

Design and Development of Bubbling Fluidized Bed Gasifier for Non-Woody Biomass Gasification

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Bubbling fluidized bed (BFB) reactor is advantageous for synthesis gas or syngas production among other available gasifiers. In this study, a BFB gasifier has been designed, utilizing non-woody biomass (rice straw) and air as gasifying medium, to investigate the effect of equivalence ratio (ER), static bed height, and operating temperature on synthesis gas yield and gasification efficiency. To calculate various structural and operating parameters, a reaction chamber with a diameter of 10 cm and a bed material of 400-500 μm has been studied. Considering the minimum fluidization velocity, slugging velocity, and terminal velocity, the optimum operating velocity has been taken as 17.25 cm/s. The calculated optimum transport disengagement height (TDH) is 86 cm, and the freeboard height is approximately 116 cm. Thus, the overall height of the reactor has come up as 202 cm. Almost 80% carbon conversion efficiency (CCE) was achieved from this BFB reactor with an optimum ER value of 0.35 during rice straw gasification. The same gasifier results in a synthesis gas yield of 3.6 Nm^3/kg with a lower heating value (LHV) of about 3.5 MJ/Nm^3 at optimum ER value. Further scaling up this process based on the findings of this study for industrial-scale synthesis gas production can pave a way for bioenergy generation from non-woody biomass.

1. Introduction

In developing countries, most of the non-woody biomass, such as rice straw, rice husk, wheat straw, is mostly used in direct combustion for heat energy generation mainly for cooking (Sharma et al., 2020, Shahsavari and Akbari, 2018). Due to a relatively lower air to biomass equivalence ratio (ER), carbon dioxide (CO_2), carbon monoxide (CO), water, and other carbonaceous solids and gaseous waste are also produced in this process (Shahbaz et al., 2020, Xue et al., 2019). Lower ER results in heat energy at a relatively lower temperature which is not suitable for steam production for electricity generation (Liu et al., 2018). In contrast, higher ER (0.25 – 6.25) is maintained in the gasification process, resulting in a sufficient supply of air for partial oxidation of biomass and self-sustain the gasification process without significantly affecting the synthesis gas (H_2 and CO) yield (Zhao et al., 2021).

Gasification is a thermochemical conversion process in which biomass undergoes partial oxidation in presence of an oxidizing agent to produce synthesis gas that can be used for liquid and gaseous fuel and electricity production (Guran, 2020, Maitlo et al., 2022). The most critical part of the gasification process is the reactor subsystem which is known as a gasifier. Several types of gasifiers are used for biomass gasification, for

instance, fixed-bed updraft and downdraft gasifier, fluidized bed gasifier. Fixed-bed gasifiers have a considerable biomass conversion rate to be employed for decentralized electricity generation at a smaller scale. However, some other crucial problems like uneven temperature distribution in the catalyst bed, severe catalyst poisoning, and higher initial heating energy requirement make them unattractive for large-scale gasification processes (Volpe et al., 2017). In addition, those gasifiers show the limitations of scaling up alongside the lower heating value synthesis gas production and higher tar yield (Jahromi et al., 2021). Fluidized bed gasifier addresses several of these limitations and provides advantages of even temperature distribution, lower residence time, short heta-up period, and effective gas-solid mixing.

Therefore, in this study, a laboratory-scale bubbling fluidized bed (BFB) gasifier was designed for non-woody biomass (rice straw) utilization. The effect of air to biomass (rice straw) ER on synthesis gas composition and yield was studied. Finally, variation of synthesis gas heating efficiency and biomass carbon conversion efficiency with the variation of ER was studied for gasification process performance evaluation.

2. Methodology

2.1 BFB gasifier design specifications

A BFB gasifier was designed for non-woody biomass (rice straw) utilization. Several assumptions were considered in this design approach. For instance, a 10 cm of inner diameter (ID) of the gasifier was fixed initially and 750 – 850°C and 101.325 kPa conditions were assumed for such gasifier operation (Rasmussen and Aryal, 2020). Air and sand were used as a gasifying agent and fluidized bed material correspondingly. Table 1 shows other crucial design parameters for this study.

