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Experimental Investigation of a bottom fed updraught Gasifier Operation for CHP and syngas Production Applications

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ABSTRACT

The conversion of waste through gasification into valuable forms of energy and fuels has gained much interest as part of the transition towards carbon neutrality. Unlike the conventional designs of the gasifier, the rising co-current gasifier combines the advantages of the fixed bed and the fluidized bed reactors in terms of the efficiency and the quality of syngas produced. However, limited research has been conducted on such design. The current study investigates the performance of wood pellets gasification under different operating conditions for combined heat and power (CHP) and biofuels production applications. The system is operated under 50 kW and 40 kW of electrical power generation demands. Further, the gasifier performance is investigated over a wider range of air flow rates (i.e., 50-75 kg/h) and with the change of the reactor bed height. Under these diverse operating conditions, the gasifier exhibited reliable gasification performance, and the resulting syngas compositions estimated in the ranges of (20.26-21.87 vol.% for CO, 18.3-17.5 vol.% for H2, 11.07-9.67 vol.% for CO2, and 2.7-1.8 vol.% for CH4). Correspondingly, the LHV, CGE, CCE varied within the ranges of 5.51-5.3 MJ/Nm3, 84.8-78.95%, and 94.8- 89.9%, respectively.

Keywords: Waste to energy, rising co-current gasifier, Stationary fluidized bed, syngas, CHP.

NONMENCLATURE

Abbreviations	
CHP	Combined heat and power
FC	Fixed carbon
HHV	Higher heating value
ICE	Internal combustion engine
LHV	Lower heating value
MC	Moisture content
VN	Volatile matter
Symbols	
$\dot{Q}$	Air flow rate (kg/h)
V_g	Gas yield (Nm^3/kg)
$\dot{m}_b$	Biomass consumption rate

1 Introduction

The utilization of biomass to obtain heat, fuels and chemicals, and electricity plays a major role in the transition of the energy supply and sustainable fuel sectors to net zero carbon emission. Gasification is the preferred biomass energy conversion technology because it can achieve high conversion efficiency and flexible gas composition [1]. The producer gas (also known as syngas) can be employed for combined heat and power (CHP) applications or processed further to produce sustainable fuels, such as hydrogen and aviation fuels [2]. Various types of gasifiers are available with different designs and sizes, which are mainly classified as fluidized bed and fixed bed gasifiers [2]. In the fluidized bed gasifiers, the bed fluidity enhances the heat transfer and the interaction between the reactants (gas and solid) compared with the fixed bed operation [3]. However, on the other hand, the tar content and particulates in the outcoming syngas is relatively high [4]. The designs of the gasifier reactor have evolved with the introduction of different concepts as reported in the review article of Janajreh et al. [5]. The rising flow co-current gasifier has emerged with a unique concept of operation, which has the potential to achieve an optimal performance of such a system [6]. This is owing to the combination of the different reactor configurations, that is, the updraught and downdraught, and the fluidised bed concepts. The gasifier is updraught in air flow, but the order of the reaction zones is the same as observed in the downdraught design, whilst a portion of the bed is also fluidised.

The design can be considered as an improved updraught system because it resembles the updraught gasifier design from the perspective of flow. The updraught gasifier designs have not been less subject to recent study and development compared to the downdraught and fluidised bed gasifier designs. The majority of the reported studies about the updraught gasifier design follow the traditional configuration, that is fed by the biomass either in a single batch or continuously from the top and ignited from the bottom.

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For instance, stratified reactors with different diameters (8.1-25 cm) have been investigated by many authors for gasifying different biomass feedstocks [7-11]. A more flexible design with multiple air inlets and ignition ports (at top, middle and bottom) to operate as updraught, downdraught, or dual bed reactor has been investigated for the gasification of woody biomass [12-14]. The LHV was reported at 4.8 MJ/Nm^3 for the updraught configuration, 3.8 MJ/Nm^3 for the downdraught condition and 4.28 MJ/Nm^3 for the dual bed reactor configuration. Another design of a bottom lit, updraught, fixed bed gasifier has been investigated by Li et al. [15], in which a double cone is installed into the bed of the reactor with a throat diameter of 22 cm and upper and lower diameters of 38 and 25 cm, respectively. The optimum LHV was 4.38 MJ/Nm^3 at the air flow rate of 1.9 Nm^3/h. Unlike the commonly followed approach of igniting the bed from the bottom, a top-lit updraught gasifier for syngas and/or biochar production has high potential to reduce the tar content [16], Interestingly, a study conducted by Pedroso et al. [17] has introduced a modification to the updraught gasifier by implementing a bottom feeding concept into the updraught fixed bed gasification system. The calorific value of the syngas was slightly lower than the typical updraught system with an average HHV of 5.52 MJ/Nm^3 and the average tar content was 26.9 g/m^3 for woodchips.

