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Review Article

Advancements and challenges in the fluidized bed gasification system: A comprehensive review

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ABSTRACT

A gasifier employs partial ignition of biomass and conversion to gaseous fuels of high calorific value. Bubbling fluidized bed gasifier is a promising one amongst other gasification technologies like fixed bed, entrained flow etc. It has several noteworthy advantages like large- and small-scale applications, efficient heat and mass transfer rates due its fuel flexibility, low capital and operating costs, etc. However, low mixing rate of biomass feedstock and gasifying agent, high tar content in the product gas and low calorific value of producer gas are some of its limitations which need sincere attention to enhance its performance. The present study analyzes the effect of design variables of the proposed gasifier reactor for different feedstock along with the operating variables on the quality of producer gas. This review paper examines the present global status of biofuels, different types of gasification technologies, approaches adopted for the gasification, different parameters affecting gasification performance, enhancement of product gas conditioning, technical and cost-effective viability and the future prospects of gasification.

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INTRODUCTION

Global warming mainly due to the increased carbon emission that is caused by the use of non-renewable energy sources has become an important concern for the environmentalists and scientists across the globe. It is observed that thermal power plants, industries and transport vehicles make a major contribution to increasing carbon emissions in the atmosphere [1]. Globally more than 36 billion tons of CO_2 is emitted and it is growing continuously, as reported by Ritchie and Roser [2]. Therefore, the use of clean energy sources needs promotion for the

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potential to mitigate the current challenge of global warming, carbon emission, scarcity of the conventional fuels etc. Biomass derived from the forestry waste, agricultural waste, municipal waste, industrial waste etc. is commercially available and is being used for the generation of heat, electricity and bio fuel production i.e. bio-diesel, bioethanol etc. The conversion of biomass into a usable form can be managed using various technologies such as gasification, combustion, liquefaction, hydrogenation, fermentation etc. [4].

In a gasification technology, solid biomass when partially burned in the presence of air, produces gaseous fuel of high calorific value. Thermodynamically, the gasification process is 80 to 85% proficient in converting volatile organic compounds into flammable gases [5]. The gasifiers produce syngas which is used to generate power in a combined cycle engine, generate power. The technology is 6 to 8% more efficient in comparison to the conventional power generation techniques [6].

Gasification comprises mainly four processes i.e. drying, pyrolysis, oxidation and reduction [7] as discussed further:

Drying: The feedstock particles typically have 10 to 35% moisture content that reduces the efficiency of gasification. To remove moisture in the feedstock particles, a drying process is used wherein the feedstock particles are heated between 100-150°C to convert moisture into steam. The process is represented by Eq. (1) [7].

$$Biomas(CHO) \xrightarrow{Heat} Moisture(H_2O) \tag{1}$$

Pyrolysis: In this process, the dry feedstock is continuously burnt without air supply and get transformed into charcoal and tar. It is done at more than 250°C temperature [7]. The Eq. (2) describes the process.

$$\text{Dry Biomas(CHO)} \xrightarrow{No\ air} \text{Charcoal \& tar} + \text{Volatiles} \tag{2}$$

Reduction: This process occurs at high temperature when no sufficient O_2 is available. The volatile substance and charcoal formed during the pyrolysis is partly combusted in air and it makes producer gas. Chemical reaction occurring in the reduction process is presented in Eqs. (3-5) [6]. The process is endothermic, thus lowers the temperature of producer gas as it exits the gasifier.

$$C + CO_2 \rightarrow 2CO - 246.7 \text{ kJ/mol} \tag{3}$$

$$C + H_2O \rightarrow CO + H_2 + 118.5 \text{ kJ/mol} \tag{4}$$

$$C + 2H_2 \rightarrow CH_4 + 74.8 \text{ kJ/mo} \tag{5}$$

Oxidation: It is the burning of biofuel and charcoal in air that produce $CO_{2,}$ water etc. as shown in Eq. (6) [6].

$$C + O_2 \rightarrow CO_2 + 406.3 \text{ kJ/mol} \tag{6}$$

The gasification technologies are mainly of the fixed-bed type, fluidized-bed type and entrained flow & plasma type [9]. All these gasification technologies are briefly discussed as under:

- **Fixed-bed technology**- A fixed-bed gasifier is usually a cylindrical shell in which the feedstock particles are kept on the bed; and a gasification agent, like air, is supplied either upward or downward. The producer gas exits in the direction of the supply of the gasification agent [9]. Fixed-bed gasifiers are mainly classified as downdraft (both air and feedstock flow in the same direction), updraft (air and feedstock flow is in the opposite flow), and cross-draft (air passes in one side of the reactor) [7]. The operating temperature of the fixed-bed gasifier is around 700-900 °C [9]. This type of gasifier can manage large size feedstock particles (about 5–20 mm) in comparison to any other gasification technology.
- **Entrained flow technology**- This type of technology is preferred for Integrated Gasification Combined Cycle Plants (IGCC). The entrained flow biomass gasifier is a co-current flow biomass gasifier, in which both biomass fuel (powder form or fuel slurry) and oxygen flow in the same direction as reported by Dai et al. [10]. The operating temperature and pressure range are about 1400°C and 20 to 70 bar respectively. It decomposes tar, oil, phenol during the pyrolysis of coal into H_2, CO and other hydrocarbon gases. [11]. The entrained flow gasification technology is of two types- slagging and non-slagging. In the non-slagging type, the ash formed during gasification process is released from the reactor by separating it downstream