Table 1: Physical properties of fluidized bed material and gasification medium alongside the operating conditions of the BFB gasifier

Parameters	Value
Operating conditions	
ID of fluidized bed, D (cm)	10.00
Temperature, T (°C)	750 - 850
Pressure (kPa)	101.325
Characteristics of fluidized bed material	
Diameter, d_p (μm)	400 - 500
Sphericity, ϕ	0.86
Porosity, ϵ_{mf}	0.42
Density, ρ_s (gm/cm^3)	2.60
Characteristics of gasifying medium	
Viscosity, μ ($\text{gm}/\text{cm}\cdot\text{s}$)	0.00018
Density, ρ (gm/cm^3)	0.00120

2.2 Calculation of BFB gasifier design parameters

The design calculations including the minimum fluidization velocity, terminal velocity, slugging velocity, operating superficial velocity, height of the reactor, plenum design, and distributor plate design were carried out using various correlations from previous studies (Table 2). The minimum fluidization velocity (u_{mf}) refers to the velocity at which bed materials start to expand. This velocity was calculated from a relationship between the drag force (by upward moving gas) and the weight of the bed particles (Kunii and Levenspiel (1991); Yang (2003)). Terminal velocity (u_t) was considered as the maximum superficial velocity and was calculated using an experimentally determined drag coefficient (C_D) of the bed materials (sand) (Table 2). Bubble rise velocity was calculated to define the slugging velocity ($u_{b,ms}$) of bed materials. Operating or superficial velocity (u_0) was suggested to maintain higher than u_{mf} but lower than u_t to overcome the slugging conditions in the riser. A relationship between expanded (H) and minimum heights (H_{mf}) of the bed ($1.2 < H/H_{mf} < 1.4$) was used to calculate u_0 (Chatterjee et al., 1995). The total height of the gasifier (above distributor plate) ($H_{Total,g}$) was calculated from the total freeboard height (H_{fb}) and height of the expanded bed (H_s). An additional 30 cm was added to transport disengagement height (TDH) to calculate H_{fb} , a location of gasifier gas outlet. This TDH was calculated from Fung and Hamdullahpur correlations using bubble diameter (d_b) (Fung and Hamdullahpur, 1993). Finally, orifices were used in the distributor plate design. As illustrated in Table 2, whole distributor plate design was based on the pressure drop in distributor plate (ΔP_{dis}), gas velocity at orifice (u_{orf}), number of orifices per unit area of distributor (N_{orf}), and distance between two orifices (pitch). An equidistance triangular layout was used for orifice distribution across the distribution plate in this study.

Table 2: Correlations used for BFB gasifier design parameters calculation and performance evaluation

Gasifier parameter	Co-relation	Reference
Minimum fluidization velocity (u_{mf})	$\frac{1.75}{\epsilon_{mf}^3 \phi_s} \left(\frac{d_p u_{mf} \rho_g}{\mu} \right)^2 + \frac{150(1-\epsilon_{mf})}{\epsilon_{mf}^3 \phi_s^2} \left(\frac{d_p u_{mf} \rho_g}{\mu} \right) = \frac{d_p^3 \rho_g (\rho_s - \rho_g) g}{\mu^2}$	Kunii and Levenspiel (1991), Yang (2003)
Terminal velocity (u_t)	$\left[\frac{4d_p (\rho_s - \rho_g) g}{3\rho_g C_D} \right]^{1/2}$	Kunii and Levenspiel (1991), Yang (2003)
Slugging velocity ($u_{b,ms}$)	$u_{mf} + 0.07(gD)^{1/2}$	Kunii and Levenspiel (1991)
Superficial velocity (u_0)	$\frac{H}{H_{mf}} = 1 + \frac{10.978 \cdot (u_0 - u_{mf})^{0.738} \cdot \rho_p^{0.376} \cdot d_p^{1.006}}{u_{mf}^{0.937} \cdot \rho_g^{0.126}}$	(Chatterjee et al., 1995)
Riser height	$H_{Total, g} = H_{fb} + H_s, H_{fb} = 30 + TDH, TDH = 13.8 \times d_b$	Yang (2003)
Distributor plate design	$\Delta P_{dis} = 0.3 \times \Delta P_{bed}, \Delta P_{bed} = \rho_p (1 - \epsilon_{mf}) H_{mf} g$ $u_{orf} = C_d \left[\frac{2\Delta P_{dist}}{\rho_{g,orf}} \right]^{0.5}, u_0 = \frac{\pi}{4} d_{or}^2 u_{or} N_{or}; P_{pitch} = \sqrt{\frac{2}{\sqrt{3}} N_{den}}$	(Basu, 2006), Kunii and Levenspiel (1991)
Synthesis gas yield (Nm ³ /kg)	$\frac{V_{syngas} \text{ (drybasis)}}{M_{afb} \text{ (drybasis)}}$	(Hervy et al., 2019)
Lower heating value (MJ/Nm ³)	$\frac{126.36 \text{ CO} + 107.98 \text{ H}_2 + 358.18 \text{ CH}_4}{100}$	(Niu et al., 2013)
Carbon conversion efficiency (%)	$\frac{C_{syngas} \times Q_{syngas}}{C_{biomass} \times Q_{biomass}} \times 100$	(Niu et al., 2013)
Cold gas efficiency (%)	$\frac{\text{LHV of syngas} \times Q_{syngas}}{\text{LHV of biomass} \times Q_{biomass}} \times 100$	(Niu et al., 2013)