Evidently there remains scope for development of the updraught gasifier design, especially with most of the reported data concerned with the fixed bed, top fed and bottom lit type gasifier [18]. Limited research has been conducted on the rising co-current gasifier to understand and evaluate its operation under different conditions. To the best of the authors' knowledge the only two studies that have been found in the literature to involve this concept are [6, 19], where they only apply one operating condition for the Italian-based wood pellets gasification. The current work studies the performance of a pilot scale, updraught co-current gasifier (model Burkhardt V4.50) which is installed at the TERC facility, University of Sheffield, UK. Changes of the reactor operating conditions, such as temperatures, gas composition and the bed height under different power conditions (with and without the electricity generator) were investigated.

2 Material and methods

2.1 Feedstock specification

Wood pellets were selected as feedstock for the gasifier because the pellets are supplied to defined standards for biomass fuel (EN Plus A1) to assure operation stability with high energy density. The proximate and ultimate analyses, and calorific value of the wood pellets are presented in Table 1. The proximate and ultimate analyses were conducted using TGA and CHNS analysers, respectively whereas the LHV was estimated using a bomb calorimeter. The bulk density of the wood pellets was 652.3 kg/m^3, and the dimensions of the pellets were 6-8 mm diameter and up to 20 mm length.

Table 1. Proximate and ultimate analyses of wood pellets.

Proximate analysis (wt.%)					
MC	VM		FC		Ash
	dry basis				
7.4	84.5		14.6		0.9
Ultimate analysis (wt.%, dry basis)					
C	H	N	S	O	Cl
50.5	6.8	0.1	0.03	41.6	0.05
Calorific Value (MJ/kg)					
Gross CV			Net CV		
18.66			17.22		

2.2 The gasifier-CHP setup

The distribution of gasification zones in the updraught, co-current gasifier design is comparable to the downdraught gasifier, that is: drying, pyrolysis, oxidation (combustion) and reduction (gasification) but in an inverted order from the bottom upward. Both the oxidant (air) and biomass are fed into the bottom of the bed and traverse upwards through the process stages. The biomass particles undergo the gasification reactions during transit up through the vessel, while the produced syngas leaves the reactor from the top as illustrated in Fig. 1. The volatile content is released while the biomass particles move through the high temperature zones, consequently the weight and size of the particles reduce, creating a fluidisation layer at the top of the bed. The residence time is extended in this process configuration because the movement of biomass is driven by two opposing forces, that is, gravity and entrained flow, which enhances the gasification process [20]. The biomass feeding is controlled by varying the rotation time of the feeding auger in seconds per minute. The temperature profile inside the reactor is measured and recorded simultaneously by 10 k-type thermocouples distributed along the height of the gasifier as illustrated in Fig. 1. Control of the bed height is accomplished based on a feedback signal from a differential pressure manometer connected to a movable stainless-steel pipe that is extended down into the bed, and the other pressure point is subjected to the free gas stream on top of the bed.

