catalytic activity in Methanation reaction was MgO , Al_2O_3 , SiO_2 , TiO_2 [69]. The addition of Ni-W/ TiO_2 - SiO_2 catalyst during gasification produces hydrogen enriched syngas. At higher temperatures syngas production increases because of the acceleration of reaction rate resulting in maximum production of syngas 63 weight percent and H_2 yield 172ml/g biomass [5].

4. CONCLUSION

Several efforts are taken to reduce the fossil fuels consumption and finding alternative energy resources that could meet the energy demand at the global level. In recent times, significant consideration has been devoted to biomass gasification technologies. The global availability of biomass and its thermochemical conversion in a number of valuable products make it one of the better alternative energy resource having the potential to replace fossil fuels. However, several investigations have been carried out on thermo chemical conversion of lignocellulosic biomass into syngas via fixed bed, fluidized bed and EFG. Different operating parameters have been examined to enhance the efficiency of the overall process. The better efficiency of FBG has been confirmed in the literature by a number of scholars as well as numerous effective operations of commercial plants in developed countries. In literature, it has been investigated that high temperature enhances carbon conversion efficiency, produces less tar and char

quantities. For rice husk gasification, the rise in temperature from 700-800°C the concentration of hydrogen (H₂) increased from 5.370-7.460%. ER from 0.3-0.4 produces less quantities of tar and enhances the syngas production. Experimental results obtained by various researchers revealed that enhancing the ER above 0.4 decreased the quantity of CO, CH₄, H₂ and C₂H₂. Besides that, smaller size of feedstock produces more C₂H₄, CO, CH₄ and less quantity of CO₂ in contrast to larger particle size. Whereas using steam in gasification process as a gasifying agent produce more H₂. Nevertheless, further exploration is necessary to increase the gas quality meant for its marketable uses with high energy content. For better syngas quality FBG with steam may increase the producer gas production and quality.

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