

An Investigation on Performance of a Horizontal Entrained Flow Gasifier

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Abstract

A novel study on biomass-air gasification using a horizontal entrained-flow gasifier has been conducted. The use of a horizontal entrained-flow gasifier reactor was employed to assess the effect of the gasifier reactor orientation on the gasification process. The gasification experiments were conducted at 800°C and equivalence ratio of 0.23 while maintaining gas hourly space velocity (GHSV) of 8000 h⁻¹. Preparation and characterisation of wood powder were performed using classical methods. The research findings showed that maximum fuel conversion and cold gas efficiency using a horizontal entrained-flow gasifier were 99% and 70% respectively compared to 91% and 62% respectively of the vertical design. Moreover, the gasifier length can also be reduced from the common 1000 - 2000 mm to 500 mm. In general, the results of this study suggest that there exists a sensitivity to the gasifier orientation on the overall gasification process.

Keywords

Gasification, Entrained-Flow, Syngas

1. Introduction

Biomass gasification has been achieved through different reactor designs including entrained-flow types. Entrained-flow gasifiers (EFG) have been used successfully for coal gasification since 1950. The majority of these gasifiers are of a slagging type and operate at higher pressures. Typical operating pressure ranges from 20 - 70 bar and temperatures are above 1400°C. Although the elevated conditions ensure high fuel conversion and destruction of tar, the conditions are achieved at the expense of high oxygen consumption, as well as needing an efficient heat recovery system. On the other hand, gasification at atmospheric

pressure is also possible. For atmospheric gasification conditions, the feed mechanisms are of the premix type and operate at high velocity to avoid flash back. High velocities lead to increased syngas yield.

There are various criteria for classifying entrained flow gasifiers including the flow configuration. The common designs are down-flow and up-flow reactors. In both designs, the fuel feedstock and oxidizing agents (usually oxygen and steam) are introduced into a reactor in co-current flow. The down-flow configuration is intended to improve slag separation and makes gravity fuel feed possible [3] [5]. However, owing to the short space residence time of the fuel particles, the length of the gasifier is crucial in attaining efficient fuel conversion. While a shorter reactor may result in poor fuel conversion, a longer reactor is associated with increased energy production cost.

On the other hand, the up-flow reactor is mainly characterized by large recirculation resulting from temperature differences, thus increasing particle residence time. This increase results in improved fuel burn-out and syngas quality. However, with excessive recirculation zones, caution must be applied, as the reverse flow may cause flash back.

Recent developments in the field of entrained-flow gasification have led to an interest in using biomass as the fuel feedstock. This arises from its higher reactivity compared to that of coal. A number of research studies have been carried out on entrained flow air gasification at non-slagging temperatures ($\sim 700^{\circ}\text{C}$ - 1100°C) [1] [2] [6]. In most cases, the gasifier reactor has been configured vertically employing a down flow regime as highlighted in **Table 1**. Although this configuration improves particulate separation from the product gas, more heat and manufacturing materials are required due to long gasifier reactors (1200 - 2000 mm). Moreover, the heating value of the product gas has been reported to be below $6.0 \text{ MJ/N}\cdot\text{m}^3$.

Thus, this study focused on the effect of gasifier reactor orientation on gasification process. The gasifier sized 3 kW was configured horizontally to increase the particles residence time as opposed to a vertical entrained-flow system, where gravity forces result in lower residence time. Additionally, the enhanced particle to metal surface contact promotes heat transfer to the particle, thus increasing fuel conversion.

Table 1. Typical geometrical parameters of the entrained-flow gasifier reactors.

| Reference | Configuration | Length (mm) | Diameter (mm) | Temperature ($^{\circ}\text{C}$) |
|-------------|---------------|-------------|---------------|------------------------------------|
| [4] | Top-down | 1200 | 75 | 750 - 1250 |
| [7] | Top-down | 2000 | 255 | 1200 |
| [8] | Top-down | 2000 | 80 | 1000 - 1350 |
| [1] [2] [6] | Top-down | 1200 | 60 | 1050 |
| [1] [2] [6] | Top-down | 1900 | 100 | 700 - 1000 |

2. Methodology

2.1. Characterisation of Sawdust

Commercial pine sawdust was reduced to pass a test sieve with an aperture of 250 μm using a grinding mill and further prepared for characterisation according to BS EN 15413:2011 standard [9]. The proximate analysis was determined using standard [10] [11] [12] [13]. Proximate analysis expresses the properties of a particular fuel with regard to moisture, ash, fixed carbon, and volatile matter. These properties are important in assessing the characteristics of a particular fuel during combustion.