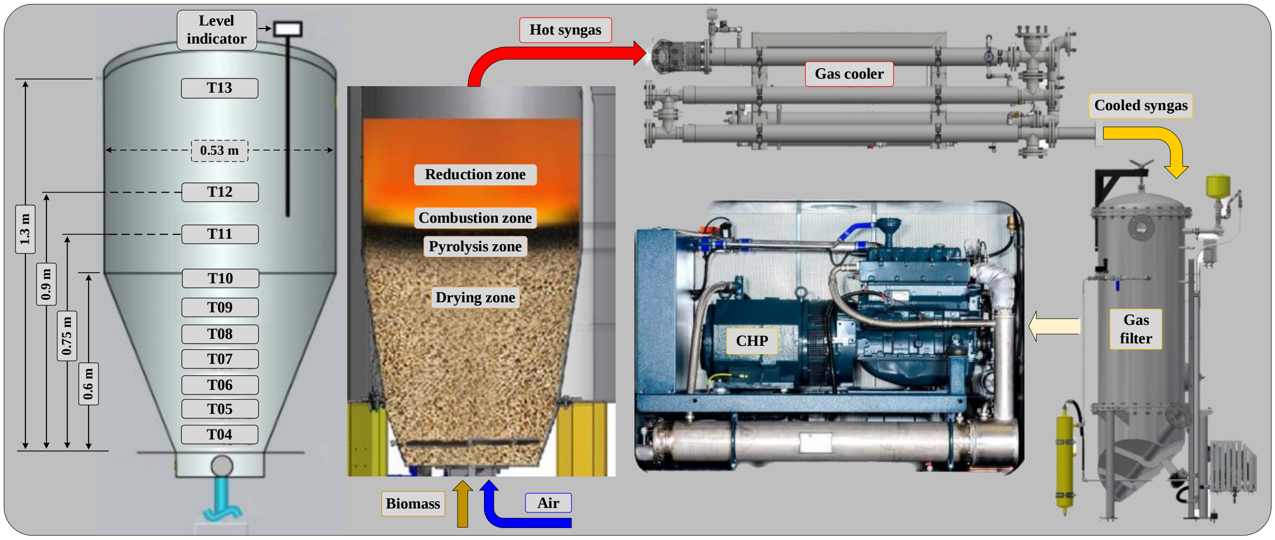


Fig. 1. Rising co-current gasifier configuration

2.3 Process evaluation parameters

The calorific value of the syngas and the cold gas efficiency of the gasification process are estimated as a function of its combustible compounds and the gas yield as follows [21]:

$$LHV_{gas} = [(10.79 \times H_2) + (12.636 \times CO) + (35.82 \times CH_4)] \quad (1)$$

$$CGE\ \% = \frac{[LHV]_{gas} \times V_g}{[LHV]_{biomass}} \times 100\% \quad (2)$$

The gas yield, V_g (Nm^3/kg of biomass), can be calculated as follows [22, 23]:

$$V_g = \frac{(\dot{Q}_{air} \times 79)}{(N_2 \times \dot{m}_b)} \quad (3)$$

where $\dot{Q}_{air}$ is the air flow rate (Nm^3/h), N_2 is the nitrogen content (vol.%) in the syngas, and $\dot{m}_b$ is the biomass consumption rate.

3 Results and discussion

3.1 Gasifier startup phase

The real time acquisition of the gasifier air flow rate, the temperature, the gas composition, and the electrical power generated at 50 kW electricity and 85 cm bed height set points are presented in Fig. 2. The startup phase of the gasifier is conducted at low air flow rate (about 40 kg/h), where the ignition front propagates until T8 reaches 200 °C, which takes about 40 minutes to be attained. The reference operating condition was applied after this temperature condition was achieved that is, the air flow is increased to 65 kg/h and the syngas analysis is initiated (see Fig. 2c and b). The biomass feeding starts when this operating mode has been incurred and that explains the decrease in T8-T10 as fresher batches of biomass are introduced into the pyrolysis bed, as can observed from Fig. 2a.

3.2 Gasifier operation for 50-kW electricity

When the CHP system is engaged with a 50-kW power generation setpoint, the air flow is adjusted by the system to an average of 74.4 kg/h, where the average dry gas composition is 21.9%, 18.0%, 9.7%, and 2.3% of CO, H_2, CO_2, and CH_4, respectively. The condition of the gasifier bed plays a pivotal role into the quality of the syngas, and this can be observed in Fig. 2 when the temperature exceeds 800 °C after around 450 minute duration. The H_2, CO_2, and CH_4 contents reduced while the CO increased slightly because of this increase in the bed temperatures. These changes could be attributed to the increased consumption of biomass with less volatilization (pyrolysis) of the fresher, incoming feedstock. This change lowered the LHV of the produced gas, therefore the air flow rate had to be increased to over 80 kg/h to maintain 50-kW power generation.

