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Research Article

Design and Development of 3 kWth Downdraft Gasifier for Biofuel Production

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Abstract

Biomass gasification is an efficient and environment friendly option for alternate energy. A single throat downdraft gasifier was designed and developed for gasification of biomass. The design of the gasifier was performed using experimental data related to hearth load, efficiency and superficial air velocity. The gasifier was designed to provide 11 MJ h^{-1} of thermal energy with 60% efficiency. The feedstock consumption rate of the gasifier was found as 1 kg h^{-1} with a gas production rate of 2.2 m^3 h^{-1}. The syngas produced by the gasifier can be used for cooking, electricity generation, fuel production and chemical synthesis.

Keywords: Biomass; Downdraft gasifier; Syngas; Equivalence ratio; Gasifier design; Reduction zone

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Introduction

Gasification is a thermo-chemical conversion process that transforms biomass into syngas. The syngas is mainly composed of carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) [1]. The syngas can be used for different applications such as electricity generation, fuel production, chemical synthesis and thermal applications [2]. Biomass gasification is an interesting option as an alternative to fossil fuel derived power due to its renewable and eco-friendly nature. The properties of syngas depend on several factors such as biomass composition, equivalence ratio and gasifier configuration. Biomass gasifiers can be classified into updraft, downdraft, crossdraft and fluidized bed gasifiers depending on the feedstock movement. The downdraft gasifiers are popular among them due to its simple design and easy operation [3].

Downdraft gasifiers are also called as co-current gasifiers as the air and the feedstock flow downwards. The air is supplied in the middle part of the gasifier which will result in high temperature. The syngas passes through this high temperature zone resulting in cracking of tar into lighter compounds. Thus, the downdraft gasifiers can produce syngas with very low tar content which lowers the cost of gas cleaning [4]. The thermal capacity of the commercial downdraft gasifiers ranges between 15 kW_{th} and 5 MW_{th}. Ojolo & Orisaleye [5] developed a 15 kW_{th} downdraft gasifier for palm kernel shells with a feedstock consumption rate of 4 kg h^{-1}. Kumar et al. [6] described the design methodology for a downdraft gasifier of capacity 5 kW_{th}. The gasifier was designed to process 2 kg h^{-1} of wood pellets with a time of operation of 2 h. Akhator et al. [7] designed and evaluated a open top downdraft gasifier for wood waste. The thermal capacity of the gasifier was 5 kW with a specific gasification rate of 2000 m^3 m^{-2} h^{-1}. The methodology for designing small-scale downdraft gasifiers are scarce in literature. Hence, the present study focuses on the design and development of downdraft gasifier of capacity 3 kW_{th}.

Materials and Methods

A lab scale single throat downdraft gasifier for syngas production from biomass was considered for the design. The assumptions and initial conditions are given in the Table 1.

Design methodology

The design equations for the development of a single throat downdraft gasifier is given below:

$$Feedstock\ consumption\ rate, kg\ h^{-1}\ (FCR) = \frac{Q}{HV \times \eta_g} \tag{1}$$

$$Throat\ diameter, mm\ (D_t) = \sqrt{\frac{4 \times G}{\pi \times H}} \tag{2}$$

$$Gasifier\ diameter, mm\ (D_g) = 14.86 \times D_t^{-0.36} \times D_t \tag{3}$$

$$Gasifier\ height, mm\ (H_g) = \frac{C}{\rho_g \times \left(\frac{\pi}{4}\right) \times D_g^2} \tag{4}$$

$$Air\ flow\ rate, m^3\ h^{-1}\ (AFR) = \frac{ER \times TAF \times FCR}{\rho_a} \tag{5}$$

$$Tuyer\ diameter, mm\ (d_{tu}) = \sqrt{\frac{1.27 \times AFR}{S \times N_t}} \tag{6}$$

$$Height\ of\ reduction\ zone, mm\ (H_R) = 2 \times D_t \tag{7}$$

$$\mathbf{Diameter\ of\ reduction\ zone, mm\ (D_R) = 2.5 \times D_t} \tag{8}$$

Table 1 Assumptions and initial conditions for the gasifier design.

Parameters	Conditions
Type of gasifier	Single throat downdraft
Thermal power (Q)	3 kW
Gasifier capacity (C)	5 kg
Heating value of feedstock (HV)	17.83 MJ kg^{-1}
Density of feedstock (ρ_g)	365 kg m^{-3}
Efficiency of gasifier (η_g)	60 %
Hearth load (H)	0.3 m^3 cm^{-2} h^{-1}
Gas production rate (G)	2.2 m^3 h^{-1}
Theoretical air to feedstock ratio (TAF)	5.33 kg air kg $feedstock^{-1}$
Superficial air velocity (S)	8 m s^{-1}
Equivalence ratio (ER)	0.4

Results and Discussion

The design calculations for the downdraft gasifier to provide a thermal power output of 3 kW is discussed below.

Feedstock consumption rate (FCR)

The feedstock consumption rate (FCR) is the ratio of energy produced by the gasifier to the energy available in the feedstock [8]. The feedstock consumption rate was found to be:

$$FCR = \frac{3 \times 3600}{17.83 \times 10^3 \times 0.6} = 1\ kg\ h^{-1}$$

Based on the total capacity and feedstock consumption rate, the gasifier can operate for a period of 5 h without any interruption.

