Research Article

Experimental Gasification of Biomass in an Updraft Gasifier with External Recirculation of Pyrolysis Gases

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The updraft gasifier is a simple type of reactor for the gasification of biomass that is easy to operate and has high conversion efficiency, although it produces high levels of tar. This study attempts to observe the performance of a modified updraft gasifier. A modified updraft gasifier that recirculates the pyrolysis gases from drying zone back to the combustion zone and gas outlet at reduction zone was used. In this study, the level of pyrolysis gases that returned to the combustion zone was varied, and as well as measurements of gas composition, lower heating value and tar content. The results showed that an increase in the amount of pyrolysis gases that returned to the combustion zone resulted in a decrease in the amount of tar produced. An increase in the amount of recirculated gases tended to increase the concentrations of H_2 and CH_4 and reduce the concentration of CO with the primary (gasification) air flow held constant. Increasing the primary air flow tended to increase the amount of CO and decrease the amount of H_2. The maximum of lower heating value was 4.9 MJ/m^3.

1. Introduction

The development of industry around the world has resulted in an enormous demand for energy that will continue to rise. However, the supply and the availability of energy from fossil fuels will decrease. Biomass is an environmentally sustainable alternative energy source that is widely available around the world [1]. Using biomass sources such as wood, rice husks, and bagasse, which have the highest energy content, together with the highest-efficiency conversion methods would add a significant amount of energy. The use of biomass for biofuels has reached approximately 9–14% of the total of energy demand worldwide [2].

Gasification is an ecoefficient and sustainable thermo-chemical conversion method [3] that creates low levels of pollution [4].

Various forms of gasifiers have been developed to meet criteria of being easy to operate, being highly efficient, and producing relatively low amounts of tar. The two most popular types of fixed-bed reactors used are the updraft gasifier and the downdraft gasifier. The updraft gasifier is easy to operate and has quite high conversion efficiency, but this type produces high levels of tar, as high as 0.2 kg/m^3 [5], because the pyrolysis gases containing high levels of tar are extracted directly from the reactor. This increases the load on the gas cleaning system and the level of carcinogenic waste produced [1].

Modifying the reactor is one common method used to reduce the level of tar produced from the gasification. The gasifier could be modified with recirculaton of pyrolysis gas and modification of gas outlet [6].

This study presents a study of a modified updraft gasifier with recirculaton of the pyrolysis gases back to the combustion zone and the gas outlet at the reduction zone. The effects on combustible gas composition, the LHV, and the tar content of the producer gas were investigated.

2. Material and Methods

The fuel used was woody biomass that was cut into pieces of 0.03 m wide and 0.03 m long and had a moisture content of 10.24%. The proximate and ultimate analyses of this fuel are shown in Table 1.

FIGURE 1: Experimental Setup.

TABLE 1: Proximate and ultimate analyses [7].

Proximate and ultimate analyses		
	Unit	Value
Proximate analysis		
Moisture (adb)	%	10.24
Ash	%	2.71
Volatile	%	71.80
Fixed carbon	%	15.25
Ultimate analysis		
Carbon	%	43.33
Hydrogen	%	5.11
Nitrogen	%	Not detected
Sulfur	%	Not detected
Oxygen		38.61
Calorific value	kJ/kg	17025
Density	kg/m^3	640