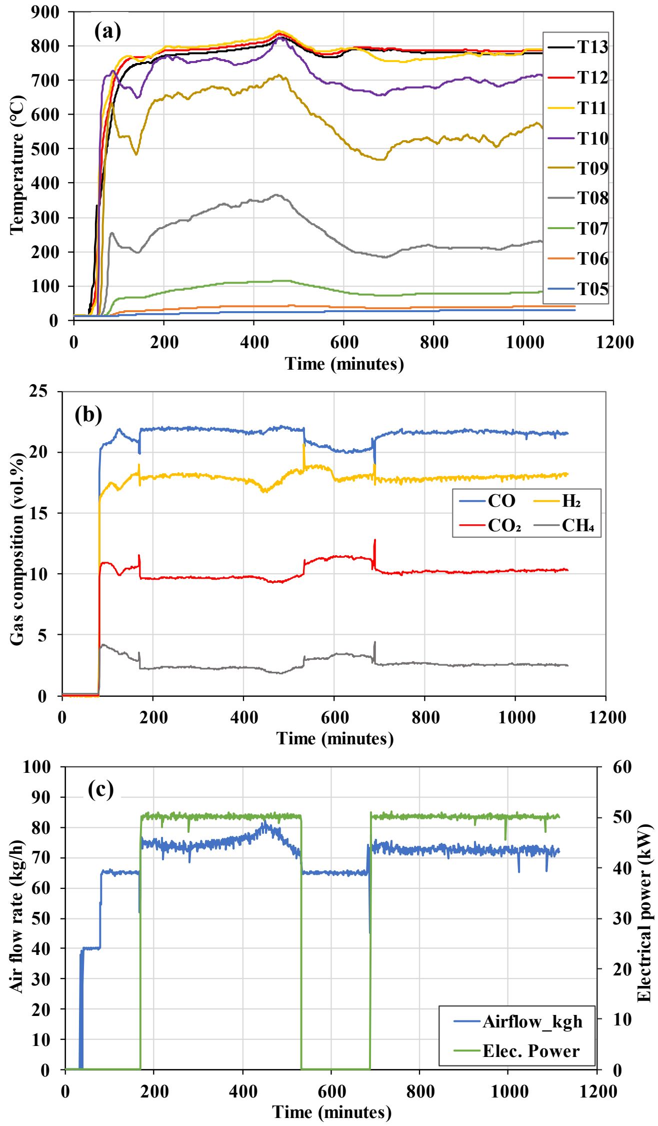
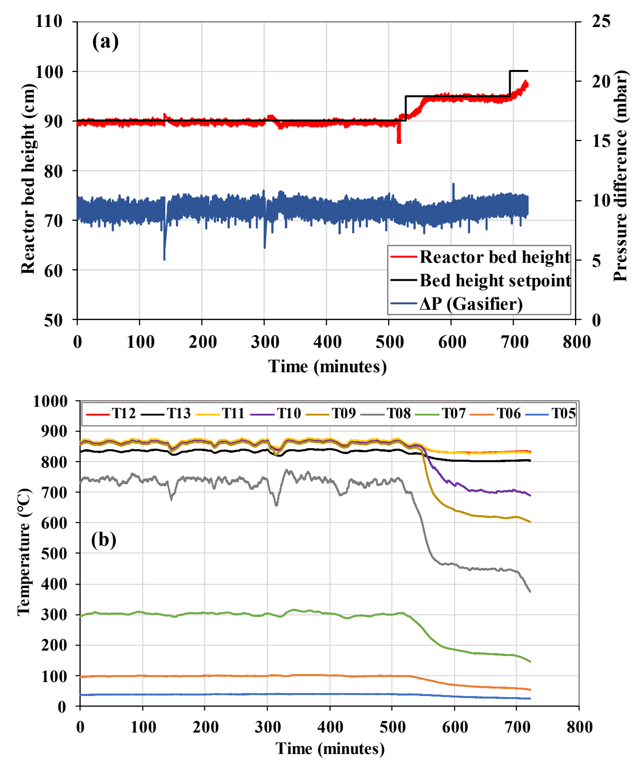


Fig. 2. Real time measurements of (a) the temperature, (b) the gas composition, and (c) the gasifier air flow along with the corresponding electricity generation at 85 cm bed height.

