Hydrodynamic and gasification studies of sawdust in a pressurized circulating fluidized bed

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Abstract. The present research is focused on the hydrodynamics and gasification studies of a pressurized circulating fluidized bed (PCFB) gasifier considering saw dust as a bed inventory. The operating pressure range of the PCFB gasifier is maintained in between 1 to 4 bar and the suspension density, syngas composition, lower heating value (LHV), gas yield, carbon conversion efficiency (CCE) and cold gas efficiency (CGE) were calculated and presented in this paper. The suspension density increases with rise in operating pressure and decreases with rise in superficial velocity. The concentration of CH\textsubscript{4} in the syngas was found to be increasing with rise in bed pressure and is found to be 4.78 % at 4 bar. However, no significant effect of operating pressure on H\textsubscript{2} concentration is observed and is found to vary between 8.3 to 7.95 %. The CO concentration increases up to 2 bar pressure and decreases gradually afterwards. The LHV, gas yield, CCE and CGE has a positive response to the rise in operating pressure and found maximum at 4 bar. The CCE and CGE of the PCFB gasifier are increased by 57 % and 58 %, respectively when the operating pressure is changed from 1 to 4 bar.

Keywords: Gasification; Sawdust; Pressurized circulating fluidized bed

1. Introduction

The worldwide energy consumption is increasing rapidly due to the development of advanced power generation technologies in the last two decades because of which the global community is suffering with fuel crises, global warming and pollutant emission from the sources of conventional fossil fuel. These serious effects attract researchers for an intensive research in field of clean energy for the next generation. Solar, biomass, wind, tidal and other renewable energies act as a bridge between environmental pollution and clean energy. Biomass is preferred over all other types of renewable resources of energy due to its control in hand, easy to transport like coal and storage in the stockyard. It has also gained popularity after coal, petrochemicals and natural gas with 14 % of the global share in energy consumption [1]. In a tropical country like India, a huge amount of biomass are stored in an un-hygienic condition which are under-utilized. The low calorific value and minimal ash content of biomasses attract investigators for the production of power in an efficient way [2-4]. Fluidized bed is one of the promising technology because of its capacity to handle a wide range of fuel and uniform-mixing of particles to enhance gasification rate inside the bed [5].

The bed hydrodynamics of the circulating fluidized bed (CFB) riser plays a vital role to investigate the different fluidization regime and design and operation of combustion/gasification. It
shows a balance of pressure and mass of the circulating loop and classifies the solid distribution in the axial direction of the riser section [6-7]. Hydrodynamic study includes the effects of superficial velocity, particle size, solid inventory and operating pressure in the bed voidage and suspension density of the riser [8]. Kalita et al. [9] studied the bed hydrodynamics, heat transfer behaviour and effects of solid inventory, particle size, and operating pressure considering blending of sawdust as a bed material.

The bubbling fluidized bed (BFB) gasification is the most preferred technology used by many researchers because of its ease of handling. Datta et al. [10] described the agglomeration behaviours of the high ash Indian coal gasification. Kumari and Vairakannu [11] studied the underground coal gasification of high and low ash Indian coal. Kumar et al. [12] also experimentally studied the air and steam mixtures in a bubbling gasifier and reported that the efficiency increases with decrease in air-fuel ratio. Miccio et al. [13] used the German brown coal and woodchips as biomass in dual fluidized bed for co-gasification at atmospheric conditions. Co-gasification of coal and biomass in a bubbling fluidized bed gasifier was also investigated by Li et al. [14]. They reported that H₂ and CO decreases with increase in equivalence ratio and increases with biomass ratio. Mallick et al. [15] studied the effect of equivalence ratio on concentration of H₂ and CO and found similar results as observed by Li et al. [14].