Ultimate analysis involves determination of the elemental composition of a fuel. Most commonly, carbon, hydrogen, nitrogen, sulphur and oxygen (CHNSO) are measured in a particular fuel through complete combustion. These elements are important in determining an appropriate air-fuel ratio for the combustion or gasification process. In this study, the ultimate analysis of pine sawdust was analyzed in a CHNSO-IR spectrometry (LECO) according to the BS 1016:1996 standard [14].

2.2. The Experimental Rig

Figure 1 shows the schematic layout and the experimental test rig used in this study. The rig consisted of a gasification reactor fitted in a tube furnace, fuel feeder (with injector), tar trap system, vacuum pump and gas chromatograph (GC). Detailed geometrical ratio of the gasifier is illustrated in **Figure 2**. Other

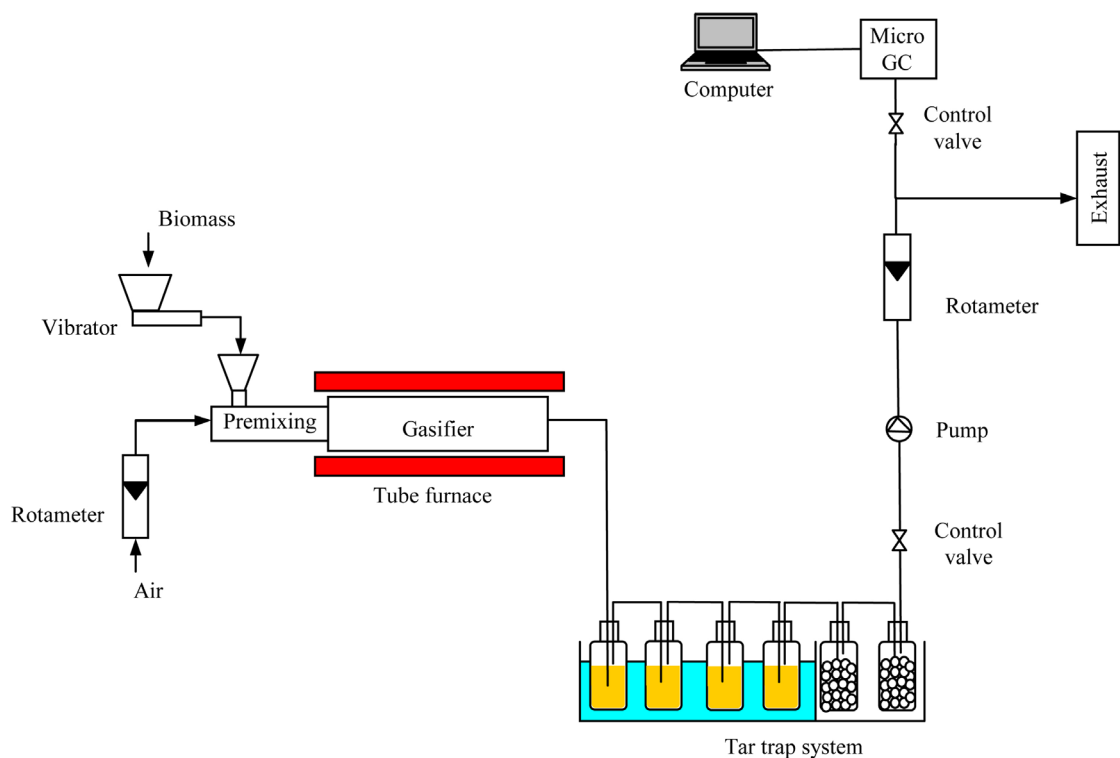


Figure 1. Schematic layout of the gasification experimental set-up.

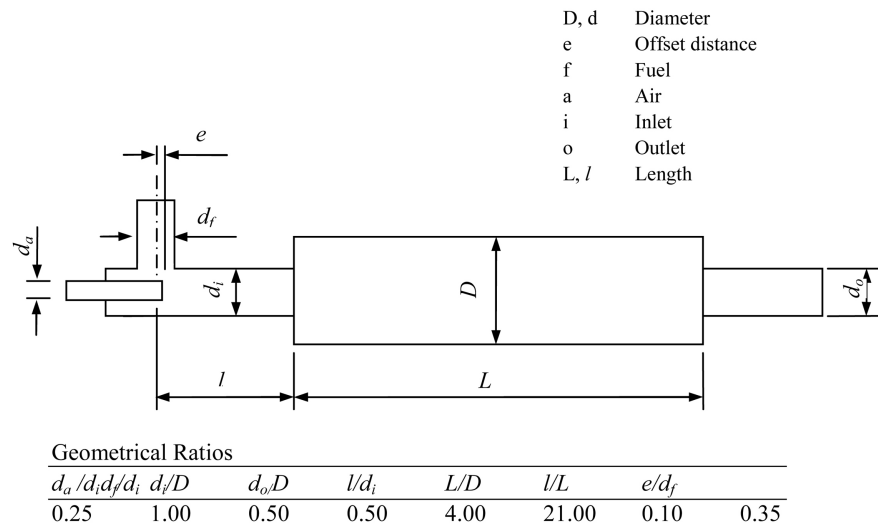


Figure 2. Geometric parameters of the gasifier reactor.