When the CHP engine was switched off, the gasifier returned to its reference condition of 65 kg/h air flow rate and the temperatures decreased. The dry syngas composition became 20.3%, 18.2%, 11.3%, 3.2% of CO, H_2, CO_2, and CH_4, respectively (see Fig. 2) because of the increased contribution by volatiles from the pyrolysis zone. The consumption of biomass had slowed down in response to the lower air flow rate, while the biomass feeding managed to provide more virgin fuel to the higher temperature zones, which promoted the pyrolysis reactions (endothermic reactions) with more volatile gases and tar being released. Further, the effect of the bed condition on the syngas composition and consequently the engine can be seen when the CHP was operated again from 700 minutes to 1115 minutes elapsed time. The LHV of the syngas was a little higher, and the required air flow for the 50-kW electricity was consequently 72.5 kg/h because the temperatures of the bed were lower (788 °C and below).

3.3 Gasifier operation for 40-kW electricity

A setpoint of 40-kW electricity generation was employed to investigate the performance of the gasifier with the CHP operating below off-design power condition (i.e., 50 kW).The real-time data acquired for the different performance variables is presented in Fig. 3. The system was operated with the gasifier bed height set position initially at 90 cm (Fig. 3a). When the gasifier is operated for CHP applications, the entire system is controlled by the ICE demand, which is, in turn, set to operate with a specific lambda value (that is, air to fuel ratio metric) for optimum combustion of the syngas in the engine. In response to the engine demand at 40 kW, the gasifier air flow rate oscillated around 66.5 kg/h, and the biomass feeding rate around 36.9 kg/h, as can be seen in Fig. 3d. The temperature of the fluidized bed from T12 to T9 was around 865 °C, and T8 was at 735 °C. These temperatures can be used to infer that about 50 cm depth of pyrolyzed particles (estimated by matching Fig. 3b with Fig. 1) were undergoing gasification reactions. The corresponding average composition of the dry syngas was 21.6%, 17.8%, 10.1%, and 2.0% of CO, H_2, CO_2, and CH_4, respectively as can be seen in Fig. 3c. Under these conditions the average pressure drop over the gasifier bed is estimated at 9.25 mbar.



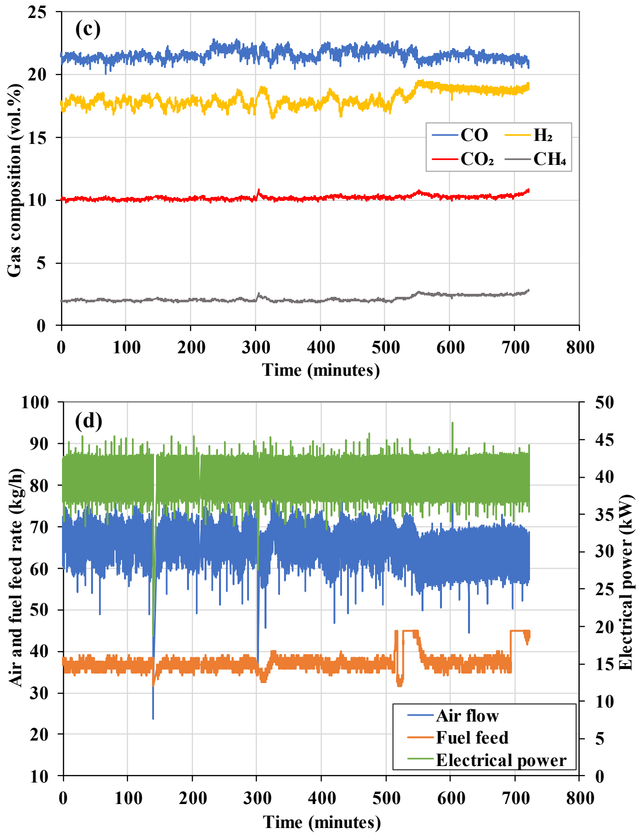


Fig. 3. Real time measurements of (a) the bed height and the pressure drop, (b) the temperature, (c) the gas composition, and (d) the gasifier air and biomass flow rates, along with the corresponding electricity generation at 90 and 95 cm bed heights.

