Biomass Gasification Systems and Different Types of Gasifiers, Effective Parameters on Gasification Process Efficiency: An Overview

Mehrdad Kordi[*1], Seyyed Masoud Seyyedi[*2]

Abstract –Biomass is considered as an effective energy carrier to meet the needs of clean energy for the whole world, which need to have sustainable renewable energy. Among the various methods of biomass, gasification is commendable. It is considered as one of the most important restoration and thermochemical methods for converting biomass energy into gaseous fuels, thermal and electrical energies, as well as its use for the production of biofuels. But there are some obstacles, which can be solve by more research in this area. In this article, various obstacles such as supply chain management include harvesting the waste, collection on the site, transportation to gasification site and storage are each a part of this chain. biomass pretreatment, generic low biomass resources and syngas conditioning from biomass energy conversion have been mentioned. Based on recent studies, the biggest challenges for biomass gasification is to produce heat and power. Also, different technologies of reactor design until reaching to the most efficient and high-efficiency reactor have been discussed in this paper. Ultimately, the most advanced gasification system with the most efficient gas conditioning technology can overcome all the mentioned obstacles.

Keywords: Biomass , Gasification, Sustainable , Renewable, Energy

1. Introduction

Climate change is becoming a central concern of the global society [1].In the past decades, the burning of fossil fuels has been identified as the main cause of climate change. The faster the reduction of fossil fuel emissions, the greater the probability to limit global warming to less than 2°C. The energy system based on fossil fuels has to be replaced by low carbon emission renewable energy sources along with improved energy efficiency. This is valid for all users of fossil energy: the cities, the countryside, buildings, industry, transport, agriculture and forestry sectors. Globally, the production of heat accounts for about 10 gigatonnes (Gt) of CO2 emissions – this is about 30% of all greenhouse gas (GHG) emissions. Presently, almost half of the global natural gas production is being used for production of heat [2].According to Intergovernmental Panel on Climate Change (IPCC) scenarios, the annual Green House Gas (GHG) emissions per capita across all the world's population should not exceed 1.6 tonne CO2 in this century, if we are to reach the climate targets with reasonable probability [3]. The European GHG emissions in 2012 were 7,9 tonnes per capita – and so 5 times higher than they should be if we are to achieve this goal [4]. This discrepancy demonstrates the urgency for action: Future investment should go to renewable energies and better efficiency, and not to fossil fuels. Bioenergy is a proven option to replace fossil fuels in the heat supply and partly in the transport sector and generation of electricity. In the battle against climate change, cities play a decisive role because a steadily growing part of the global population is living in the cities. Without a targeted policy for cities to reduce their CO2 emissions, climate mitigation policies for countries or the world cannot be successful. Despite many benefits of biomass energy as a clean energy source, commercial uses are still less common due to some of the problems and challenges associated with supply chain management and generic shortcomings is the key element of these challenges. Another challenge facing biomass energy is the high moisture in agricultural residues (> 50%). This means they should be completely dried before storage.

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In addition, according to reports, the transportation of moist agricultural waste is very high [5,6].In the discussion of supply chain management, in addition to providing biomass, there are some other important factors in pretreatment such as drying, densification, and grinding are needed. These are similarly very important factors in the process of biomass energy efficiency and effectiveness. Various methods are used to dry the biomass, including the use of solar energy, which loses all its good properties when the weather is cloudy. There are other conventional ways which are much more effective and drying rate is high but are expensive and use more energy [7].The fuel gas obtained from biomass gasification can be used to generate electricity in various ways. These ways include using the gas indirectly inside the steam turbine or inside the internal combustion engines. In a steam turbine the producer gas is fed to the boiler to generate high pressure steam which passes through a steam turbine connected to an alternator for electricity production [8]. Internal combustion gas turbines are for high-efficiency use on a small scale. However, they suffer from many technical problems. For example, a mixture of fuel gas with impurities can damage the gas expansion and cause corrosion. corrosion due to impurities can reduce turbine blades [9,10]. If the location of the biomass energy conversion unit is not close to the main power grid, the distribution of power generated by the biomass is a complex process and also construction of transmission facilities are expensive and these increases in cost determine the economic profit ratio and IRR of the project [11]. The purpose of this study is to review of challenges, advances, opportunities and strategies of sustainable development of biomass gasification and expected to be useful for researchers.

2. Biomass sources

The base of biomass fuels is solid carbonaceous materials which are remnant of animals and plants. Generally, the biomass can be categorized into the following groups [12]:

1. Waste from food processing operations like the rice milling, the refining of cane sugar, and the canning of vegetables and fruits and as well as waste from the processing wood into lumber, plywood, and pulp.
2. Crop debris such as straw and energy crops like fast-growing trees, sugar crops manure from cattle, poultry and hogs.

Bulk density, heating value, moisture content, elemental composition, ash content and volatile matter content are of the important bio- mass properties. Investigation of different types of biomass and also study effect of operating parameters on the performance of the system are required for the design and operation of the gasifier [13]. The most important parameter in the biomass is its heating value. From the efficiency and economy aspects, biomasses that having high heating value play a significant role in more energy recovery and improving the operating performance of the system. On the other hand, using various kinds of biomass wastes with different composition and heating value is possible by providing reactors with effective heat and mass transfer properties [14,15]. Table 1 shows the Ultimate analysis and Low Heating Value (LHV) of the selected biomass feedstock material.

Table 1: Ultimate analysis and LHV of selected biomass feedstock material [14].