The atmospheric fluidized bed gasification is an established technology while pressurized fluidized bed gasification is still in very young age in research [16-17]. Gul et al. [18] studied the pressurised bubbling gasification and the syngas composition under different mass flow rates with an additional CO₂ reagents. Huang et al. [19] investigated the gasification of coal in a pressurized bubbling fluidized bed and reported the increase of gasification with increase in pressure. They also reported syngas composition to be a function of temperature but had a little effect of pressure on syngas composition with change of pressure from range 0.5 to 1.4 MPa. Srinivas et al. [20] studied the thermodynamic equilibrium model for a PCFB gasifier. They reported that the syngas concentration of H₂ and CO₂ decreased and CH₄ and CO increased with increases in gasifier pressure. They also reported that the effect of pressure on gas composition was very little while it affected the temperature, LHV of gas and exergy efficiency. Kitzler et al. [21] explored the pressurized gasification in a bubbling fluidized bed considering woody biomass as a bed inventory. They reported that concentration of H₂ was higher if the gasification temperature was greater than 820°C and the pressure was less than 4 bar. The concentration of H₂ in a pressurized bubbling fluidized bed gasification taking sawdust as an inventory was reported by Long et al. [22]. They found an increase of concentration of H₂ and CH₄ and a decrease of CO₂ and CO with the increases in gasifier pressure from 1 to 4 bar. Berrueco et al. [23] investigated the effect of temperature and dolomite on formation of tar and gas concentration in a pressurized fluidized bed at constant pressure of 0.5 MPa. They reported that with introduction of dolomite as a bed material instead of sand, there was an increase of syngas concentration of H₂, CO, CH₄ and CO₂ with the increase in temperature. Sanchez et al. [24] studied a new model for coal gasification in a bubbling pressurized fluidized bed, and reported the pressure to have a significant effect on gas composition. Also, there was a decrease in H₂ and CO while concentration of CH₄ and CO₂ increased with pressure.

It is observed that a very limited study has been reported regarding utilization of sawdust in PCFB. Further, PCFB has gained importance in recent time due to its compactness and high efficiency. Therefore, the current study is an attempt to investigate the hydrodynamic behaviour and gasification study of PCFB with sawdust as a bed inventory. The variation of suspension density, bed temperature, gas concentration, LHV, gas yield, CCE and CGE are studied under various operating conditions viz. pressure and superficial velocity.
2. Experimental setup and procedure

The schematic diagram of the PCFB unit is presented in Fig. 1. The PCFB unit is comprised of various components such as a riser, a distributor plate, a cyclone separator, a downcomer. The riser is fabricated with ID (internal diameter) of 100 mm, OD (outer diameter) of 110 mm and height of 3000 mm, which is further connected to cyclone separator through a connecting pipe. The cyclone separator is fabricated from stainless steel having dimensions of 660 mm in length and having barrel ID of 160 mm. The top part of the cyclone separator is used for collection of syngas where the bottom end is connected to the downcomer of ID 50 mm. Subsequently, the return leg is connected to the bottom of the riser column at 150 mm, above the distributor plate. A gateway valve is installed in the downcomer section to avoid any backflow from the riser. The pressure drop along the height of the riser is measured by using ten pressure sensors above the distributor plate and suspension density is calculated at those points. Similarly thirteen thermocouples are mounted along the height of the riser from distributor plate to monitor the bed temperature.

![Figure 1. Experiment set up of hot bed PCFB unit.](image)

For the atmospheric circulating fluidized bed (ACFB) experiments, the blower delivery air passes through an electric heater box before entering into the bottom of the riser through the distributor plate. On the other hand, for the PCFB experiments, a reciprocating compressor is used for pressurizing the air, which passes through a tubular heater before entering to the riser through distributor plate. The atmospheric/pressurized air is further routed through a straight-hole based distributor plate having opening area of 16.4%. A mass flow meter is installed for calculating the mass flow rate of the air that is entering into the riser.