The gasification process included a gasification reactor with a diameter of 0.22 m and a length of 0.63 m and constructed of stainless steel (SUS 304 [7]), as shown in Figure 1. Type-K thermocouples were placed at the bottom of the reactor wall to measure the temperature inside the combustion zone reactor. Two air supplies were used in this process: the primary air and the motive flow (ejector air). The primary air for combustion was supplied using a blower and the motive flow for driving pyrolysis gas was supplied by a ring blower. The flow rates of the primary air, the motive flow, and the recirculated gas were measured using orifice plate flow meters. The producer gas outlet from the reactor was at a height of 0.13 m above the grate (at reduction zone). Recirculation pipes with a diameter of 0.05 m running from the top (drying zone) to the bottom of the reactor (the combustion zone) were constructed from stainless steel and equipped with control valves to manage the recirculation flow. The pyrolysis gas was driven to the combustion zone by the motive flow (air ejector) in the recirculation pipes. The recirculation pipes were heated using an electric heater to a temperature of 623°K to prevent tar condensation [8]. The tar content in the producer gases was measured using six impinger bottles, five of which were filled with a solvent (isopropanol) and one which was empty, as in [7, 9, 10]. Approximately 0.00005 m^3 (50 mL) of solvent was used to fill each of the five bottles. Subsequently, the solvent containing the tar was vaporised at a temperature of 380°K [11, 12]. The tar that was not vaporised was measured to determine the mass of the tar (kg/m^3). The gas composition was taken using sample tight bags, then it was analyzed using gas chromatography with thermal conductivity detector (TCD).

The ejector was a constant-mixing-area type, and the convergence nozzle had the following dimensions: the diameters of the inlet and outlet air were 0.025 m and 0.0075 m, respectively, and the nozzle exit position (NXP) was −0.03 m before the entrance of mixing chamber [13].
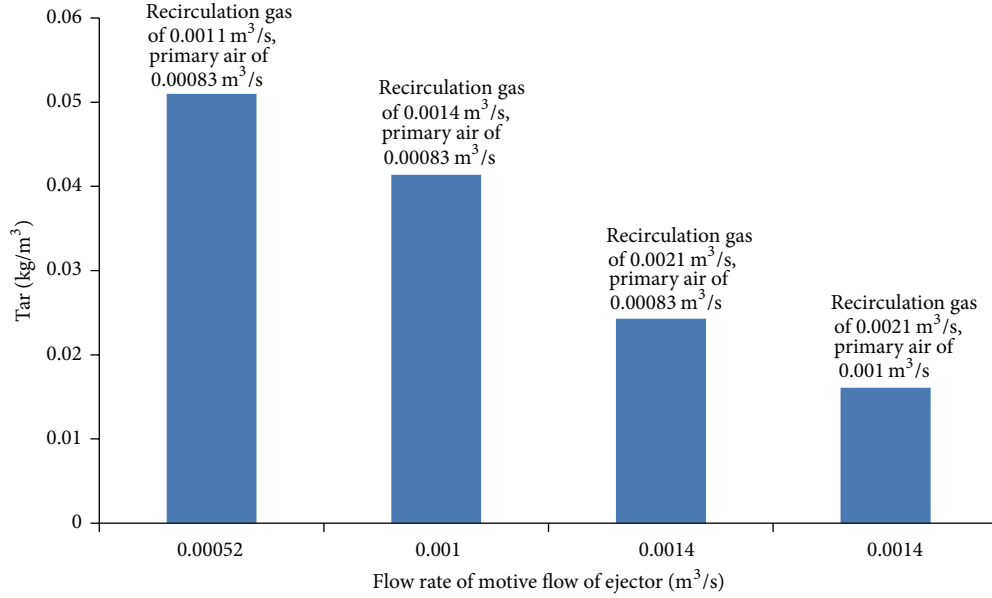
FIGURE 2: Tar content versus motive flow ejector.

The lower heating value (LHV) of producer gas was calculated using calorific value of moles fraction of combustible gas (CO, H_2, CH_4) [14]:

$$\text{LHV } (kJ/m^3) = y_{CO} \cdot 12621 + y_{H_2} \cdot 10779 + y_{CH_4} \cdot 35874, \tag{1}$$

where y_i values are volume fractions of main combustible gas in the producer gas.