Biomass type	Ultimate analysis (db, wt% /wt.)					Proximate analysis (wt% /wt.)				LHV (MJ/kg)
	C	H	O	N	S	ASH	VM	FC	M	
Cedar wood	51.1	5.9	42.5	0.12	0.02	0.3	80–82	18–20	0	19.26
Wood sawdust	46.2	5.1	35.4	1.5	0.06	1.3	70.4	17.9	10.4	18.81
Olive oil residue	50.7	5.89	36.97	1.36	0.3	4.6	76	19.4	9.5	21.2
Rice husk	45.8	6	47.9	0.3	0	0.8	73.8	13.1	12.3	13.36
Rice straw	38.61	4.28	37.16	1.08	0.65	12.64	65.23	16.55	5.58	14.4
Pine sawdust	50.54	7.08	41.11	0.15	0.57	0.55	82.89	17.16	0	20.54
Spruce wood pellet	49.3	5.9	44.4	0.1	0	0.3	74.2	17.1	8.4	18.5
Coffee husk	46.8	4.9	47.1	0.6	0.6	1	74.3	14.3	10.4	16.54
Coffee ground	52.97	6.51	36.62	2.8	0.05	1	71.8	16.7	10.5	22
Larch wood	44.18	6.38	49.32	0.12	0	0.12	76.86	14.86	8.16	19.45
Grapevine pruning waste	46.97	5.8	44.49	0.67	0.01	2.06	78.16	19.78	0	17.91
Jute stick	49.79	6.02	41.37	0.19	0.05	0.62	76-78	21.4-23.4	0	19.66
Sugar-cane bagasse	48.58	5.97	38.94	0.2	0.05	1.26	67-70	28.74-30.74	0	19.05
Corn cob	40.22	4.11	42.56	0.39	0.04	2.97	71.21	16.11	9.71	16.65
Peach stone	51.95	5.76	40.7	0.79	0.01	0.65	81.3	18.1	8.53	21.6
Wheat straw	46.1	5.6	41.7	0.5	0.08	6.1	75.8	18.1	0	17.2
Cotton stem	42.8	5.3	38.5	1	0.2	4.3	72.3	15.5	7.9	15.2
Straw	36.57	4.91	40.7	0.57	0.14	8.61	64.98	17.91	8.5	14.6
Camphor wood	43.43	4.84	38.53	0.32	0.1	0.49	72.47	14.75	12.29	17.48
Beech wood	48.27	6.36	45.2	0.14	0	0.8	81	18	0	19.2
Switchgrass	47	5.3	41.4	0.5	0.1	4.6	58.4	17.1	20	18.1
Oil Palm Shell	53.78	7.2	36.3	0	0.51	2.21	73.74	18.37	50	22.14
Wood Chip	51.19	6.08	41.3	0.2	0.02	1.16	80	18.84	20	19.9

3. Biomass supply chain management

Biomass in various forms and at different scales including forest wastes, crop wastes, municipal wastes and wood ashes all over the world. Each of these kinds of wastes are generated in its own area, for example, agricultural wastes made in rural areas and forest wastes mostly are found in forest areas. so biomass energy characteristics include moisture, content, calorific value and density are very much related to the geographical area which they are extracted [16]. Therefore, knowing the characteristics of biomass is a key factor before establishment and decisions for energy production and transfer. For example, moist biomass may have low calorific value and make transportation difficult due to the unusual shape and size. biomass supply chain management plays a vital role in the development of the biotransformation unit. It consists of a large numbers of sub-processes including biomass harvesting, collection, pretreatment and transportation which mentioned below in detail [17-19]

3.1. Harvesting

Biomass harvesting requires a lot of work and cost during the harvesting process which needs machinery equipment and transportation fuels for operation [20]. This amount of harvesting cost directly depends on various factors such as the type of biomass to be harvested, the economic situation of the country as well as the biomass yield in a particular area and also The availability of harvesting infrastructure [21]. For instance, biomass from rice or wheat simply collected in just three simple stages like cutting, raking and balling but biomass from wood must be first harvested felled timber then chipped into different shapes using saws for easy utilization of the wood to use in different forms af applications [22].

3.2. Collection

Biomass is abundantly available and widely distributed in many areas. Although biomass collection is the most important and biggest challenge in the supply chain management for energy production, it is one of the most costly challenges to generate electricity. There are many complexities in this area such as the high humidity of its contents and its low density, with no extra time for farmers to prepare future crops. Therefore, economically and efficiently there are techniques for collecting biomass that prevent a reduction in profits and prohibiting the development of technology. Moreover, biomass has an unstable market due to instability due to the lack of proper documentation and insufficient advancements in tracking mechanisms[23].

3.3. Transportation

Transportation and delivery of biomass to the power generation unit is another major challenge in the operation of biomass technology, especially biomass gasification. Globally, many factors such as the physical nature of biomass, wet biomass content and fuel costs are reported as major problems in biomass transport. For example, transporting rice husk and rice straw, as well as wheat straw, is very difficult to transport due to its very low density because it takes up more space which impacts directly to the transportation cost[24]. But solid biomass energy fuels, such as whole tree wood debris, can be more easily chopped packaged and transported. On the other hand, high humidity biomass makes it heavy and economically expensive to transport. Uncertainty of transport fuel prices is another obstacle to the process of transporting. In addition, it also requires machinery, heavy and a large number of fuels and therefore increase the costs of energy to produce energy from biomass. Biomass transportation is also influenced by important factors such as the distance of the energy conversion unit from the main field to the generation unit and transportation ways, such as railways, road, sea, etc. [25,26].

3.4. Storage

Harvested biomass storage can increase the availability of a uniform and integrated operation of the biomass power plant. So, harvested biomass storage is another important factor in the biomass supply chain management after biomass harvest. Because biomass is biodegradable and highly vulnerable to moisture, protecting it from rainstorms and insects such as termites requires shelter or shed for them. Full ventilation and for stored biomass is required due to the presence of several types of aerobic microbes which can damage the biological properties of biomass [27,28]. Biomass moisture level is better to be below 10% for long term storage, while for palletization, it can be increased to 30%. Meanwhile biomass must always be dried completely, whether before or after compaction, and this amount of biomass may be affected by bacterial activities that can reduce the impact of the process. In addition, great care must be taken to prevent biomass fires due to high drought. Stored stability can be achieved by various techniques such as ammonia fiber expansion, wet oxidation and extrusion without using any external binding agents at elevated temperature [29-39].