2.3 Gasification process performance evaluation

A homogeneous biomass feedstock supply was used in this study. Rice straw was grounded in Willey mill and sieved through a 50 mesh screen. Proximate analysis (GB 28731-2012 method) and ultimate analysis (Flash EA 1112 CHNS-O analyzer, Thermo Fisher Scientific Inc., UK) of feedstock were conducted to determine moisture content, fixed carbon, volatile matter, and ash content. The performance of the gasification process was evaluated in terms of synthesis gas yield (V_{syngas}) and mass of ash-free biomass (M_{afb}), lower heating value (LHV), carbon conversion efficiency (CCE) (calculated by carbon content (C_i), and flow rate (Q_i) of synthesis gas and biomass), and cold gas efficiency (CGE) (Table 2). An online gas composition analyzer (Varian micro-GC 490) was used for synthesis gas composition analysis continuously.

3. Results and discussion

3.1 Structural parameters of the BFB gasifier

Correlations described in section 2.2 are used to calculate the various structural and operating parameters (u_{mf} , u_t , $u_{b,ms}$, u_0 , TDH, ΔP_{dis} , u_{orf} , N_{or} , and P_{pitch}) of the BFB gasifier. Table 3 shows that the operating velocity of the designed gasifier is 17.25 cm/s for non-woody biomass gasification. The TDH of the gasification column is calculated 86.00 cm compared to the 116 cm height of the freeboard. Those heights are merged to design the total height of the gasifier riser. Design parameters of the distributor plate are also tabulated in Table 3. Those structural parameters were used to design BFB gasifier, and the schematic of the gasifier is shown in Figure 1. Biomass and air are fed into the gasifier in a counter-current manner to improve the fluidization efficiency that consequently reduces the tar formation as well. Other contaminants, such as dust, are entrained by adding a cyclone separator at the end of the fluidization region before synthesis gas composition analysis (Hossain et al., 2019). Previous studies also reported that the counter-current flow in BFB gasifiers enhanced biomass conversion due to effective solid-gas mass transfer in the fluidization region. In addition, counter-current flow prevents the slugging phenomena effectively inside the gasifier. To prevent plugging in the fluidization region,

this velocity must be higher than the minimum fluidization velocity (Khezri and Ghani, 2017). Table 3 shows that $U_{b,ms}$ is maintained at 22.23 cm/s, higher than the U_{mf} of 14.26 cm/s. However, counter-current flow in the gasifier comparatively lowers the heating efficiency even at higher ER (Cardoso et al., 2018). Since this flow pattern improves the operational complexity (slugging phenomena), the counter-current flow pattern is widely used in smaller-sized biomass gasification (Shahlan et al., 2018). Finally, a two-dimensional numerical model can be developed based on the above laboratory-scale gasification process. Experimental data from the laboratory scale process can be used to validate the developed numerical model which can be used to predict the pilot-scale gasification process afterward. Numerical results from the pilot-scale process can be validated against the results available in the literature for a similar process. At the same time, experimental errors must be recorded to predict the uncertainty in this scale-up process.