The mass of tar was calculated based on differences of mass impinger bottle containing tar and empty impinger bottle:

$$\text{Gravimetric tar } (kg/m^3) = \frac{\text{mass of bottle containing tar } (kg) - \text{mass of empty bottle } (kg)}{\text{flow rate of tar sampling } (m^3/s) \times \text{time of tar sampling } (s)}. \tag{2}$$

3. Results and Discussion

3.1. Tar Content.
Figure 2 shows the effect of the flow rate of the recirculated pyrolysis gases on the amount of tar

To begin the tests, approximately 0.5 kg of fuel was placed in the reactor and burned until the temperature reached the maximum of 473°K. Next, approximately 6 kg of additional fuel was placed into the reactor until the reactor was nearly full. After 900 seconds of operation, the combustible gases were obtained. The primary air gasification (primary air flow) was varied of 0.00083 m³/s and 0.001 m³/s. The motive flow of ejector (air ejector) was varied of 0.00052 m³/s, 0.001 m³/s, and 0.0014 m³/s. The experiment was carried out at constant primary air gasification and the air ejector was increased, then the air ejector was held constant and the primary air was increased. The gas composition was taken for the sampling at the temperature of combustion zone was stable. Tar samples were taken at the temperature of the combustion zone was stable, while the flow rate of gas sampling was set at 3.3×10^{-5} m³/s and the sampling time was about 240 seconds for each experiment.

produced. At recirculated pyrolysis gas flow rates of 0.0011, 0.0014, and 0.0021 m³/s, generated with ejector motive flow rates of 0.00052 m³/s, 0.001 m³/s, and 0.0014 m³/s, respectively, the resulting tar concentrations were approximately 0.051, 0.0414, and 0.0243 kg/m³ respectively, indicating a reduction in the tar content. At a motive flow rate of 0.0014 m³/s, the primary air flow rate was increased to 0.001 m³/s, and the tar concentration was reduced to 0.0161 kg/m³. This reduction in the amount of tar resulted from the cracking (reactions (8)) and reforming (reactions (9) and reactions (10)) process of tar into combustible gases (H_2 and CO) at a temperature of approximately 923–973°K [15, 16]. Figure 5 shows the temperature in the combustion zone for every operating condition above 1073°K for which cracking and reforming tar is possible. The cracking and reforming of the tar will contribute more to H_2 (reactions (8), and (9)) production when the primary air flow rate is constant and the motive flow of the ejector is varied. When the primary gasification was increased, there was a tendency towards an increased contribution of tar reforming to CO production (reactions (10)) as an effect of the increase
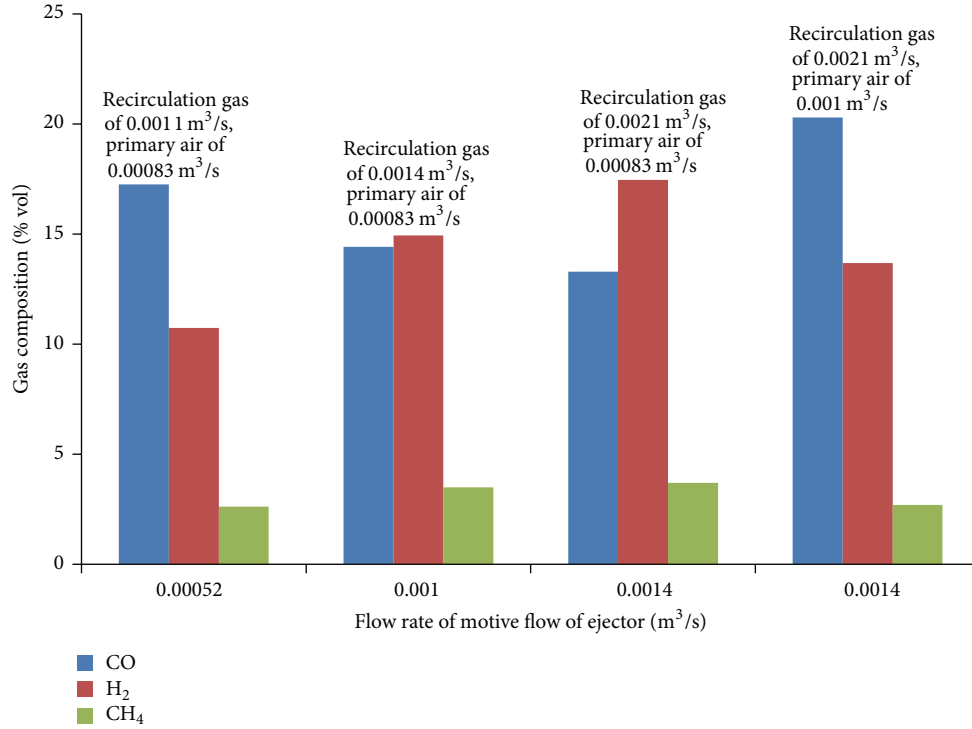
FIGURE 3: Gas concentration versus motive flow ejector.