Initially, the sawdust is sieved into particle size of 600 μm and further desired quantity of inventory is fed into the PCFB unit through the top of the riser. The air from the compressor passes through a heater before enrooting into the distributor plate. To regulate the airflow rate from the blower and compressor, a valve is installed. The temperature in the riser increases due to the burning of the sawdust and takes almost 10-20 minutes to achieve steady state flow regime in the riser during hot bed studies. In the meantime, the syngas is collected through the top of the cyclone separator. Furthermore, the gas chromatography is conducted to find out the quality of the collected syngas. After 30 minutes, the sawdust burns out in the riser and the temperature and the quality of syngas decrease. During the hot bed studies, experiments are conducted both at atmospheric as well as pressurized conditions. All the readings are recorded throughout the experiments with the help of the data acquisition system.
The experimental uncertainty is determined for suspension density by considering all the parameters. The parameters affect the suspension density are bed voidage and density of both air and sawdust. While calculating the bed voidage, the error during the measurement of pressure drop via pressure sensor is also taken into consideration. For suspension density, the overall uncertainty in the experimentation is found to be $\pm 3.25\%$ [25].

3. Results and discussion
The sawdust collected locally is used as an inventory for the present experiments. The properties of sawdust is same as those given by Mallick et al. [15]. The suspension density along the height of the riser, and effect of pressure on gasification studies i.e. effect of temperature, gas composition, LHV, gas yield, CCE and CGE is described in subsequent sections for the batch type study in a PCFB gasifier.

3.1. Effect of pressure and velocity on suspension density with sawdust as inventory
The variation of suspension density with pressure along the riser height at different superficial velocity for 1000 gm saw dust is shown in Figs. 2 through 4. The suspension density seems to be increasing as the pressure increases at a particular superficial velocity and also decreases with an increase in superficial velocity. As perceived from the figures, suspension density is having higher magnitude at the lower section of the riser height, which then, decreases up to the top middle zone, and then starts increasing to the exit of the riser. The maximum suspension density is observed in case of 4 bar operating at superficial velocity of 3 m/s. In view of deducing the effect of superficial velocity at fixed operating pressure, the maximum suspension densities magnitudes have been compared. This shows a decrement of 25 % and 41 % for 4 m/s and 5 m/s superficial velocity, respectively in comparison to 3 m/s condition. For the hydrodynamics study, the optimal operating conditions are superficial velocity $= 3$ m/s, and operating pressure $= 4$ bar where the magnitude of suspension density is higher i.e., $12.33 \text{ kg/m}^3$.

![Figure 2. Variation of suspension density with operating pressure along the riser height](image)

![Figure 3. Variation of suspension density with operating pressure along the riser height](image)

![Figure 4. Variation of suspension density with operating pressure along the riser height](image)

![Figure 5. Variation of temperature with time along the riser height](image)
3.2. Effect of temperature with saw dust as inventory
The temperature along the height of the riser for operating pressure of 2 bar at different time instances is shown in Fig. 5. The temperature increases in the lower part of the riser i.e. till 500 mm from distributor plate and after that it decreases gradually. With respect to time, the temperature is found to be increasing up to 15 minutes of operating duration, and then starts decaying. The temperature increases rapidly due to the minimum heat loss to the atmosphere at the pressurized condition. During the time when the lower part of the riser achieves a temperature range of 300-550°C, syngas is produced and collected. It takes normally 15 minutes time for gasification of 1000 gm sawdust and after 15 minutes the temperature inside the riser decreases and the syngas is produced up to 20 minutes. Generally, the syngas is collected up to 10 minutes with an inventory of 1000 gm of sawdust.