Table 3: Parameters for BFB gasifier design for non-woody biomass utilization

Design parameters	Value
Minimum fluidization velocity, u_{mf} (cm/s)	14.26
Terminal velocity, u_t (cm/s)	273.11
Slugging velocity, $u_{b,ms}$ (cm/s)	22.23
Operating velocity, u_0 (cm/s)	17.25
TDH (cm)	86.00
Pressure drop across distributor plate, ΔP_{dis} (pa)	783.26
Gas velocity at orifice, u_{orf} (cm/s)	22.73
Number of orifices per unit area of distributor, N_{or}	4572
Orifice layout pitch, P_{pitch} (cm)	1.60

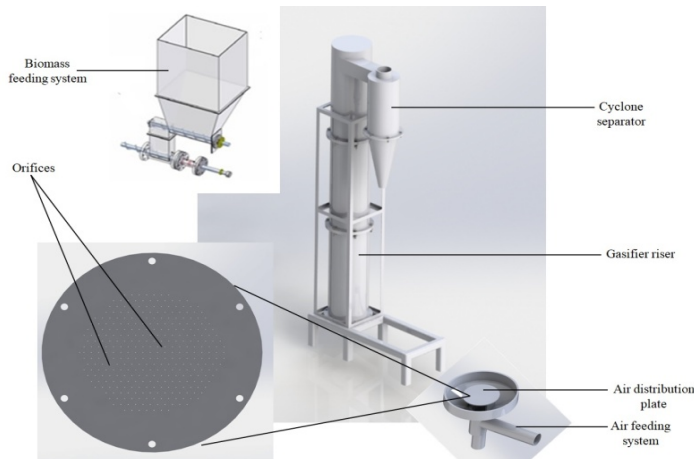


Figure 1: Schematic of the laboratory scale BFB gasifier (air and biomass feeding system, gasifier riser, and cyclone separator are shown in the schematic).

3.2 Effects of ER on gasifier efficiency

The characterization of rice straw feedstock (moisture content 13.38%) is presented in Table 4. Figure 2a shows that both the hydrogen (H_2) and methane (CH_4) mole percentage in synthesis gas decreased with an increase of ER. Increasing ER means that amount of air flow inside the gasification region increases. With the increasing ER, carbon monoxide (CO) molar proportion rises as well- about 40-mole percentage at 0.30 ER. CO molar percentage decreases with a further increase in the ER value (0.30). In contrast, the carbon dioxide (CO_2) mole percentage shows an opposite trend of the CO molar proportion. The mole percentage of CO_2 decreases at the beginning (0.20 – 0.30 ER) whereas this molar proportion increases with the gradual increment of ER value. Synthesis gas (molar) composition varies with the increase of ER value because of varying combustion characteristics of biomass in the gasification region. A lower amount of air flow initially increases the CO mole percentage due to incomplete combustion (Niu et al., 2013). With the increasing ER value, complete combustion of biomass generates more CO_2 but this accompanies the decrease of other gaseous components, such as CO, H_2 , and CH_4 , the molar percentage in the synthesis gas (Hervy et al., 2019). Varying biomass combustion

characteristics also affect the synthesis gas yields in Figure 2a. Synthesis gas yield increases from 2.5 Nm³/kg to 4.2 Nm³/kg between 0.20 – 0.50 ER value, but nitrogen exclusion from the synthesis gas shows that only 2.1 to 3.0 Nm³/kg yield increase in the same ER range. Nitrogen dilution improves the synthesis gas yield but lowers the LHV of the synthesis gas (Hervy et al., 2019). Figure 2b represents the continuous reduction of LHV due to increased airflow (ER) in this study. Similar nitrogen dilution also lowers the CGE after the ER value of 0.30 in Figure 2b. In this ER value (0.3), biomass CCE also reaches the maximum value of about 80%, beyond that CCE remains at the plateau value.