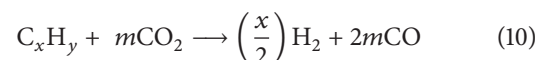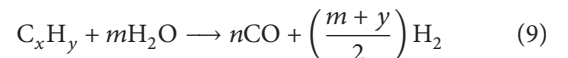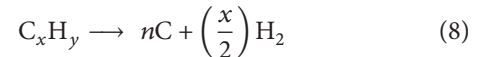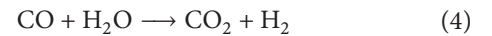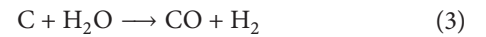of combustion reaction (reaction (7)), as shown in Figure 3.

3.2. Gas Compositionzz.

Figure 3 shows the concentrations of the gases resulting from the recirculation of the pyrolysis gases back to the combustion zone.

Increasing the recirculation of the pyrolysis gas from $0.0011 \, m^3/s$ to a maximum of $0.0021 \, m^3/s$ at a constant primary air flow rate of $0.00083 \, m^3/s$ caused the concentration of H_2 to increase from 10.74% to 17.46% and the concentration of CH_4 to increase from 2.62% to 3.7%; however, the concentration of CO decreased from 17.25% to 13.29%. This upward trend was caused by the water vapour (H_2O) present in pyrolysis gases reacting with the C and the CO at high temperatures (above 1073°K) to produce H_2 (reactions (3)) and (reactions (4)). According to Kumar et al. (2009), the water gas reaction should increase at temperatures between 1023°K and 1073°K [17]. The reaction of tar cracking (reactions (8)) and steam reforming of the tar (reactions (9)) at temperatures of approximately 923°K to 973°K [15, 16] would contribute to an increase in H_2. The decrease in the CO concentration due to a decrease in the dominance of the boudouard reaction (reactions (5)) caused a temperature reduction. The increase in the CH_4 level was caused by an increase in the methanisation reaction (reactions (6)) because the pressure increased in the gasifier as an effect of the pressure of the ejector. According to Kaupp and Gross (1981) [18] and Donaj et al. (2011) [19], an increase in the pressure inside the reactor increases the concentration of CH_4.

When the recirculation flow rate was at a maximum of $0.0021 \, m^3/s$ and the primary air flow rate was increased to $0.001 \, m^3/s$, the concentration of CO increased from 13.29% to 20%, but the concentrations of H_2 and CH_4 decreased from 17.46% to 13.68% and from 3.7% to 2.69%, respectively. Because the increase in the primary air flow rate increases the combustion reaction (reactions (7)) and the temperature inside the reactor, this contributed to a reduction in the reaction that produces H_2 (reaction (3)) and (reaction (4)) and an increase in the boudauard reaction (reaction (5)) [20] and dry reforming of the tar (reaction (10)). The decrease in H_2 contributed to a reduction in CH_4 (reaction (6)) The increased temperature inside the reactor (Figure 5) contributed to the decrease in the CH_4 concentration [20, 21].