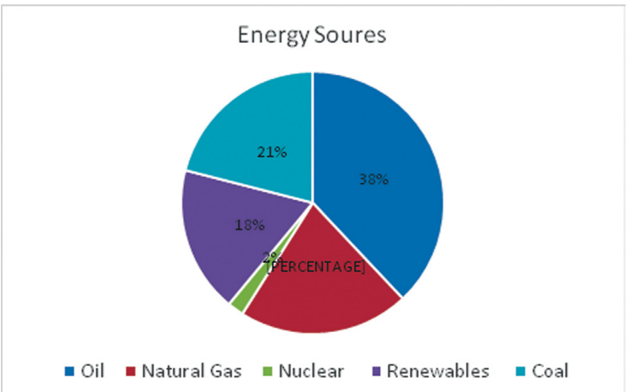

Figure 1. Global energy utilization from primary energy sources (modified from [3]).

in the process; but in the slagging type ash collapses on the reactor walls while the reaction occurs [11].

- **Plasma torch type**- The gasifiers based of plasma torch technique is the most reliable one in improving the product gas quality. It uses a plasma electrode in which the torch forms an arc when a strong current jumps the gap between the electrodes. The arc produces heat; and the temperature of the combustion chamber of reactor reaches more than 1000°C. This type of gasifier does not require air, so the pressure of the reactor remains negative, due to some air leakage [12].
- **Fluidized bed type** – This gasifier is very efficient and has many good things like large- and small-scale application, efficient heat and mass transfer rates due to its fuel flexibility, low capital and operating costs, higher carbon conversion rate, good quality of product gas etc. [13-17]. The gasification process is carried out in the fluidized bed into which the compressed air is supplied through the holes of the channel of the distributer plate and the compressed air is then heated. It reacts with the biomass feedstock particles after passing through a bed of hot sand particles as shown Figure 2 [18]. In the fluidization process, the grinded particles behave as a fluid and it is passed with the moving fluid. In the bubbling fluidized bed gasifier, the feedstock is supplied at top of the bed of reactor but the oxidation agent is supplied beneath the bed. At the starting, the bed reactor is heated up to 400 °C using gas or coal burners [18]. The gasification is maintained by supplying air and biomass in a defined stoichiometric ratio [18].

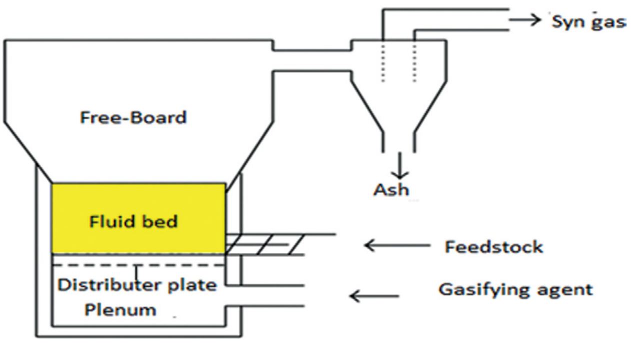

Figure 2. Bubbling fluidized bed gasifier layout (modified from [18]).

Many researchers [19-22] studied the influence of process parameters, but a few focused on the effects of feedstock characteristics and design parameters of the bubbling fluidized bed gasifier. The effects of various design and process parameters of a small-scale bubbling gasifier are tabulated in Table 1.

GASIFICATION VARIABLES

Broadly there are three factors that affect the performance of any gasifier i.e. feedstock characteristics, process