3.3. Gasification studies on pressure conditions
The effect of gas composition with varying pressure from 1 to 4 bar is shown in Fig. 6. The effect of pressure on gas composition is very less significant for hydrogen. With increase in pressure from 1 to 4 bar, hydrogen content decreases from 8.3 to 7.95 %. The percentage of CO increases form pressure 1 to 2 bar and decreases gradually from 2 to 4 bar. There is an increase in CO$_2$ from 11.2 to 15.2 % with increase in pressure from 1 to 4 bar. The concentration of methane increases slowly with increase in pressure from 1 to 4 bar. It increases from 3.23 to 4.78 for pressure 1 and 4 bar respectively. The trend of the syngas is different as suggested by different researchers but most of them suggested that there is an increase in CO$_2$ with increase in gasifying pressure which is also evident in Fig. 6. The reaction \[ \text{Char} + \text{O}_2 \rightarrow \text{CO}_2 + \text{CO} \] plays an important role in the increase in CO$_2$ in the syngas composition with an increase in operating pressure.

The lower heating value and gas yield of the syngas with different operating pressure is represented in Fig. 7. The lower heating value of the syngas is calculated by using the equation \[
\text{LHV}_{\text{Syngas}} = 4.2 \times \left[ (25.7 \times H_2) + (30 \times CO) + \left( 85.4 \times CH_4 \right) + 151.3 \times \left( C_2 H_2 + C_2 H_4 + C_2 H_6 \right) \right].
\] If there is a slight increase in percentage of methane, it affects the value of LHV. The LHV of syngas gas increases with increase in operating pressure, as it is the function of the coefficient of gas compositions. For calculation of LHV, the higher order terms of $C_nH_m$ is neglected, because during gas composition, these values can not be measured in gas chromatography. There is a impulsive increase in LHV from 1 to 2 bar and then it increases steadily from 2 to 4 bar. The drygas yield increases with an increases in operating pressure. It increases from 1.78 to 2.20 with increases in pressure from 1 to 4 bar. With increase in pressure, N$_2$ decreases and this is the reason for increase in dry gas yield of the syngas. Moreover, as the temperature increases with pressure, the gas yield also increases with pressure.

The carbon conversion efficiency (CCE) and cold gas efficiency (CGE) have been calculated by using the relationship given by Mallick et al. [15]. The (CCE) of the gasifier increases with an
increases in operating pressure (Fig. 8). With increases in pressure, more amount of air is introduced into the riser and with increases in air the amount of O$_2$ increases. With increase in O$_2$, there is an increase in gasifying temperature and heat transfer in the riser which results in enhancing the gasification rate and thereby increasing the total carbon content of the syngas. The CCE of the gasifier increases from 50.33 to 79.35 with an increases in pressure from 1 to 4 bar. Similarly, the cold gas efficiency also increases from 37.71 to 59.66 with an increase in pressure from 1 to 4 bar. For the gasification study, the optimal operating condition of pressure = 4 bar where the lower heating value (4746.86 kJ/Nm$^3$) is higher. The value of CCE and CGE at 4 bar is 79.35 and 59.66 %, respectively.

![Figure 8. Variation of carbon conversion and cold gas efficiency with operating pressure](image)

4. Conclusions
In this present investigation, hydrodynamic behaviour and gasification study have been carried out in a PCFB gasifier experimentally. Sawdust is considered as a solid bed inventory and the pressure is maintained in the range of 1 to 4 bar. The key findings of the study are summarized below:
- The suspension density increases with operating pressure but decreases with increase in superficial velocity.
- In the syngas, concentration of CH$_4$ and CO$_2$ increases with increase in operating pressure.
- The effect of pressure on gas concentration is very less significant for hydrogen. There is a small decrease in hydrogen content from 8.3 to 7.95 % when the pressure increases from 1 to 4 bar.
- The concentration of CO increases when the pressure changes from 1 to 2 bar and decreases gradually from 2 to 4 bar.
- The LHV, gas yield, CCE and CGE has a positive response to the rise in bed operating pressure and are found maximum at 4 bar. The CCE and CGE of the PCFB gasifier are increased by 57 % and 58 %, respectively when the operating pressure is changed from 1 to 4 bar.

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