components included standard fittings to provide connections. Air rotameters (from Fisher Controls Ltd.) were used for measuring the air inflow rate and the syngas outflow. Their operating limit ranged between 0 and 24 l/min at $\pm 5\%$ accuracy of full scale. The air rotameter for syngas measurement was adjusted based on the density difference to take account of the syngas composition. The density of syngas (ρ_{gas}) was determined using Equation (1) and the volume flow rate (\dot{V}_{gas}) was determined using Equation (2). The general set-up allowed sampling the whole gas stream to avoid bias caused by flow dynamics.

$$\rho_{gas} = \sum_{i=1}^n \rho_i \quad (1)$$

$$\dot{V}_{gas} = \frac{\rho_{air}}{\rho_{gas}} \dot{V}_{air} \quad (2)$$

where i is the gas component in the syngas as determined by GC in the preliminary tests while ρ_{air} and \dot{V}_{air} are density and volume flow rate of air respectively.

2.3. Experimental Data Measurements

2.3.1. Temperatures

The gasification process is highly dependent on operating temperatures as it affects the product gas composition. Similarly, the isopropanol solvent solution requires low temperatures to prevent vaporization which reduces the performance of the tar sampling system [15]. Measuring these temperatures was important in controlling the overall process.

Throughout the experimental work, the temperatures were recorded using a thermometer (YCT YC-737D) data logger manufactured by TMS Europe Ltd. The thermometer had 3 thermocouple input channels with data logging up to 10,000 records per channel at resolution of 0.1°C . The accuracy of the thermometer using these thermocouples is $\pm 0.1\%$ full scale reading $+0.7^\circ\text{C}$ at a range of

100°C - 1300°C. Prior to gasification trials, the temperature distribution along the gasifier was measured to ensure uniform heating and establish a reference position for the thermocouple. The furnace was heated to 800°C where the temperatures were taken at an interval of 50 mm using a K-type thermocouple, while purging air at a flow rate of 5 l/min. During the gasification trials, the time interval for data acquisition was set at 30 seconds.

2.3.2. Syngas Analysis

In this study, the syngas composition was analyzed using a micro gas chromatograph (Varian, CP-4900). The GC was controlled with a Galaxie Workstation using software version 1.9.3.2. Prior to measurements, the GC was calibrated on air and a standard syngas mixture (sourced from Scientific & Technical Gases Ltd.). The standard was composed of 15% H₂, 15% CO, 15% CO₂, 5% CH₄, 2% C₂H₆, 2% C₃H₈, 1% n-Butane and the balance was nitrogen in volume percentage. This gas composition is typically found in gasification processes where air is employed as an oxidizing agent. On average, the accuracy of the GC for the calibration gas was found to be ±1% error.

2.4. Fuel Conversion and Cold Gas Efficiency

Fuel conversion and cold gas efficiency (CGE) are major parameters for assessing the performance of the gasification process. The former expresses the fuel proportion converted into gas products. While the latter, is defined as the ratio of energy content in the syngas to the biomass energy content. Fuel conversion was calculated using Equation (3) and the CGE was calculated using Equation (4) [2]. The fractions of char in the gasification residues were determined using a Leco SC-144DR, Total Carbon Analyzer.

$$X_f [\%] = \left[1 - \frac{m_c}{m_f} \right] \times 100 \quad (3)$$

$$\eta_{CGE} [\%] = \left[\frac{m_g \times LHV_g}{m_f \times LHV_f} \right] \times 100 \quad (4)$$

where m_c , m_g and m_f are the mass of unburnt carbon, syngas and fuel respectively. LHV_g is the lower heating value of syngas and LHV_f for the parent solid fuel.