4. Biomass pretreatment

There are different classifications for biomass resources; But in general, biomass can be divided into lignocelluloses' biomass, microbial biomass and municipal, animal and food wastes. Lignocelluloses, which have the largest share in biomass production, include agricultural and wood industry wastes, forestry residues and energy production grains. These three are among the most important sources of lignocellulosic biomass production. For example, biomass, including sugarcane, native plants, some weeds Auto (Weeds), maize, spruce, poplar and a variety of plants and waste related industries, agricultural, paper, residual trees and plants, bran, stems and roots are also in These categories fit [40]. Lignocellulosic biomass is also considered as a source of energy. This substance is majorly composed of three elements: hemicellulose (20-35%), cellulose (35-50%) and lignin (15-20%), as well as its minor elements, including carbohydrates, protein, ash, pectin, minerals, etc. [41]. The composition and physical and chemical properties of major and minor elements vary by region, so in order to have stability during the biomass conversion process, pretreatment is required before entering to the gasifier reactor [16]. The main pretreatment methods of biomass follow: i) physical pretreatment (drying, densification, grinding, extrusion, etc.), ii) chemical pretreatment (ammonia fiber expansion [42], ammonia percolation [43] ozonolysis [44], alkaline wet oxidation [45] etc.) under various alkaline conditions such as alkaline hydrogen peroxide [46], NaOH [47], lime [48], soaking aqueous ammonia [49], liquid hot water [50] and neutral and acidic conditions [51,52], iii) physicochemical pretreatment (supercritical carbon dioxide explosion [53,54], steam explosion [55], etc.) and iv) biological pretreatment.

4.1. Drying

In recent years, much research has been done on the effect of moisture content on biomass yield [56-58].The equilibrium moisture content of biomass depends on the relative humidity and air temperature. As biomass moisture increases, energy production by biomass likewise pyrolysis process will decrease. Gaseous product can directly affect by the high moisture content. High value of moisture content for a downdraft gasifier has been reporter to be 40%, but this figure imams down gas can be 40%, but it can be higher for a updraft gasifier [59,60].Biomass can be dried in two different ways. The first is the use of solar energy and the second is the use of conventional electric dryers. The first is less expensive, but due to several factors such as atmospheric humidity, solar radiation and changing climatic conditions which can impact drying process and lead to longer drying time [61]. Drying using solar energy is a slow conversion method and it takes a long time, in the end it causes biological degradation. On the other hand, the conventional drying method Electric dryers are extremely expensive and energy consuming but in this method drying rate is higher.

4.2. Densification

The use of mixed biomass can cause many feed supply problems for the gasification system [62]. The biomass mixture can have logistical and energy production benefits, for example biomass such as wood chips and palm kernel shell (PKS) can easily be used as an energy feedstock in gasification, while many agricultural biomass wastes, such as rice husks, wheat straw, grass, etc. cannot be used because they have high adhesion, causing slag and ash formation [63-66]. All problems related to the feeding of biomass can be filled through the densification process. The densification process can be used to fill the internal spaces in the biomass and increases its bulk density [67]. The most common technologies for biomass densification include balling, briquetting and pelletizing. Although densification is energy intensive and involves expensive equipment, however, biomass densification to a suitable size/format can significantly enhance heat transfer rates in the gasification process [68].Despite all the complexities and costs of densification, the briquetting method is used as an attractive method for commercial use [69-72]. In addition, the briquetting method has many benefits in different fields, such as transportation, storage and feeding the gasification unit. The particle size of biomass is a key factor and plays an important role during the conversion process for achieving the required temperature and energy as well as high quality gaseous fuel [73,74].

4.3. Grinding

The process of grinding or pulverization of biomass increases the surface area to volume ratio of particles and promotes uniformity of feed to the gasification process [75]. The physical pretreatment of biomass is the prominent method which includes mechanical processing (grinding, milling and extrusion) to obtain a reduction in the particle size while increasing the surface area of biomass particles for better heat transfer conditions.

5. Gasification process

The gasification process is based on the transformation of carbonaceous material such as municipal waste, tires, and coal into syngas. This process is thermochemical process and it takes place at very high temperature under low oxygen conditions [76]. The synthetic gas generated through the process mainly consists of carbon monoxide and hydrogen [77,78]. Usually, the initial step in gasification is called pyrolysis, a process where the carbonaceous matter goes under decomposition through heating and it is converted into volatile matters and no-volatile matter that is char and it comprises of high content of carbon [79]. Thereafter, the reaction between heated char is take place with the carbon dioxide and gaseous H2O. The result of this process is the production of synthetic gas that consists of methane, hydrogen and carbon monoxide along with some incombustible gases [80–83]. Fig. 1 provides the clear illustration of the reaction sequence about gasification process.

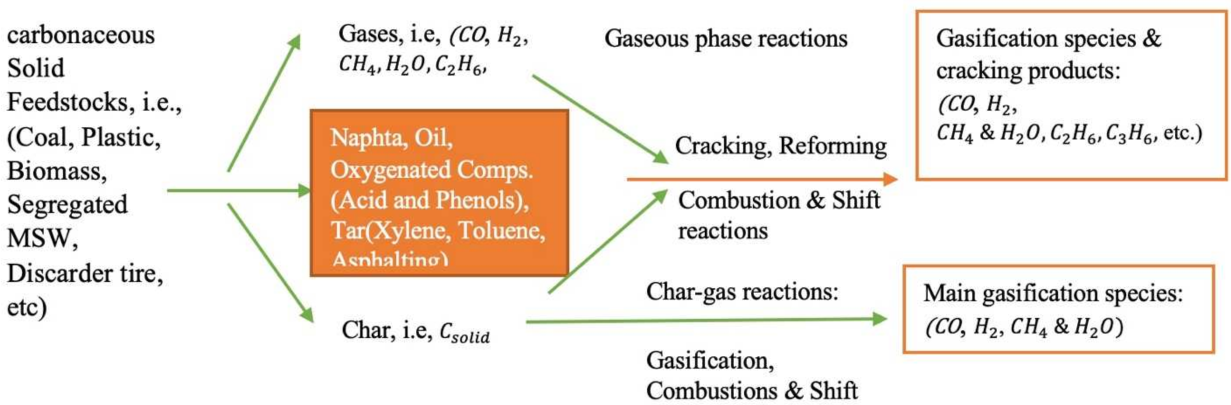

Fig. 1. Gasification process reaction sequence, reproduced from Higman and coworker [83,84].