It is worth noting that when comparing the performance of the system operating with 40 kW electricity demand against the maximum 50 kW, a consistent oscillation was observed in the power generation and the gasifier air flow rate, as can be seen in Fig. 3d. This fluctuation can be attributed to the limitation of the controlling criteria of the lambda value and the power. The lambda control relies on a motorised throttle valve mounted on a three-way manifold to adjust the air/syngas mixing ratio following a feedback signal to attain the lambda set point of 1.3. The engine power control is accomplished by adjusting the gasifier air flow to meet the power needed. When the throttle valve position is changed to achieve the lambda setpoint, it directly affects the pressure in the syngas line, and consequently the air flow into the gasifier. These two competing controlling criteria make the system operate with unsteady operation. Furthermore, this fluctuation in the gasifier air flow, in turn, affects the syngas quality and the LHV, which adds extra disturbance to the engine operation.

3.4 Effect of changing the bed height

Another important parameter to be considered is the change in the gasifier bed height. Fig. 3 shows how the performance of the gasifier is affected when the bed height is increased from 90 to 95 cm. The bed temperatures (T10-T6) are directly affected by the increase of the bed height since a higher feeding rate of biomass is applied to reach the new targeted level of the bed, which leads to the introduction of fresh, colder biomass into the hot zones, as can be seen in Fig. 3b. This reduction in temperature of the bed is owed to the endothermic pyrolysis process of the incoming biomass. Further, the release of the volatile content from the pyrolised particles contributed high H_2, CH_4 and tar content into the syngas [23], which is reflected in the air flow rate that was necessary for the engine to achieve the 40-kW power generation. It can be observed in Fig. 3c, after 550 minutes, that the H_2 and CH_4 are the most affected compounds as the concentrations measured changed from 17.8% to 18.9% and from 2.0% to 2.5%, respectively. Whereas the CO and CO_2 remained relatively unchanged. The corresponding air flow rate changed from 66.5 to 63.5 kg/h as a result of the slightly increased LHV.

3.5 Effect of air flow rate on the gasifier performance

The air flow rate is the main driver of the process and in order to understand its effect on the rising co-current gasifier performance, the investigation was extended to include a wider range of air flow rates. The gasifier is operated on flare mode when the air flow rate was reduced to 60 or 50 kg/h to mitigate the considering the instability of the ICE observed under low power generation conditions. The change of gas composition as the air flow rate was varied within the range of 50 to 75 kg/h is presented in Fig. 4.The CO content is the only syngas component that increased with the increase of air flow rate, while the H_2, CO_2 and CH_4 decreased. For instance, CO increased from 20.3% to 21.9% (+7.95%), H_2, CO_2, and CH_4 decreased from 18.3% to 17.5% (-4.4%), from 11.1% to 9.7% (-12.6%), and from 2.7% to 1.8% (-34.0%), respectively. These gas composition trends were principally due to the shortened residence time as well as the increased temperature of the bed when the air flow rate was increased.

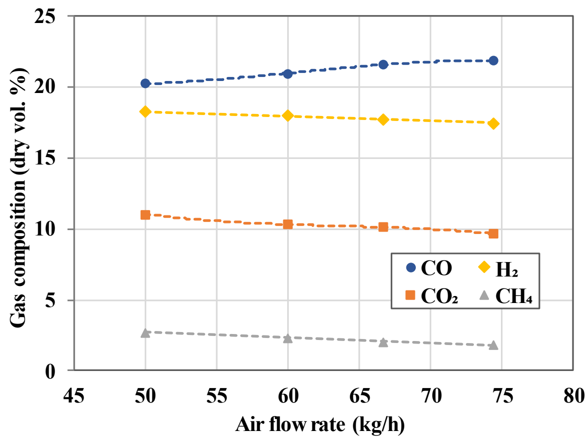


Fig. 4 Effect of air flow rate on the syngas composition.