3. Results and Discussions

3.1. Material Characterisation

Table 2 highlights the proximate and ultimate analysis of a commercial wood powder. It can be seen that the fuel is composed of mainly volatile matter (approximately 82%) with fixed carbon around 14%, while ash content is considered to be of trace amount. The observed low moisture content (2.47%) is a result of preconditioning the fuel through a drying process. Drying increases energy density of the feed fuel and is of particular importance as it enhances the

Table 2. Proximate and ultimate analysis of sawdust.

| Proximate Analysis | (% wt) | Ultimate Analysis | (% wt) |
|-----------------------------------|--------|-------------------|--------|
| Moisture content | 2.47 | C | 49.40 |
| Ash | 0.43 | H | 5.90 |
| Volatile matter | 82.73 | S | 0.02 |
| Fixed carbon | 14.37 | N | 0.30 |
| Total | 100.00 | O by difference | 40.68 |
| Gross calorific value, (MJ/kg) | 19.09 | | |

pneumatic feed which is crucial in entrained flow gasification. The ultimate analysis show that carbon and hydrogen values are 49.40% and 5.90% respectively. The oxygen content is high at 40.68 which must be taken into account during the gasification process. Sulphur is found in trace amount (0.02%) which consumes oxygen during combustion, thus, need to be considered in determining air-fuel ratio for gasification process.

3.2. Gasification Conditions

This section highlights the nominal conditions for the gasification process used during the experimental study. The temperature in the gasifier reactor was taken at the center which was 250 mm from the gasifier inlet. The measured temperature for the gasifier and tar trap system during biomass gasification test are shown in **Figure 3(a)** and **Figure 3(b)** respectively.

It can be seen from **Figure 3(a)** that temperature in the gasifier peaked at the start of the gasification test and stabilizes thereafter. The peak reached 872°C and thereafter remains in the range of 853°C to 798°C. From **Figure 3(b)** it can be seen that the temperature in the tar sampling system increased with time from -10°C to 16°C.

The observed peak in the gasifier highlights the existence of the combustion process favoured by high air-fuel ratio for the gasification process. For the tar sampling system, the rise in temperature can be linked to the heat exchange between syngas and isopropanol solution. It should be noted that tar compounds such as benzene and toluene can slip in the tar sampling system at ambient temperatures due to their low volatility [16]. Therefore, a combination of sampling time and temperature of the isopropanol can affect the concentration of tar compounds. The loss of isopropanol due to temperature rise has also been reported by Malhotra [17].

3.3. Performance of the Horizontal Entrained-Flow Gasifier

3.3.1. Fuel Conversion

The performance of the horizontal entrained-flow gasifier on fuel conversion (FC) is shown in **Table 3**. The maximum fuel conversion attained for gasification was found to be 99.0% compared to 91.4% by Hernandez *et al.* [2] and

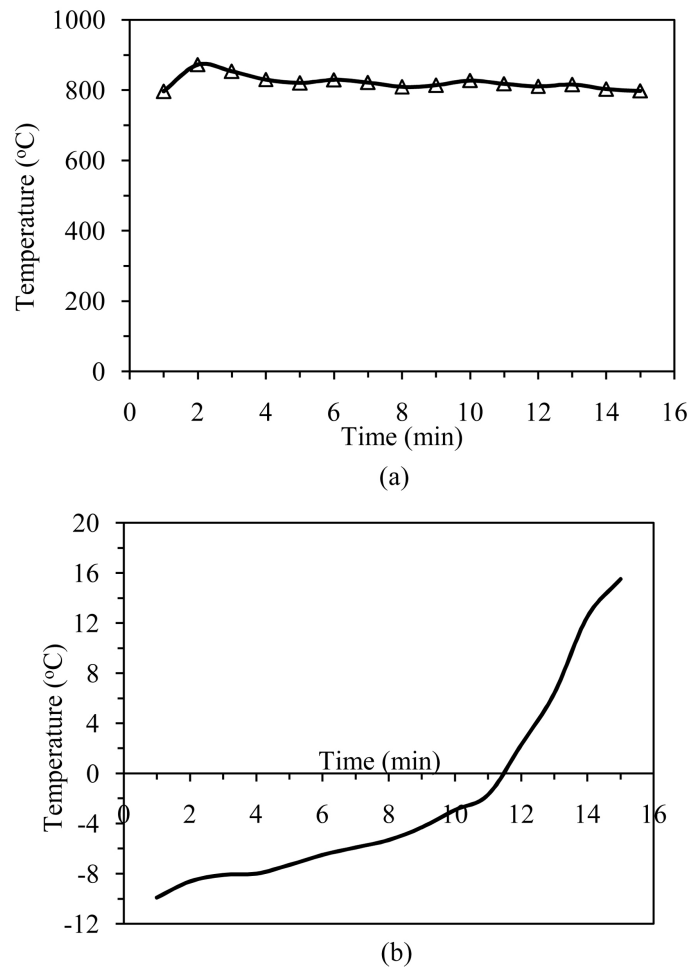


Figure 3. Temperature pattern of the experimental set-up. (a) Temperature profile in the gasifier; (b) Temperature profile in the tar sampling system.