However, for detailed analysis, the process of gasification can be categorized into the de-moisturization, devolatilization or pyrolysis, volatile combustion, char combustion [83–87]. These steps take place successively. Reduction of oxidized species into syngas is also involved during the combustions steps. Fig. 2 illustrate the sequence of these steps and are detailed further herein.

5.1. Drying

Drying involves the reduction of moisture quantity in the biomass matter [80,87]. The moisture content in the feedstock depends on the type of feedstock. For example, bituminous coal contains moisture of nearly 10%. Other type of coal such as lignite and subbituminous coal contains higher moisture as compared to bituminous coal. However, anthracite contains lowest quantity of moisture as compared to all other three types. Similarly, biomass comprises of moisture from 5% to 40%. The main objective of the drying is to minimize moisture content (less than 2%) because the lesser is the moisture contents, as fuel particles moves into devolatilization and reduction zones, the higher is the quality of coal or biomass as fuel. Drying is an endothermic process and uses the latent heat of evaporation which is nearly 2400 KJ/kg for water.

5.2. Devolatilization (pyrolysis)

This process involves the decomposition of biomass or coal under higher temperature and zero oxygen conditions [88,89]. Pyrolysis results in the reduction of volatile matter and production of hydrocarbon gases. The hydrocarbon gases can be reduced into liquid form at low temperature [90].

5.3. Oxidation

CO and CO2 is the outcome of the oxidation process when solid carbonized biomass reacts with some oxygen in the air [91]. Moreover, oxidation of hydrogen also takes place which is available in the biomass. Due to the oxidation of both hydrogen and carbon, a significant amount of heat is released. However, carbon monoxide may produce if the oxygen is available in stoichiometric quantities [92]. The oxidizer is also considered as a temperature control parameter and hence its amount in pure or as diluted form as in the case of air is adjusted according the stipulated and desired gasifier temperature. CO_2, H_2O and N_2 even He are referred as moderators as generally their induction reduces the environmental temperature of the gasifier as they feed on its sensible heat. Therefore, their high temperature regeneration is necessary under system integration to ensure high process efficiency as for the case of IGCC. Oxidations always are strongly exothermic reactions and they are responsible of providing the gasifier heat needed for all subsequent endothermic reactions.

5.4. Reduction

These types of reactions occur when very low amount of oxygen is available. Thus, in oxygen's sub-stoichiometric presence, a number of oxidation/reduction reactions take place under the high temperature conditions of 800–1000 °C [93]. The reduction reactions are generally endothermic type of reactions [94] that include boudoir reactions, water–gas reactions, shift reactions and methane reactions [95,96]. These reactions are promoted per the desired syngas or CO/H_2 proportion for the gasifier. For example, for hydrogen production such as for ammonia synthesis or simple proton exchange membrane (PEM) fuel cell application, CO shift and CH reformed reaction under the presence of steam is targeted. Otherwise, for solid oxide fuel cell where CO is the desired commodity moderation and reduction under CO2 is the natural pursued solution.