Table 4: Proximate and ultimate analysis for rice straw characterization

Proximate analysis (dry basis) (wt%)			Ultimate analysis (dry basis) (wt%)				
Ash	Volatile matter	Fixed carbon	C	H	O	N	S
15.07	73.38	11.55	42.85 ± 0.82	5.73 ± 0.35	36.49 ± 0.41	0.46 ± 0.11	0.14 ± 0.04

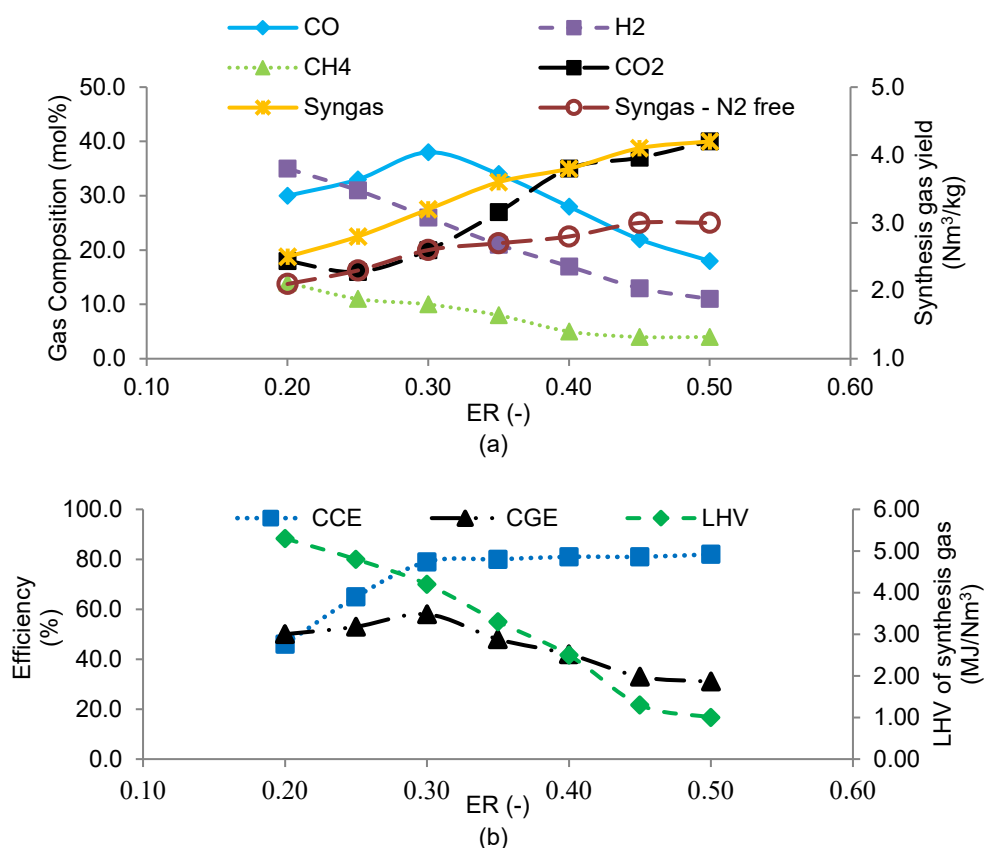


Figure 2: Effects of ER value on (a) synthesis gas molar composition and yield and (b) synthesis heating characteristics and carbon conversion efficiency.

4. Conclusions

Designed BFB gasifier can be used for the non-woody biomass (rice straw) gasification for synthesis gas production. Minimum fluidization velocity is calculated 14.26 cm/s for this gasification process. Maintaining the operating velocity (17.25 cm/s) higher than minimum fluidization velocity prevents the slugging conditions in the gasification zone. Orifice meters were used in the distributor plate for airflow to create fluidization conditions inside the BFB gasifier and a total of 4572 orifice meters were used in a 1.60 cm pitch distance. In addition, optimum ER is calculated at 0.30 in the designed BFB gasifier, using rice husk at 300 μ m particle size. At optimum ER, both the CCE and CGE reached the maximum values, about 80% and 58% correspondingly. Beyond this ER value of 0.30, the gasification process starts generating more CO₂ (>20%) than CO (< 38%). Moreover, LHV also decreases significantly after ER of 0.30, and therefore, this is considered as the optimum ER value for rice straw gasification in the designed BFB gasifier.

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