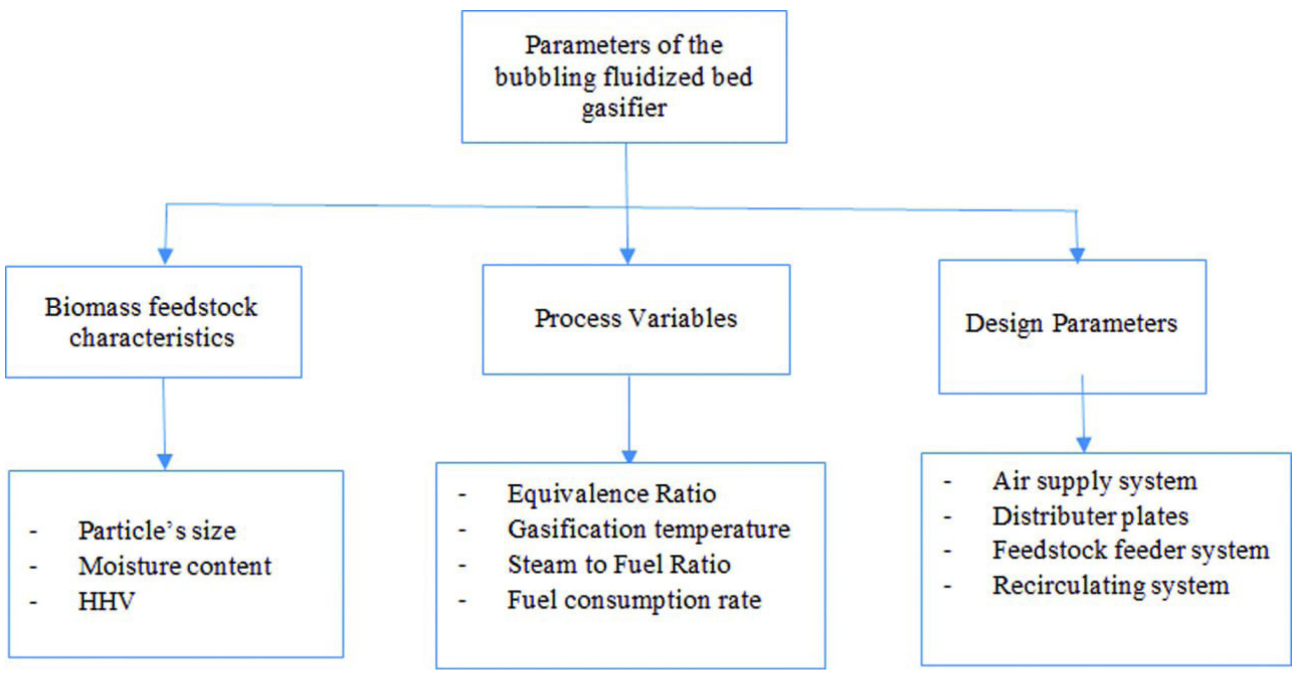

Figure 3. Classification of the factors affecting gasifier performance.

variables and design parameters. These factors are further classified as shown in Figure 3 [23-70].

Feedstock Characteristics

The size of the feedstock particles and its moisture content strongly affect the quality of producer gas as discussed below:

Biomass particles size:

The size of feedstock particles can vary between 0.5 to 5mm [23]. Mallick et al. [24] studied on co-gasification of coal and biomass and they observed that when the size of the fuel particles is reduced to 0.5 mm, the gas yield got increased to 1.91Nm^3/kg and the tar yield decreased to 5.61g/kg. Inayat et al. [25] reported that the heating value as well as gas yields was increased with the reduced size of wood chips particles. The percentage of CO, CH_4, H_2 and CO_2 in the gas composition was found to decrease while using the large feedstock particles. The maximum percentage of CO, CH_4 and H_2 was 25.60%, 2.79% and 10.91% respectively using 5-10 mm size of fuel particles. Ghani et al. [26] obtained more HHV of the product gas with the biomass (Malaysia agricultural waste) size less than 1 mm.

Moisture content:

The moisture content in the biomass strongly affects temperature in the reactor. The feedstock with high percentage moisture content decreases the heating value of product gas because of the incomplete pyrolysis process amid gasification [27]. The greater the amount of moisture content in biomass, the lower the temperature of the gasifier, higher the by-products such as tar, ash, coke etc., and reduction of the organic material. Thus a gradual decline in the carbon conversion efficiency happens with the high moisture content. Chaurasia [28] examined the same and found that lower heating value of the producer gas was increased to 4.65 MJ /m^3, when the moisture content of the feedstock particles was decreased to 8%. Cold gas efficiency is calculated using equation (7) [30]. Morita et al. [29] found similar outcome and reported that lowering the moisture content up to 5%, increased the cold gas efficiency by more than 75%.

$$\text{Cold gas efficiency} = \frac{(Flow\ rate)_{Product\ gas} \times (LHV)_{Product\ gas}}{(Mass\ flow\ rate)_{Fuel} \times (HHV)_{Fue}} \quad (7)$$

Bronson et al. [31] studied the influence of physical pretreatment of the moisture content biomass and its effect on the system capacity.

Higher heating value (HHV)

The quality of producer gas is also affected by the HHV of the biomass feedstock. HHV can be determined by proximate and ultimate analysis. The proximate analysis is determining the physical quantities like moisture content, volatile mater, fixed carbon and ash content of the biomass feedstock. The ultimate analysis determines elements such as percentage of Carbon %, Hydrogen %, Sulphur %, Nitrogen % and Oxygen % of the biomass feedstock [32]. The HHV is different for different biomass feedstock and it can be calculated directly by bomb calorimeter [33].

The HHV of biomass feedstock is determined using Eq. (8) [30]:

$$(HHV)_{Biomass} = 33823 * \%C + 144249 \left(\%H - \frac{\%0}{8}\right) + 9418 * \%S \quad (8)$$

Process Parameters

Equivalence ratio, gasification temperature, steam to fuel ratio and feedstock consumption rate are the main process parameters. The effect of these parameters on the fluidized bed gasifier is discussed as under:

Equivalence ratio

The equivalence ratio (ER) is defined as the ratio of actual air supply (m^3/hr) used for the combustion of fuel (kg/hr) to the stoichiometric air fuel ratio. Equivalence ratio mainly affects the gasification temperature, producer gas composition, calorific value (CV) and cold gas efficiency

The equation (9) describes the equivalence ratio [6].

$$\text{Equivalence Ratio} = \frac{(\text{Air fuel ratio})_{\text{Actuial}}}{(\text{Air fuel ratio})_{\text{Stoichiometric}}} \quad (9)$$

The lower heating value (LHV) is determined using eq. (10) [6].

$$(LHV)_{Producer\ gas} = \frac{282.99 \times V(CO) + 802.34 \times V(CH_4) + 241.83 \times V(H_2)}{100 \times 22.4} \quad (10)$$

The effect of ER on CV of producer and gas yield is shown in figure 4 [34]. It is observed that when the equivalence ratio is decreased from 0.33 to 0.23, the CV of producer gas is enhanced to 4.6MJ/m^3 and the gas yield is decreased to 3.9 m^3/h. In this study, woodchips had been used as feedstock. [34].

Meng et al. (2019) [20] reported that the heat value of the product gas increased to 12.5 MJ /m^3, when ER was decreased to 0.20 with oxygen as the gasification agent. It was also found that increasing the ER, enhanced the gasification temperature and gas composition when wood dust was used as a feedstock.