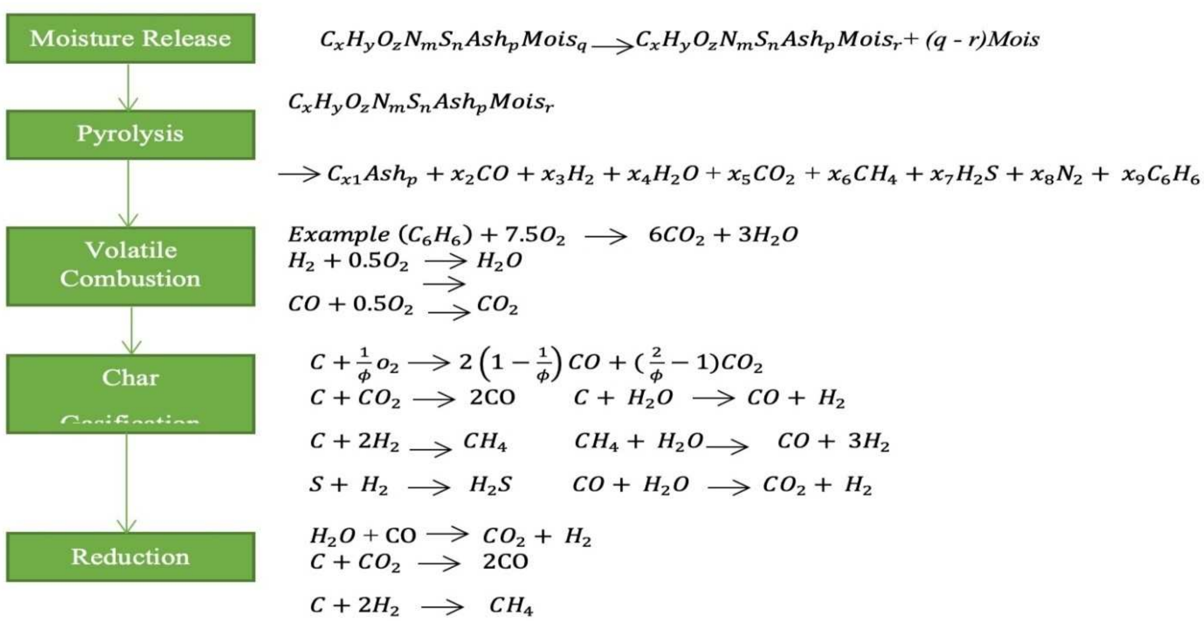

Fig. 2. Illustrate the sequence of the gasification steps

6. Biomass gasification

Gasification is the process of conversion of a carbon-rich solid fuel into a gaseous fuel in the gasifier that takes place in an environment with specific oxygen (O_2) amount. The reaction can take place at a medium which can be air, O_2, subcritical steam or a mixture of them [97]. Biomass gasification is the thermochemical conversion of solid biomass fuel of combustible fuel in the presence of oxygen less than the stoichiometric combustion. Gasification is carried out in a reactor called a gasifier and can convert carbonaceous materials into combustible gas or liquid fuels for use in various applications such as gas engine or gas turbines, direct heating applications and fuel cells. although this technology is a promising technology for energy production, but biomass gasification has several obstacles that limit its commercialization. In engine operation, the producer can be used as an alternative fuel for transportation and generation of electricity. The producer gas must have all the characteristics of an ideal fuel to operate the engine efficiently. These characteristics include high gas purity and high calorific value, very low tar content (< 100 mg/Nm3) and the absence of poisonous gases like ammonia and sulfur dioxide [98]. The quality of producer gas depends on multiple factors like, type of feedstock, reactor design, operating conditions, and gas cooling and cleaning techniques [98].

6.1. Type of feedstock

Each types of biomass feedstock have its own composition and characteristics. Generally, it includes biopolymers such as cellulose, hemi- celluloses and lignin as well as three other basic elements, carbon, oxygen and hydrogen, in an approximate proportion of about 50% of Carbon, 6% of Hydrogen and 44% of Oxygen on a moisture and ash free basis, as discussed previously. Bulk density, heating value, moisture content, elemental composition, ash content and volatile matter content are of the important bio- mass properties. Investigation of different types of biomass and also study effect of operating parameters on the performance of the system are required for the design and operation of the gasifier [13].

Table 2: Composition of producer gas obtained from various biomass types in downdraft gasification

Biomass	Gas composition (% by volume)					Calorific value (MJ/m^3)	Cold efficiency (%)
	CO	H_2	CH_4	CO_2	N_2		_
Charcoal	28-31	5-10	1-2	1-2	55-60	5.65	_
Wood	17-22	16-20	2-3	10-15	55-60	5.86	62.5
sawdust	19.48	18.89	3.96	_	_	6.32	48.7
Wood chips	26.5	7.0	2.0	_	_	5.06	_
Coconut shells	19-24	10-15	_	11-15	_	7.20	_
Rubber wood	20.2	18.3	1.1	_	_	_	_
Corn cobs	18.6	16.5	6.4	_	_	6.29	_
Rice hulls pelleted	16.1	9.6	0.95	_	_	3.25	_
Pine wood blocks	25.53	28.93	6.82	_	_	4.76	_
Hazelnut shells	16.8	14.12	1.70	_	_	4.55	51.53

6.2. Reactor Design

The design of a biomass gasifier depends on the fuel availability, shape and size, moisture content, ash content and end user applications. Different types of biomass gasifiers are available in various size and design depending on the requirements and basically, classified as fixed and fluidized bed type gasifiers [99]. As gasification systems involve an interaction of air/oxygen/steam and biomass in the fixed bed type gasifier hence, they can be classified according to the way of interaction of either air/oxygen or steam with biomass such as, downdraft, updraft, and cross draft gasifier and are shown below in Fig. 3.

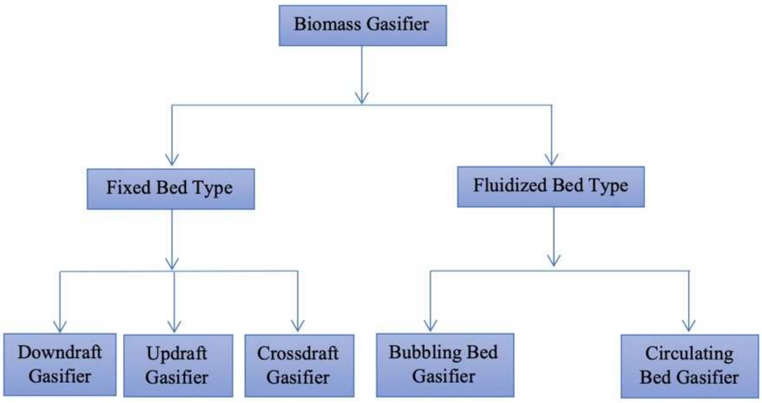

Fig.3. Classification of biomass gasifier [99]

6.2.1 Fixed Bed Gasifiers

Fixed bed gasifiers are the oldest gasifiers. They are also known as moving bed gasifiers. There are three major kinds of fixed or moving bed gasifiers which are updraft gasifier, downdraft gasifier, and cross-draft gasifier. These names are given based on the directions of the flows of the fuel and the oxidant in the gasifier. Fixed bed gasifiers are suitable for small-scale application up to 10 MW. Therefore, fixed bed gasifiers are mostly used for decentralized power generation using biomass.

6.2.2 Downdraft or co-current gasifier

In downdraft gasifier, as clear from the name itself, air interacts with the solid biomass fuel in the downward direction which results in the movement of wastes and gases in the co-current direction and hence, these gasifiers are also called as co-current gasifiers. All the decomposition products from both pyrolysis as well as drying zones are forced to pass through the oxidation zone for thermal cracking of volatile materials and produce less tar content and hence, the better quality fuel gas. Here, air interacts with the pyrolyzing biomass before it contacts the char and accelerates the flame which maintains the process of pyrolysis. At the end of pyrolysis zone, the gases obtained in the absence of oxygen are CO2, H2O, CO, and H2, called flaming pyrolysis. In flaming pyrolysis, the gases obtained during downdraft gasification are due to consumption of 99% of the tar in the process itself leading to low particulate and tar content in the gas and hence, suited for small scale power generation applications [100,101].