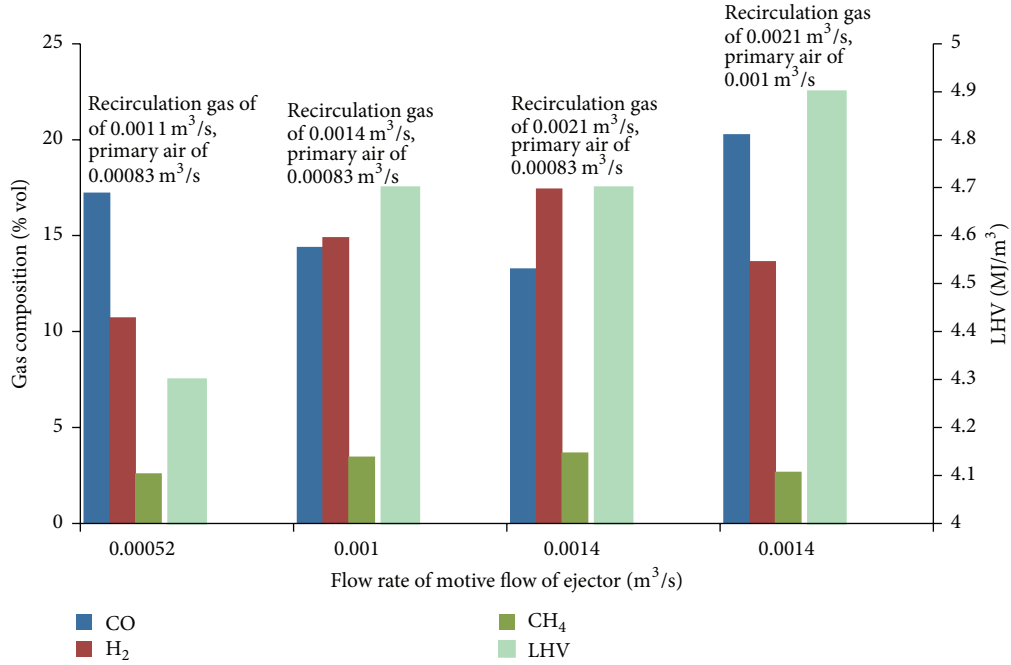Consider gasification, tar cracking, and tar reforming reaction as follows:

$$C + H_2O \longrightarrow CO + H_2 \tag{3}$$

$$CO + H_2O \longrightarrow CO_2 + H_2 \tag{4}$$

$$C + CO_2 \longrightarrow 2\,CO \tag{5}$$

$$C + H_2 \longrightarrow CH_4 \tag{6}$$

$$C + O_2 \longrightarrow CO_2 \tag{7}$$

$$C_xH_y \longrightarrow nC + \left(\frac{x}{2}\right)H_2 \tag{8}$$

$$C_xH_y + mH_2O \longrightarrow nCO + \left(\frac{m+y}{2}\right)H_2 \tag{9}$$

$$C_xH_y + mCO_2 \longrightarrow \left(\frac{x}{2}\right)H_2 + 2mCO \tag{10}$$

FIGURE 4: Lower heating values of gases versus motive flow ejector.
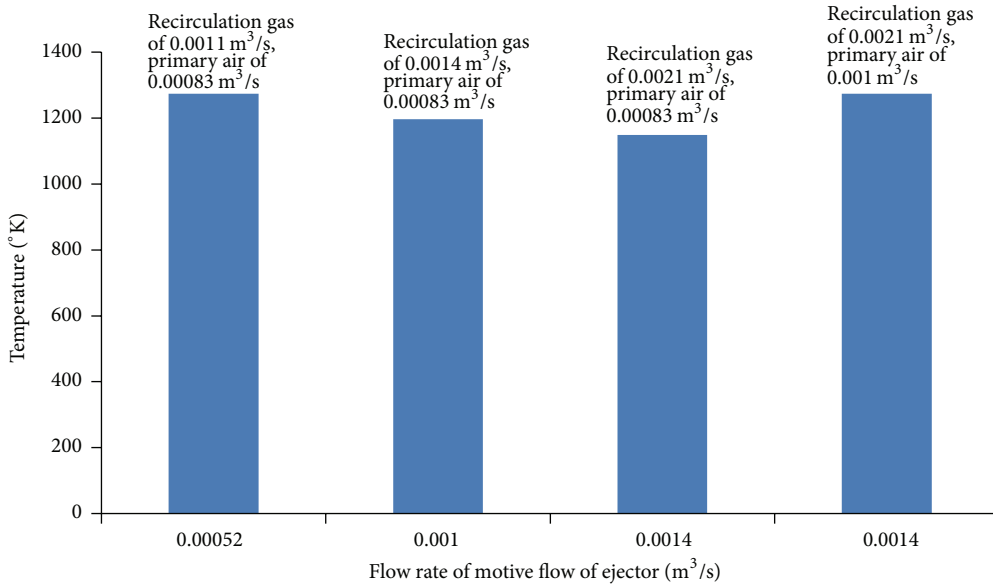

FIGURE 5: Combustion zone temperature versus motive flow ejector.

3.3. The Lower Heating Value of the Producer Gas.

Figure 4 shows the effect of the flow of the pyrolysis gases in the combustion zone on the lower heating value of the gas.

When the pyrolysis gas recirculation rate was increased from $0.0011\,m^3/s$ to a maximum of $0.0021\,m^3/s$ at a constant primary air flow rate of $0.00083\,m^3/s$, the lower heating value of the gas increased from $4.3\,MJ/m^3$ to $4.7\,MJ/m^3$. This increase resulted from a significant increase in the concentration of H_2 and a moderate decrease in the concentration of CO. Furthermore, there was an increase in the concentration of CH_4, which has a greater heating value than that of the other gases. When the primary air flow rate was increased to $0.001\,m^3/s$ and the pyrolysis gas recirculation rate was held constant at $0.0021\,m^3/s$, the lower heating value increased from $4.7\,MJ/m^3$ to $4.9\,MJ/m^3$ because of the significant increase in the concentration of CO.

3.4. Combustion Zone Temperature. Figure 5 shows the variation in the maximum temperature in the combustion zone with the ejector flow rate. When the pyrolysis gas recirculation was increased from $0.0011\,\mathrm{m^3/s}$ to a maximum of $0.0021\,\mathrm{m^3/s}$ at a constant primary air flow rate of $0.00083\,\mathrm{m^3/s}$, the maximum temperature in the combustion zone decreased from $1273°\mathrm{K}$ to $1148°\mathrm{K}$ because the endothermic reaction that produces H_2 (reactions (3)) became more dominant. The lower pyrolysis gas temperature led to a need for more heat to increase its temperature, causing a decrease in the temperature of the bed [17]. The temperature inside reactor was constant at over $1148°\mathrm{K}$ so that the cracking and steam reforming of the tar were continuous.

When the primary air flow rate was increased to $0.001\,\mathrm{m^3/s}$ and the pyrolysis gas recirculation was held constant at $0.0021\,\mathrm{m^3/s}$, the temperature in the combustion zone increased from $1148°\mathrm{K}$ to $1273°\mathrm{K}$ because the increase in the flow rate of the primary air contributed to an increase in the exothermic combustion reaction (reaction (7)).

4. Conclusions

The recirculation of pyrolysis gases from the top of gasifier (drying zone) to the combustion zone and gas outlet from reduction zone in a modified updraft gasifier in this study resulted in maximum lower heating value of $4.9\,\mathrm{MJ/m^3}$. Increasing the flow of the pyrolysis gases to the combustion zone tended to reduce the amount of tar produced. The concentration of H_2 tended to increase and the concentration of CO decreased with increasing motive flow rate and constant primary gasification air. Increasing flow rate of the primary gasification air tended to increase the amount of CO and decrease the amount of H_2 produced.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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