Gasification temperature

Gasification temperature strongly affects efficiency of the gasification process. Makwana et al. [35] obtained 3.75 MJ/m^3 calorific value of the product gas at the temperature of 780°C, and it decreased with the increase in gasification temperature. The amount of tar particles of the product gas was decreased from 7.2 g/Nm^3 to 0.85 g/Nm^3 with the rise in temperature from 720°C to 860°C. Zhang et al. [36] found that the H_2 and CO amount is enhanced with the rise in the temperature of reactor bed, but the percentage of CH_4 and CO_2 is decreased due to the endothermic reaction (as shown in the Eq.3-5) with the increase in gasification temperature from 700°C to 800°C. The gasification temperature is mainly affected by the ER and it increases with the rise in equivalence ratio.

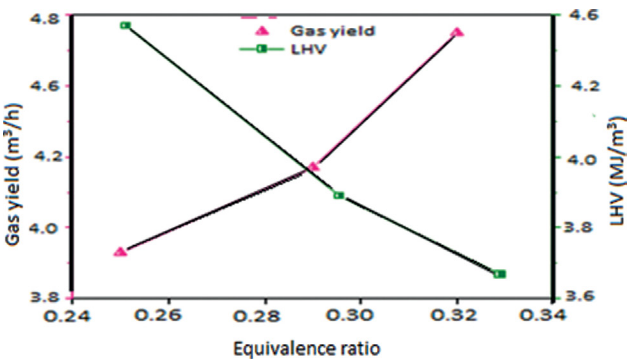

Figure 4. Equivalence ratio on LHV and Gas yield (modified from [34]).

Steam to fuel ratio (S/F)

To improve the gas composition and heating value of the producer gas, steam to biomass ratio needs to enhance. Karatas et al. [37] reported the increase in lower heating value of the product gas from 10 MJ/m^3 to 12 MJ/m^3 with the steam to fuel ratio varying from 0.40 to 0.70 using pistachio shells as a feedstock. Vélez et al. [38] studied the co-gasification of coal and biomass and reported that at constant air-to-biomass mixing ratios, the concentration of H_2 and CO are increased with the increase in steam-to-biomass.

Design Parameters

Design parameters can be classified as biomass feeding technique, air supply method, recirculating system and tar removal method. Sub-classification of these parameters is shown in the figure 5 [39-70].

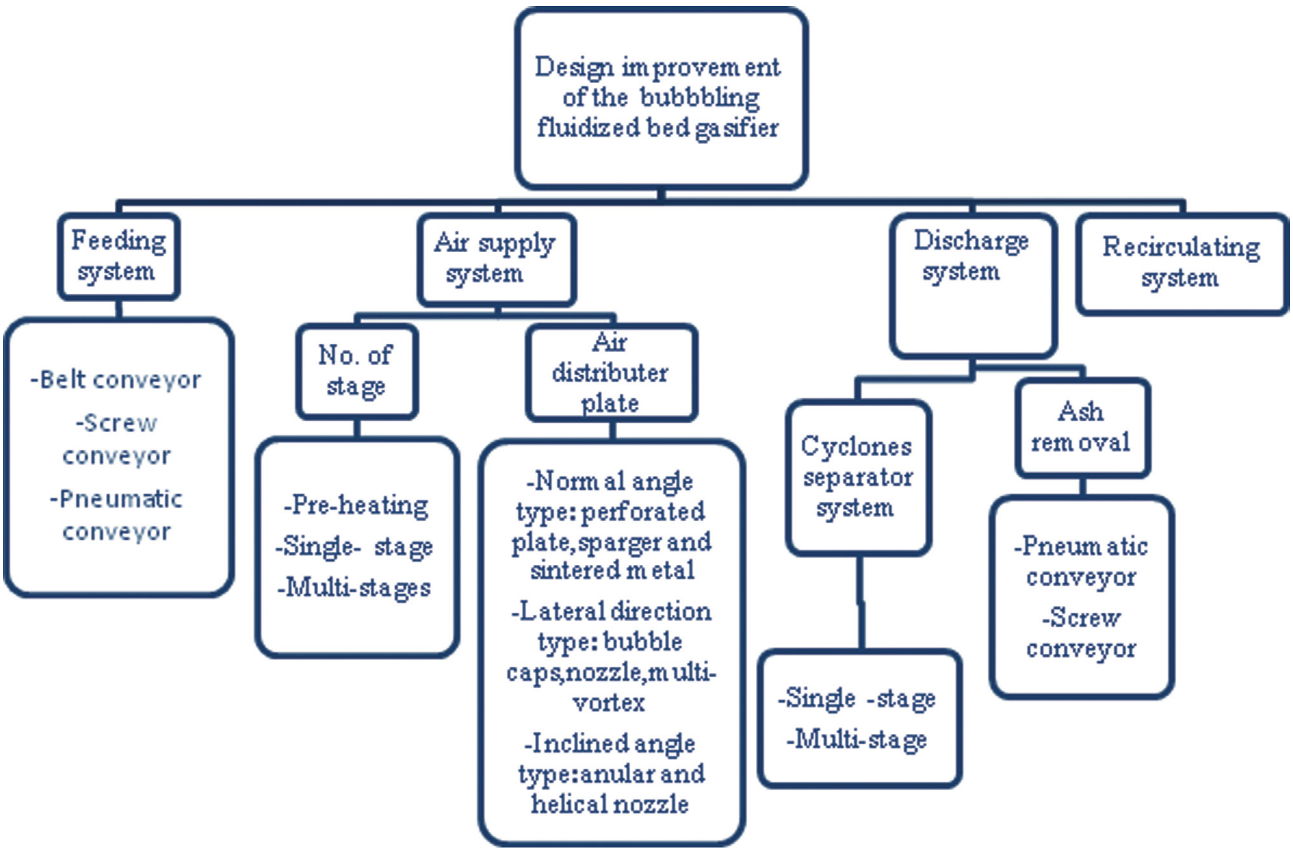

Figure 5. Design parameters of the bubbling fluidized bed gasification system.