6.2.3 Updraft or counter-current gasifier

In updraft gasifier, the gasifying agent such as, air, oxygen and steam are introduced at the bottom to interact with biomass and the combustible gases in counter current direction and hence, these gasifiers are also called counter-current gasifier. In addition to the pyrolysis products and drying zone steam, the gas produced in the reduction zone with high calorific value leaves the reactor. In some updraft gasifiers, steam is evaporated into the combustion zone to obtain quality fuel gas and prevents the gasifier from overheating as well. This type of gasifier has the highest thermal efficiency as the hot gas passes through the fuel bed and leaves the gasifier unit at low temperature whereas some part of the sensible heat of producer gases is also used within the system for biomass drying and steam generation [24]. The main advantages of updraft gasifiers are good thermal efficiency, small pressure drop and the slight tendency to slag forma tion. These gasifiers are suitable for the applications where the high flame temperature is required and a moderate amount of dust in the fuel gas are acceptable. However, some bottlenecks such as, great sensitivity to tar and moisture content of the fuel, low production of syngas, long start up time of the engine, and poor reaction capability are also associated with these systems [99].

6.2.4 *Cross-Draft Gasifier*

Here, the fuel is introduced from the top of the gasifier. The gasifying agent is introduced from one side of the gasifier, and the product gas is taken out from the other side. The exit of the product gas and the entry of the gasifying agent are kept almost at the same level. As the fuel moves down through the gasifier, it is dried, devolatilized, pyrolyzed, and finally gasified before leaving the gasifier. The oxidation zone is located near the entry of the gasifying agent, and the gasification zone is located near the exit. The pyrolysis zone is located above the oxidation/reduction zone, and the drying zone is located above the pyrolysis zone. In cross-draft gasifier ash bin, oxidation zone and reduction zone are separated which impose the restriction for using different type of fuels. The exit gas temperature in cross-draft gasifier is very high which has an effect on gas composition like it produces gas with higher carbon monoxide content and low hydrogen and methane content [102]. All three types of fixed bed gasifiers are shown below in Fig.4.

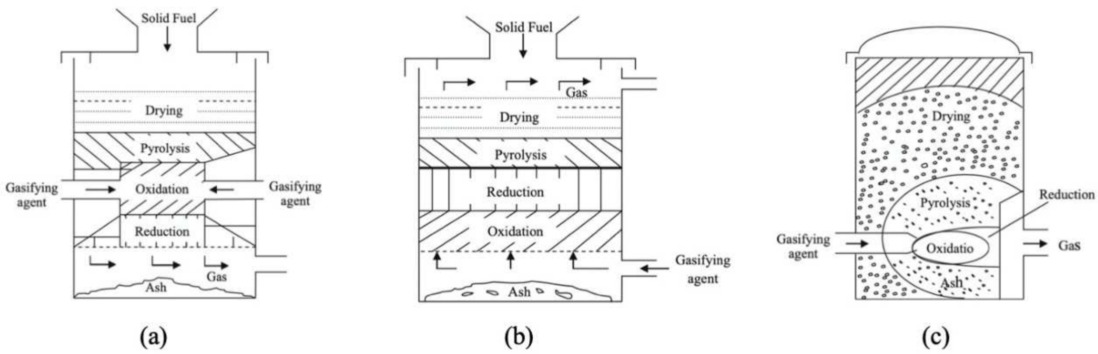

Fig. 4. Schematic view of (a) Downdraft (b) Updraft and (c) Cross draft gasifier [103, 104]

6.2.5 *Fluidized Bed Gasifier*

Fluidization is the operation by which a bed of solid particles is transformed into a fluid-like state by the application of gas. The fluidized bed system requires the feedstock to be finely ground into small particles, and the gasifying/fluidizing gases are introduced through a distributor plate near the bottom of the reactor. In fluidized bed gasifier drying, pyrolysis, oxidation, and reduction zones are not apparent at any specific region of the gasifier like in fixed bed gasifiers. These processes occur in the entire gasifier, and thus the fluidized bed gasifiers are more homogeneous type of reactors. In a fluidized bed gasifier, the gasifying agent also acts as the fluidizing agent to fluidize the particle bed. The distinct advantages of fluidized bed over fixed bed gasifiers are uniform and controllable temperature due to excellent gas–solid mixing, high carbon conversion rate, low tar production, flexibility in terms of use of different types of fuel, feed rate, particle size, and moisture content [105]. In fluidized bed gasifiers, reaction rates are much faster than in the fixed bed gasifiers because of intimate gas–solid contact and the increased solids surface area resulted from smaller particle size. Because of the aforementioned features, scale-up and operation of the fluidized bed gasifiers are much easier. The fluidized bed gasifiers are designed to be accompanied by a cyclone separator downstream of the gasifier to capture the particles that are entrained by gas and leave the gasifier as a result of the fluidity of the bed and the velocity of the gas rising through the bed. After separation, these particles are either recycled back into the gasifier or removed from the gasifier. Most of the problems associated with the fixed bed gasifiers could be overcome in fluidized bed gasifiers. Therefore, fluidized bed gasifiers are more popular than fixed bed gasifiers. There are different types of fluidized bed gasifiers like bubbling fluidized bed gasifier, jetting fluidized bed gasifier, circulating flui- dized bed gasifier, and dual fluidized bed gasifier. The residence time of fuel particles in fluidized bed gasifiers is generally less than that of fixed bed gasifiers. However, the residence time may be increased by re-circulating the particles again and again like in circulating fluidized bed gasifiers. Fluidized bed gasifiers are suitable for small to medium scale (500 kW to 50 MW) application. Although the fluidized bed gasifiers are used for gasification of both coal and biomass, but they are becoming more popular for biomass gasification due to lower gasification temperature of biomass compared to coal. Different types of fluidized bed gasifiers are discussed below.