The evaluating parameters of the gasification process under the range of air flow rate studied were estimated and are presented in Fig. 5. The LHV reduced from 5.5 to 5.3 MJ/Nm^3, in approximately linear gradient, when the air flow rate increased from 50 to 75 kg/h. Both the CGE and the CCE decreased when the air flow rate increased, but a slight change was observed when the air flow rate changed from 50 to 60 kg/h, while the reduction intensified at the higher air flow rates. The CGE and the CCE changed from 84.8% to 83.8% and 94.8% to 94.1%, then reduced to 79.0% and 89.9%, respectively. The reduction in the CGE is attributed to a reduction in the gas yield (V_g), which is, in turn, influenced by the shortened residence time at high air flow rate. Whereas the CCE reduced as a consequence of the high consumption of biomass to maintain the required bed height. This increased consumption of biomass resulted from the increased gas-borne char particles transported out of the reactor at high air flow rates.

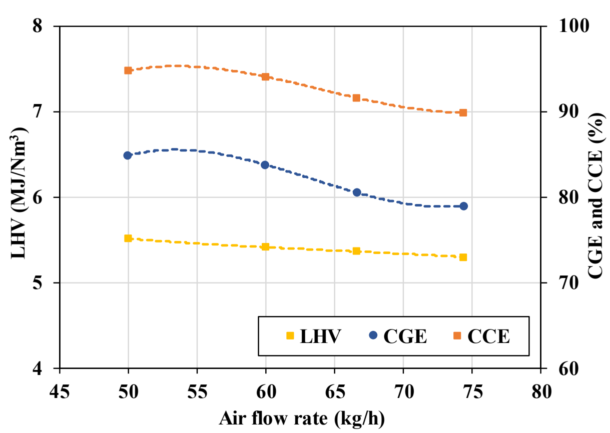


Fig. 5 The effect of air flow rate on the syngas LHV and the CGE and CCE of the gasification process.

It is worth mentioning that the relation between the air flow rate and the biomass feeding rate exhibits nearly a linear trend with a gradient of 0.58 kg fuel/kg air, as shown in Fig. 6. The linearity of this relationship has been reported in other studies with different gasifier designs [23, 24].

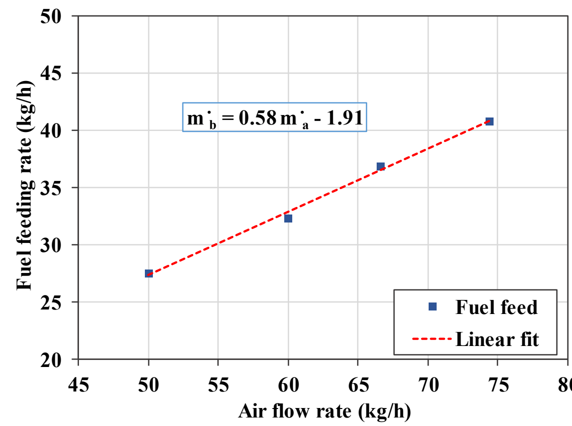


Fig. 6 The effect of air flow rate on the biomass consumption rate.

4 Conclusions

The rising co-current gasifier represents a promising concept to efficiently convert biomass into high quality syngas for CHP and biofuels production applications. To fully understand the performance of such a design, the system was investigated under different operating conditions with and without the CHP power generation unit operating. The gasifier was operated continuously for many days without any interruption, demonstrating that the system was operable for long production durations. The main outcomes of this study are summarised as follows:

1. The optimum stable operation of the system with power generation achieved was 50 kW electricity generation. As for the case of 40 kW, the system was running with high variability owing to the challenges of controlling the engine power and maintaining the optimum lambda value condition.
2. The condition of the gasifier bed was pivotal in affecting the quality of the syngas produced and consequently the gasifier air flow rate required to achieve the electric power set point.
3. The average gasification temperature of the rising co-current gasifier was about 800 °C, and this can be changed by varying the air flow rate and the bed height.
4. The lower the gasifier air flow rate the higher the LHV, the CGE and the CCE but this compromised the gas composition generated and let to higher methane content, which is a direct representation of the tar content.
5. The relation between the gasifier air flow rate and the biomass feeding rate was nearly linear, following the equation $\dot{m}_b = 0.58\,\dot{m}_a - 1.91$.

The current study provides initial technical details of the rising co-current gasifier under different operating conditions, which can help in the utilization of this gasification technology for many applications including H_2 and biofuels production.

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