Feeding System

The feeding system design affects efficiency of the gasifier. Feeding systems include screw, pneumatic and belt conveyors. The feeding rate of the biomass to the hopper is managed by motor speed. It is a function of the density of feedstock [39]. Various feeders used to carry feedstock particles from the hopper to the reactor or the conveyor belt are briefly described as under:

Bulk biomass feeder

Bulk feedstock feeder can carry a large amount of feedstock from hopper to the container of biogas plant. Belt conveyer system and screw conveyer system are the two important type of bulk biomass feeders. The screw type conveyor system transfers feedstock material from hopper to the gasifier reactor by rotating the screw [40]. Some important features of this type conveyor system are low initial cost, easy to operate, can deliver fuel even at high inclination, small space required etc. [40].

Pneumatic conveyor system

In pneumatic conveyor system, the feedstock material is conveyed from hopper to the gasifier reactor by compressed air [40]. The discharge rate and cross-section area of this system depend on the fuel feeding requirement. [41]. This type of conveying system is used for low density feedstock. Some important features of the pneumatic conveyor system are quick response, easy to maintain and operate, simple construction, low power consumption, etc. [40].

High pressure feed vessels (HPFVs)

This is a kind of feeder vessel in which feedstock particles are stored at high pressure. The working is almost similar to the pneumatic conveyor system but high fluid pressure is used in this system. A lock hopper is connected with the blow tank and the feeding rate is controlled by the revolutions of the screw feeder [40]. Simple construction and easy handling of pneumatic element, easy maintenance, high pressure capacity, speed and force etc. are some of the benefits of rotary type system [40].

Rotary valve feeder

In this type of conveyor system, the feedstock material is conveyed from hopper to the gasifier reactor by the rotor and drive shaft. The system consists of a shaft, housing, head plate, rotor, and bearing [40]. The main objective of this type of feeder is to maintain the pressure difference and this is done by making an air seal using a multi-way rotor. Low cost, long life, high locking air rate, simple construction etc. are some of the advantages of rotary type system [42].

Hydraulic feed system

In this type of system, the feedstock particles are transported from hopper to the reactor by a hydraulic cylinder. The system consists of hydraulic motors, pumps, directional valves, and power amplifiers. This type of system is capable of carrying heavy loads and also provides more force than others conveyor systems [43].

Distributer Plates

The air distributor is a system through which the gasification agent is supplied and controls as well as improves the performance of the fluidized bed gasification system, as shown Figure 2. Some types of air distributers are briefly discussed as below [44].

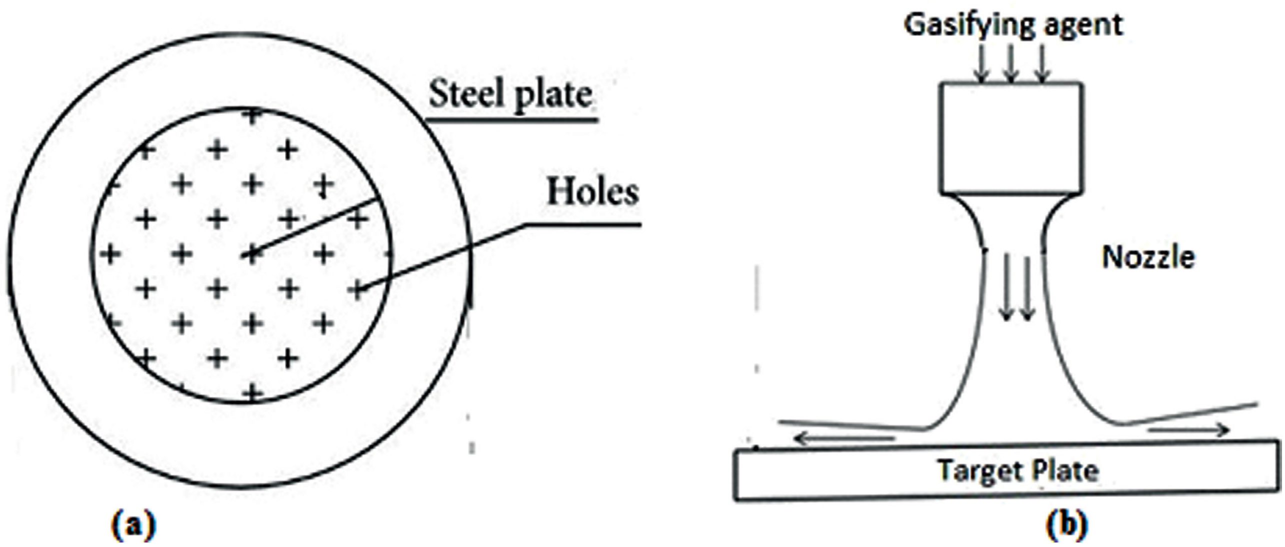

Figure 6. (a): Perforated distributer plate (modified from [45]), (b): Nozzle type distributer plate (modified from [46]).