87.4% by Zhao *et al.* [1] who used a vertical configuration. A possible attribute to this higher conversion could be due to the particle to metal contact. It should be noted that the gasifier wall acts as a heat source to initiate and sustain the gasification process in addition to the heat of combustion from the feedstock. Stainless steel is believed to have good heat transfer properties, thus, improving fuel conversion. Another attributing factor could be the geometrical ratios of the gasifier reactor which enhances low temperature gradient across the reactor.

3.3.2. Cold Gas Efficiency (CGE)

Although a comparative high fuel conversion was achieved in the gasifier reactor, the higher conversion could be attributed to the combustion rather than intended gasification process. Thus, further verification of the performance was determined and expressed in terms of cold gas efficiency (CGE). The CGE is the measure of conversion of the chemical energy in the primary fuel (wood powder) to the secondary fuel (syngas). The maximum CGE achieved in this gasifier reactor was 70%. With the exception of sensible heat, the balance is the loss of

Table 3. Syngas composition and yields from biomass gasification using a horizontal entrained-flow gasifier reactor.

| Parameter | Gas Composition (vol. %, db) | Gas yield (N·m ³ /kg fuel, db) |
|----------------------------------|------------------------------|---|
| H ₂ | 14.33 | 0.29 |
| CO | 22.11 | 0.45 |
| CO ₂ | 13.97 | 0.29 |
| CH ₄ | 3.62 | 0.07 |
| C ₂ H ₆ | 1.66 | 0.03 |
| C ₃ H ₈ | 0.38 | 0.01 |
| N ₂ | 43.93 | 0.90 |
| Char (g) | 0.18 | |
| Gas ratios | | |
| CO/CO ₂ | 1.58 | |
| H ₂ /CO ₂ | 1.03 | |
| CH ₄ /CO ₂ | 0.12 | |
| H ₂ /CO | 0.65 | |
| LHV (MJ/N·m ³) | 6.67 | |
| Fuel Conversion (%) | 99.0 | |
| Cold gas efficiency (%) | 70.0 | |

energy mainly in the form of tar and fractions of char. Comparing with the previous studies for the vertical entrained flow gasifier undertaken at similar conditions, the highest CGE achieved was in the range of 40.77% to 62.8% [1] [6] [18]. The observed increase on CGE substantiates the conversion efficiency of the horizontal entrained-flow gasification of biomass feedstock.

3.3.3. Syngas Composition

Table 3 shows the syngas composition from gasification of biomass using a horizontal entrained-flow gasifier reactor. It can be seen from the table that the maximum H₂ achieved was 14.33%, while CO, CO₂ and CH₄ were 13.97%, 22.11% and 3.62% by volume respectively. Moreover, light hydrocarbons such as ethane (C₂H₆) and propane (C₃H₈) were detected in trace amounts. With this gas composition, the corresponding low heating value was found to be 6.67 MJ/Nm³ compared to a maximum of 6.0 MJ/N·m³ reported on vertical configuration. Furthermore, the CO/CO₂ and H₂/CO₂ ratios were more than 1 and the yield of total energy containing gases (H₂, CO, CH₄, C₂H₆ and C₃H₈) was 0.85 N·m³/kg of fuel.

An interpretation to these results can be explained by a number of factors. The observed high CO/CO₂ and H₂/CO₂ ratios confirm the existence of partial oxidation atmosphere which favours the gasification process. The observed high concentration of H₂ and CH₄ could also be related to the tar cracking in the gasifier reactor promoted by low temperature gradient.

4. Conclusion and Recommendation

It has been shown that there exists a sensitivity to the gasifier orientation on the overall gasification process. The horizontal configuration showed high fuel conversion compared to the vertical design. The maximum fuel conversion was 99% while syngas heating value and cold gas efficiency were 6.67 MJ/N·m³ and 70% respectively, while the vertical design has 80% - 91% fuel conversion with CGE ranging 40% - 63%. Furthermore, using a horizontal configuration, the gasifier reactor length can be reduced from 1000 - 2000 mm to 500 mm with an inlet to the reactor diameter ratio of 0.5. The experimental work covered in this study was mostly conducted at a fixed gasifier reactor temperature and equivalence ratio to provide a strong basis for further investigations. Possible future studies may include experimentation at different operating conditions such as temperature, equivalence ratio and gasifying agent to explore their effect on the syngas.

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