6.2.6 Bubbling Fluidized Bed Gasifier

In a typical reactor with solid particles, when the velocity of fluidizing gas is increased, a situation is reached when the solid particles are just suspended by the upward flowing gas. At this situation, the drag force between particles and fluid counterbalance the weight of particles and the pressure drop between any two points along the height of the bed equals the weight of fluid and particles in that section. At this point, the bed is called to be at minimum fluidization condition and corresponding velocity is called the minimum fluidization velocity. With an increase in velocity beyond the minimum fluidization velocity, bubble formation starts. These small bubbles grow in size while traveling through the bed. On the way up through the bed, bubbles withdraw particles from surroundings and thereby set the particles in motion. On reaching the bed surface, bubbles burst and particles splash into free-board region [103].

6.2.6 Circulating Fluidized Bed Gasifier

It consists of a high-velocity riser, a cyclone separator, a downcomer, and a loop-seal/ L-valve. If the velocity of gasifying agent is increased beyond the bubbling fluidized bed, solid particles are distributed across the whole riser height and most of the particles are entrained by the gas. Particles are separated from the gas with the help of cyclone separator, come down through the loop-seal through the downcomer, and return to the bottom of the riser, forming a solids circulation loop. Then it becomes a circulating fluidized bed or fast fluidized bed gasifier. In circulating fluidized bed, particles arrested by cyclone separator are generally fed back to the riser either by using a loop-seal or L-valve. The solid circulation flux is controlled by the gas velocity in the riser and as well as in the loop-seal. The driving force for the solid circulation is the pressure difference in different parts of the circulating fluidized bed system. Higher gas velocity in circulating fluidized bed results in more intense mixing of the gas and particles in the bed which provides excellent gas–solid contact [106]

6.2.7 Entrained Flow Gasifier

Figure 5 shows the schematic diagram of an entrained flow gasifier. Here, solid fuel and the gasifying agent are fed from the top and they flow co-currently to the gasifier. Very fine fuel particles are required for entrained flow gasifier compared to the fluidized bed gasifiers. Oxygen or air both can be used as the gasifying agent, but most of the commercial plants use oxygen as the gasifying agent. Here, the velocity of gasifying agent is even higher than in circulating fluidized bed gasifier. The small fuel particles are entrained by the gasifying agent, and they flow through the gasifier in a dense cloud. The residence time of particles is very less which requires the entrained flow gasifier to be operated at high temperature (about 1200–1500 °C). High temperature and extremely turbulent flow inside the gasifier cause rapid fuel conversion which also allows high throughput. The gasification reactions occur at a very high rate. Product gas from entrained flow gasifier contains lesser amount of tar and condensable gases due to high-temperature operation. The major part of the ash is removed as slag because the operating temperature of the gasifier is well above the ash fusion temperature. It has the ability to gasify any type of fuels. However, fuels with low moisture and ash content are favored to reduce the oxygen consumption. Entrained flow gasifiers are suitable for large-scale application (>100 MW). It is a well-researched and developed technology for gasification of fossil fuel like coal, refinery waste. The entrained flow gasification technology has been commercialized in large-scale integrated gasification combined cycle (IGCC) coal power plants. In most cases, the gasifiers are operated under pressure (~20–50 bar) with pure oxygen and with capacities in the order of several hundreds of MW [107]. However, the application of entrained flow gasifiers in biomass gasification is still under development. Most of the integrated gasification combined cycle (IGCC) plants installed worldwide used the entrained flow gasification technology.

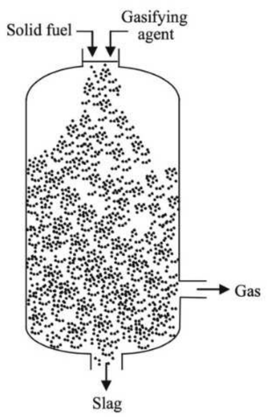

Fig. 5. Entrained Flow Gasifier

6.2.8 Plasma Gasifier

This type of gasifier is heated by a plasma system (plasma torch or plasma arc) located near the bottom of the gasifier. In the gasifier, the fuel is generally introduced from the top of the gasifier and it passes through the plasma zone. Gasifying agent is introduced near the plasma system and work as ionized gas. Gasification takes place at very high temperatures driven by the plasma system [108]. The high operating temperature breaks down the fuel into their respective elemental constituents which significantly increases the rate of the various reactions occurring in the gasification zone and also helps to converts all organic materials into a fuel gas. The gas is taken out from the top of the gasifier. Any residual material from inorganic constituents of the fuel is melted and produces a vitrified slag. All three types of fluidized bed gasifiers are shown below in Figs.5,6.

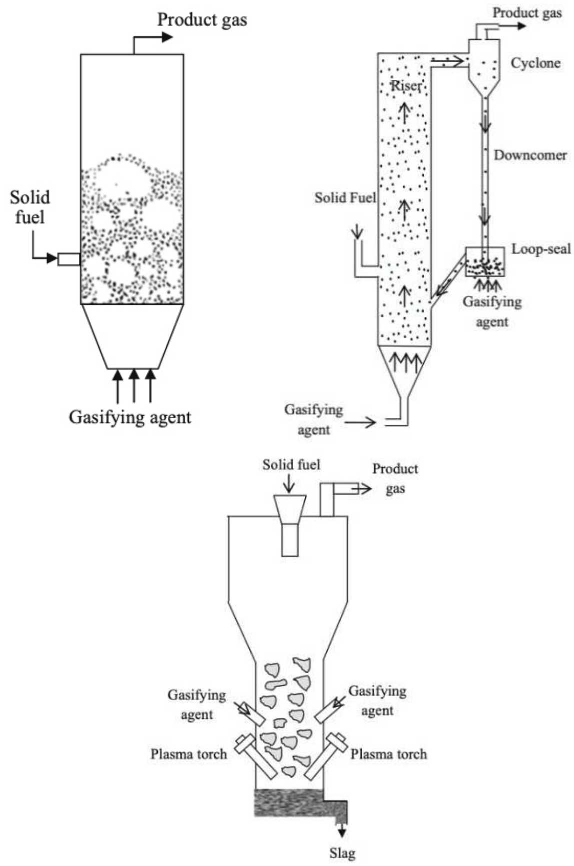

Fig. 6. Schematic view of (a) Bubbling (b) Circulating and (c) Plasma gasifier [103]