Normal angle type

Gasification agent in this kind of distributor enter normal to the rector bed; some important type is perforated distributer, sparger and metal distributer. A perforated distributor plate is a circular plate [45], in which holes are made to supply the gasifying agent in the gasifier reactor as shown in Figure 6 (a).

Lateral direction type

The gasification agent enters the reactor bed in the lateral direction: examples are nozzles and multi-vortex. In the nozzle type distributor plate, as shown in Figure 6(b), it is often used to manage flow rate, speed, direction, mass, pressure of the gasification agent, as well as to increase the mixing rate of the gasification agent and feedstock [46].

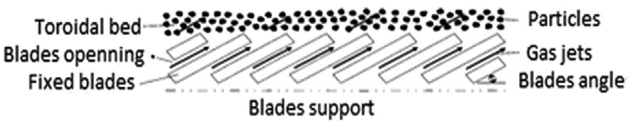

Figure 7. Toroidal distributer plate (modified from [47]).

Inclined angle type

This type of distributor plate supplies the gasifying agent to the reactor bed at certain angles like angular tilt blades and helical nozzles distributer. The toroidal distributer plate type is an example of this type of distributer which is shown in Figure 7. It increases mixing of air and feedstock, thereby increases quality of the product [47].

Gasifying Agent Supply System

Saleh et al. [48] reported that with the use of multi-stage air gasification system, the producer gas tar content is decreased up to 30% whereas, the H_2 and CO composition is increased. Ependi et al. [49] found that the cold gas

Table 1. Comparison of different design and process parameters of small-scale bubbling fluidized bed gasifiers

Different design and process parameters	Observations	Ref.
– Reactor: 20 kW thermal capacity, internal diameter 0.15 meter in gasification zone and 0.2 meter in the freeboard above, and a total height of 3.5 meter. – Biomass Feedstock: dried sewage sludge, straw pellets and wood pellets – Feedstock Feed Rate(kg/h): 4 and 7 – Air supply rate (meter/second.):0.4 – Equivalence ratio: 0.25 – Gasification agents: oxygen, steam and nitrogen – Gasification Temperature Range (°C): 800-920.	– Tar quantity of the product gases is reduced from 15 - 28 gm $m^{-3}$to below 6 gm m^{-3} by addition of calcined limestone with inert silica sand bed. – The optimum composition of producer gas with a mole fraction of 40% H_2, take after 32% CO2, 20% CO and 6% CH_4	[52]
– Reactor: 50 kg/h capacity – Biomass Feedstock: rice husk – Biomass Feedstock system: biomass hopper, screw feeder – Discharge system: cyclone separator, bag filter, water scrubber – Air Supply System: air blower, distributer plate – Equivalence ratio:0.25, 0.35 and 0.45 – Gasification agents: air – Gasification Temperature Range(°C): 600–800	– The Higher Heating Value (HHV) of product gas increased from 5.130 MJ/Nm^3 at 600°C to 5.280 MJ/Nm^3 at 750 °C and at E.R. of 0.35 – The maximum HHV of prod. gas approached 6.50 MJ/Nm^3 at 0.25 ER and 725°C temperature – The higher heating value of producer gas and gas yields growth reduced with the rise Equivalence ratio (ER) – H_2 and CO increases, CH_4 and CO_2 reduces with rise in bed temperature	[53]
– Reactor: ID of 200 mm, a total height of 1500 mm – Biomass Feedstock: Chinese herb residues – Biomass Feedstock system: two feeding augers – Discharge system: Cyclone – Air Supply System: air compressor, Air blower – Equivalence ratio: 0.20-0.32 – Gasification agents: air and steam – Gasification Temperature Range (°C):600-800.	– CV and gasification efficiency are more than 8 MJ/m^3 and 75% respectively at gasification temperature from 750 and 800°C with ER of 0.23-0.26 and steam to biomass ratio 0.4-0.6. – Percentage of H_2, CO_2 is increased and CO decreased gradually with the rise in moisture percentage of feedstock – The amount of CO_2 improves gradually, and CO decreases slightly, C_nH_m and CH_4 remained smoothly as with the increase of steam to fuel ratio	[54]

Different design and process parameters	Observations	Ref.
– Reactor: ID of 0.15 meter with a height of 2.5 meter – Biomass Feedstock: coal – Biomass Feedstock System: screw conveyor feeder and variable speed DC motor – Biomass particles size (mm): 2.5-3 and 2-3 – Discharge system: ash collector, three-layer sand bed filter with 2,1 and 0.5mm hole diameter, water scrubber – Air Supply System: air compressor and distributor plate – Biomass Feed Rate (kg/h):20.2 and 16.2 – Air supply rate (Nm^3/h): 23.2-40 – Steam Flow rate (kg/h): 2.4-4.0 – Air to Fuel ratio: 1.23-2.0 – Steam to Fuel ratio :0.15-0.25 – Equivalence ratio: 0.35,0.30 and 0.20 – Gasification agents: air and steam	– The cold gas efficiency increases from around 59% to 66% with decrease the air to coal ratio from approximate 1.75- 1.5. – Maximum Gas calorific value is 4.81 MJ/Nm^3 with ER 0.25 and average bed temp. of 951°C – Calorific value of the producer gas reduces with the growth in the air to coal supply rates ratio. – Total carbon conversion grows with a reduce in the air to fuel ratio – Cold gas efficiency grows from 63.6% to 77.70% with increase the steam to fuel ratio from 0.150 to 0.250	[55]
– Reactor: inner diameter 750-millimeter, height 3500 millimeter – operating pressure of Reactor (bar) :2.6-2.7 – Biomass Feedstock: Turkish Coal – Biomass Feedstock system: Coal Hopper, Screw feeder – Biomass particles size (mm):0.5 and 1 (diameter and length) – Discharge system: cyclone separator and ash collector – Air Supply System: wind box and the distributor plate with 4 nozzles – Biomass Feed Rate(kg/h):80–83 – Air supply rate (Nm^3/h) :10 – Oxygen supply rate (Nm^3/h) :21-28 – Steam Flow rate (kg/h): 100 -140 kg/h. – steam to Carbon ratio(S/F):2.0 and 2.8 – E.R. value:0.25–0.33 – Gasification agents: air, steam, O_2 and CO_2 – Gasification Temperature Range (°C): 850 -920.	– N_2 and CH_4 contents of product gas are vary in ranges between 6.7–7.8% and 4.0–4.6% – The cold gas efficiency is approximately 58.3% – LHV of product gas varied between 8.2 to 8.6 MJ/Nm^3 – Cold gas efficiency slightly decreases with increase steam – The H_2 content is proportional to the steam to coal ratio but inversely proportional to the ER – The range of carbon monoxide content in product gas is varies between 18.6 and 22.0%	[56]
– Reactor: Overall height of 2.29 meter and an ID of 82 millimeters, made of the AISI 310S stainless steel – Biomass Feedstock: different type Turkish coals, Kale-1, Kale-2, Orhaneli and Goynuk – Biomass Feedstock system: biomass hopper, two screw feeders – Biomass particles size (mm):1.0 and 2.0 – Discharge system: ash collector and cyclone separator – Air Supply System: air compressor, distributor plate – Biomass Feed Rate (kg/h):0.85 – Equivalence ratio: 0.15-0.45 – Gasification agents: Air and N_2 – Gasification Temperature Range(°C): 720-890	– For the Orhaneli, Kale-2 and Kale-1, LHV of producer gas are 5.44, 5.39 and 5.23 MJ/Nm^3 with ER of 0.28. – For the Kale-1 coal, the LHV of the producer gas is observed from 4.36 to 6.16 MJ/Nm^3 with equivalence ratio limit of 0.44 to 0.17. – The concentration of CO is obtained between 12 and 19% within equivalence limit of 0.44 to 0.17. – The lower heating value raises with decrease equivalence for all coal samples. – Concentrations of H_2 is increase with decrease ER	[57]

Different design and process parameters	Observations	Ref.
– Reactor:100 kW thermal capacity, an ID of 304 millimeter and height of 2.35 meter – Biomass Feedstock: Lignite (Rhenish lignite mining, Germany) – Biomass Feedstock system: three feedstock hopper, two screw feeder – Biomass particles size (mm):2–6 – Air Supply System: air compressor – Biomass Feed Rate(kg/h):16.9-17.0 – steam to carbon ratio(S/C):1.3-2.1 – steam to Fuel ratio(S/F):0.9-1.4 – Gasification agents: steam and Air – Gasification Temperature Range (°C):650–906	– The GC–MS-detectable tar amount range between 3.0 and 3.3 g/Nm^3 – The composition of H_2, CO, CO_2 and CH_4 is closer to 48.2 to 50.7, 25.3 to 29.5, 12.9 to 15.1 and very close to 4.4 vol. %.	[58]
– Reactor:85 kW paper sludge (BFB), an internal diameter of 0.26 meter and height of 2meter – operating pressure of Reactor (bar): – Biomass Feedstock: paper sludge – Biomass Feedstock system: a screw feeder – Biomass Feed Rate(kg/h):15 – Air Supply System: air compressor – Air Flow rate (NI/min): 270 – Equivalence ratio:0.2–0.4 – Gasification agents: Air	– The LHV of product gas is closer to 2.7 MJ/Nm^3 – H_2, CO, and CH_4 composition of product gas are vary in between 3-13,7-25 and 0.1-0.8%	[59]
– Reactor: ID of 234 millimetre, and height of 2.05 meter – Biomass Feedstock: two mixes of a German brown coal and pine woodchips pellets – Biomass Feedstock system: screw feeders – Biomass particles size (mm):6 and 10–20 (diam. and length) – Discharge system: a combustor (78 mm of ID and 2.20 m of high), cyclone and ceramic candle filters, candle filters – Air supply rate (m^3/h): 1.5-8.0 – Steam supply rate (kg/h):1.6-4.0 – Steam to Fuel ratio(S/F):0.37-1.03 – Equivalence ratio: 0.07-0.37 – Gasification agents: air, steam – Gasification Temperature Range (°C): 663-917	– In the case of GBC30, the composition of H_2, CO, CH_4 and CO_2in producer gas is closer to 35.4,8.9,5.7 and 19.1 vol.% at equivalence ratio of 0.07 – Low tar quantity observed for GBC50 with regard to GBC30 – Tar concentration decrease, when replace from inert to partly catalytic bed for the GBC30 – Tar concentration decrease with increase equivalence ratio for GBC30 – GBC50 got high H_2 and CO concentrations with respect to GBC30 – H_2 concentration of producer gas increase with increasing the steam/fuel ratio	[60]

Table 2. Brief description of cold gas particulate matter removal technologies [62-65]