6.3 Operating parameters

6.3.1 Temperature

The temperature of biomass gasification is a significant factor and plays an important role in controlling gas composition, tar concentration, reaction rate, and char and ash formation. Thus, the control of temperature inside the reactor or gasification zone is necessary for attaining the enhanced process characteristics. However, it is not an easy task and has been of interest among researchers seeking a standardized temperature profile for gasification. The high operating temperature has been reported to be suitable to achieve higher carbon conversion rates which ultimately reduces the tar content and produces more combustible gases [109]. However, in one study [110], the hydrogen concentration was observed to increase initially and then to decrease gradually with increasing temperature.

6.3.2 Pressure

In general, gasification takes place under atmospheric and high pressure conditions but for some downstream applications, such as syngas conversion to methanol or other biofuel products using the Fischer-Tropsch process, require a high pressure product gas. Many studies have investigated this and revealed some important findings and research needs. One study [37] reported a significant reduction in tar yield with an increase in gasifier pressure, while other investigations of fluidized bed gasification identified an increase in tar concentration with increasing gasifier pressure from 0.1 to 0.5 MPa, affecting syngas composition. The high pressure drop across the gasifier bed is considered to lead to high formation of ash and slag as well as poor syngas quality, and therefore not to be favorable [100]. Another study [111] reported a high pressure drop in the non-firing mode of a gasifier relative to a freshly charged gasifier bed, due to the high resistance of gas flow. The pressure drop across the entire system was observed to be the function of particle size and operating time.

6.3.3 Gasifying agents

Gasifying agents/media like air/oxygen, steam and CO2 are commonly used to initiate gasification, depending on the requirements for quality of the end products for different downstream applications. These media also affect widely process characteristics, so they have been considered as important process parameters when examining the performance of the system at different scales. Air as the gasifying agent produces syngas with low heating value since it gets diluted by nitrogen, whereas the combination of steam and oxygen yields syngas with a medium heating value. However, steam in combined form with air results in a high yield of hydrogen and reduces the energy requirement of the system [112,113]. Various gasifying agents are listed in Table 3 along with their characteristics.

Table 3: Characteristics of gasifying agents [114,115].

Gasifying agent	Characteristic
Air	• Partial combustion for heat supply of gasification • Moderate char and tar content
Oxygen	• Enhanced carbon conversion characteristics • Enriched H_2 , CO and CH_4 in producer gas and reduced tar levels
Steam	• Improved heating value and producer gas (10-15 MJ N/m^3) • Enriched H_2 in producer gas
Carbon dioxide	• High heating value of producer gas • High concentration of H_2 and CO in producer gas and reduced CO_2

6.3.4 Air fuel ratio and equivalence ratio

Biomass gasification requires limited excess air and its proportion must be compatible with the biomass fuel to be gasified, while the combustion of fuel requires stoichiometric air-fuel conditions to attain complete oxidation [116]. Therefore, the equivalence ratio, defined as the ratio of the air to fuel ratio required for gasification to the stoichio- metric air to fuel ratio required for combustion, is an important parameter. The equivalence ratio significantly influences the gasification process and the composition of end products, including reducing tar formation at higher temperatures. A higher equivalence ratio also results in a reduction of syngas heating value [117]. A study by Rahardjo [118] revealed high potential for hydrogen yields and tar cracking at high steam/biomass ratios due for the water gas shift reaction. For effective gasification, the optimum value of equivalence ratio has been reported to be from 0.2 to 0.4

6.3.5 Residence time

Residence time is another factor which should be considered when designing a reactor for gasification as it influences tar formation and gas composition significantly. Kinoshita et al. [119] analyzed the composition of tar compounds with respect to residence time and reported a decrease in oxygen-containing compounds along with one and two aromatic ring compounds with increasing residence time. However, three and four ring compounds of tar were reported to increase with increases in residence time. In another study, Olivares et al. [120] observed a decrease in tar content due to the augmentation of space-time in biomass gasification having a dolomite bed. James et al. [121] evaluated the performance of an in-chamber tar cracking and syngas reforming unit having NiO as a catalyst in an updraft biomass gasifier. A tar removal rate of 95% was reported at a residence time of 0.35 s and 10% nickel loading. An increment of 36% in heating value of producer gas was also observed using the nickel based catalyst, whereas a gas residence time of 0.2–0.3 s and a Ni loading of 5–10% were reported to be suitable for producing a cleaner syngas with low tar content.

7. Conclusion

Biomass gasification is a promising bioenergy technique for converting raw low-value lignocellulosic biomass into high-value fuel gas, particularly for heat and power generation applications. The fuel gas obtained from gasification can also be utilized for producing such value added products as fuel cell fuels, biogas, ethanol, bio-diesel, etc. However, gasification is a complex, inflexible and less competitive process than other biomass conversion routes, so it is not a mature technology and is subject to risks and challenges, from biomass collection to fuel gas utilization in end use applications. With considering new strategies on gasification efficiency improvement and reduction of gasification plant final costs, the gasification process can be more available and affordable for everyone to start new business which simultaneously have a lot of benefits for both investors and environment.

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