Type	Tar removal efficiency	Working principle
Spray scrubber	Tar particles size greater than 5 mm; 90%	In this system, water-like fluid spreads from the spray nozzle to the moving product gas at the same time or counter ally.
Dynamic wet scrubber	Particle size greater than 5 mm; up to 95%	This type of equipment uses mechanical motions such as turbines or fans with blades. After a turbulent mixture of product gas and water by this mechanical motion system, the tar particles are separated from the gas by water droplets.
Cyclonic scrubber	Submicron particles; 60–75%.	In such a system, the product gas passes through the top side of the scrubber with water and is discharged from the underside of the scrubber after a spiraling motion. This process causes the gas tar particles to separate with a drop of water.
Impactor scrubber	Large particle; greater than 98% %	The product gas with the tars particles passes into the perforated plate or others plate with small holes, the tar particles in the gas are washed away with regular water.
Venturi scrubber	Submicron particles; greater than 50%	The product gas as well as the water passes into the convergence to divergence section with high velocity, the water washes the tar particles with fine small drops in the product gas.
Electrostatic scrubber	Submicron particles; about 99%	Previously or in view of applying electric charge, water is sprinkled into the product gas stream

Table 3. Brief description of hot gas tar removal technologies [62, 64, 66-68]

Method	Working principle	Remarks
Thermal cracking	• Such cracking is carried out by high temperatures up to 1000to 1400 °C, resulting in large size tar particles of the product gas being converted into smaller non-condensing gases.	• Tar removal rates are up to 80 times more, depending on initial concentrations
Catalytic cracking	• This type of cracking has a lower temperature range than thermal cracking. After passing through catalytic media such as Ni-based, metal-based, mineral-based and iron-based catalysts, large-sized tar particles of product gas are converted into smaller-sized particles.	• The catalytic cracking method has a higher process control rate than thermal cracking. • The yield rate of product gas is better by using nickel-based catalysts and it is mostly used in industry. • The tar removal rate of metal-based catalysts is efficient as compared to Ni and mineral based catalysts.
Plasma cracking	• In this process plasma (which is produced by the effect of a high collision electron particle) is used to decompose tar particles. Some important types of plasma are microwave plasma, pulsed corona, RF plasma, dielectric resistor discharge and others,	• The initial cost of plasma technology is much higher than others. • Pulse corona plasma is the most relevant technique through which tar particles can be decomposed at a temperature of about 400°C.
Physical separation	• In this type of cracking, a lower temperature range is used and scrubbers and electrostatic precipitators are some important examples of this type of cracking.	• In the physical separation, tar particles can decompose at a temperature of about 450°C. • The partial cooling necessity of gas flow limits the use of mechanical separators at high temperatures.

efficiency reaches up to 5.13% and simultaneously reduces the tar content of product gas by 34.39 mg/Nm^3. In this study wood pallets were used as feedstock.

Tar Removal and Discharge System

Tar or ash in a product gas is of concern when it is used in an I.C. engine. The maximum allowed tar content in product gas for an I.C. engine is 0.1 gm/Nm^3 [50]. So as to limit its content during engine operation and to increase the performance of gasifier, it is essential to decrease the tar in the producer gas. The technique of reducing tar or ash can be classified as hot gas tar cleaning and cold gas tar cleaning [51]. The cold gas cleaning methods consist of spray scrubber, dynamic wet scrubber, cyclone scrubber and others as shown the Table 2, whereas, hot gas cleaning methods consist of thermal cracking, catalytic cracking, plasma cracking and others as shown in the Table 3. Catalysts are also used for hot gas tar removal wherein tar particles of the product gas are removed by passing gas into a catalytic media [51]. Bio-oil scrubber and char filter are equally effective in reducing tar [61].

Recirculating System

Gasifier design van be improved by an attachment of the producer gas recirculating system. It allows the producer gas to circulate in the drying area or the biomass feed hopper. The heat of producer gas removes moisture of the biomass fuel. No direct contact is there between the producer gas and the feedstock in drying zone [69]. Additionally, the system does cooling of the gas before exiting the biomass gasifier. Cooling modifies efficiency of the gasifier-engine system when producer gas is used to fuel the engine [70].

CONCLUSIONS

The producer gas is a high calorific value gaseous fuel, which extracts from biomass with the help of the gasification process. The quality of producer gas is affected by biomass feedstock characteristics, process and design parameters of the bubbling fluidized gasifier. Some important mentions of the present study are as under:

- The present worldwide scenario of bioenergy is reviewed.
- Investigating various types of gasification technologies used for the gasification process.
- Demonstrates techno-economic feasibility of gasification process for various types of gasification technologies.
- Presented various clean-up technologies employed for conditioning of product gas.
- The selection of gasification system relies upon several parameters such as characteristics of biomass, process parameters and design parameter. The quality of producer gas is increases by using inclined type distributer plate as compared to others and the tar composition of producer gas is reduced up to 30% by using a multi-air supply system. The cold gas efficiency of a gasifier reactor is more than 75% when the moisture content of fuel is less than 8% and air equivalence ratio is about 55%. The heating value of the producer gas increases when the size of the feedstock particles is less than 1 mm. When the ER value is less than 0.25, the calorific value of the producer gas increases by more than 4.5 MJ/m^3. The tar particles of the product gas are decreased from 7.2 g/Nm^3 to 0.85 g/Nm^3, with temperatures increasing from 720°C to 860°C.

During the study it was found that the performance of the gasifier can be increased at the optimum value of ER, gasification temperature, size of feedstock particles and moisture content in the fuel. Even proper selection of design parameters such as distributer plates as well as different type of air supply system can improve the performance of a gasifier.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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