Throat diameter (D_t)

Throat is the constricted section of the downdraft gasifier which aids in better gas production and tar cracking [9]. The throat diameter was found as:

$$D_t = \sqrt{\frac{4 \times 2.2}{3.14 \times 0.3}} \times 10 = 31\ mm$$

The computed throat diameter could ensure tar cracking in addition to avoiding bridging and channeling problems.

Gasifier sizing

The diameter of the gasifier determines the specific gas production of the gasifier and height defines the capacity of the gasifier [10]. The diameter and height of the gasifier were computed as:

$$D_g = 14.86 \times 31^{-0.36} \times 31 = 130\ mm$$
$$H_g = \frac{5\times1000}{365\times\left(\frac{3.14}{4}\right)\times\left(\frac{130}{1000}\right)^2} = 1000\ mm$$

Air tuyeres

In a biomass gasifier, tuyeres provide the sufficient oxidant for the gasification reactions to occur. The gasification agent chosen for this study is air due to its abundant availability. The number of tuyeres (N_t) and its diameter (d_{tu}) are crucial for sufficient contact between the feedstock and the air. Multiple tuyeres are required for uniform supply of air across the reaction zone [11]. The downdraft gasifier was designed with 4 tuyeres placed uniformly along the circumference of the gasifier. The diameter of the tuyeres was calculated as:

$$AFR = \frac{0.4\times5.33\times1}{1.225} = 1.74\ m^3\ h^{-1}$$
$$d_{tu} = \sqrt{\frac{1.27\times\frac{1.74}{3600}}{8\times4}} \times 1000 = 4.4\ mm$$

Totally 4 numbers of tuyeres at the designed diameter could distribute air uniformly throughout the gasifier without any channeling effects.

Size of the reduction zone

The reduction zone in a downdraft gasifier ultimately determines the composition of the syngas. The reactions which take place in the reduction zone are: Boudouard reaction ($C+CO_2 \rightarrow 2CO$) and char gasification reaction ($C+H_2O \rightarrow CO+H_2$). The generation of major combustible gas compounds (CO and H_2) depends on the size of the reduction zone. Hence, the reduction zone should be properly sized. The diameter and height of the reduction zone were determined as:

$$H_R = 2 \times 31 = 62\ mm$$
$$D_R = 2.5 \times 31 = 78\ mm$$

This proper sizing of the reduction zone in the downdraft gasifier can help enhance the content of CO and H_2 in syngas. The CO and H_2 in syngas can be utilized as a feed for Fischer-Tropsch synthesis to derive liquid hydrocarbons.

Development of the gasifier

The downdraft gasifier was developed with SS 304 for longer life as the temperature of the gasifier in the reaction zones could reach upto 1200 °C. The schematic and pictorial view of the developed gasifier is shown in Fig. 1.

The gasifier can produce a thermal energy of 11 MJ h^{-1} with biomass as the feedstock. Considering a compression ignition engine efficiency of 35%, the gasifier can give an electrical output of 1 kW. The capacity of the gasifier design available in literature were: 15 kW [5], 5 kW [6] and 130 kW [11]. The CO_2 emissions for coal and natural gas-based power generation systems were 804 and 432 g kW^{-1}, respectively. The CH_4 emissions were 0.44 and 1.72 g kW^{-1} for coal and natural gas-based power generation systems, respectively [12]. It should be noted that the power produced by the gasifier is clean, eco-friendly and carbon neutral. Hence, the developed gasifier could reduce these greenhouse gas emissions if wider utilization is possible.

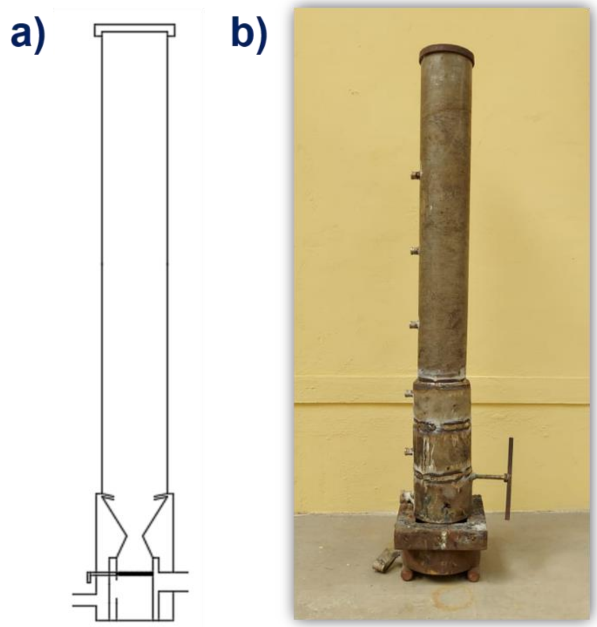

Fig. 1 View of the downdraft gasifier a) Schematic and b) Pictorial

Conclusion

A lab scale single throat downdraft gasifier was designed and developed for gasification of biomass as feedstock. Downdraft gasifier was selected due to its simple design, easier operation and low tar content in syngas. The gasifier was designed to give a thermal output of 3 kW. The feedstock consumption rate was found to be 1 kg h^{-1}. The diameter of the throat and the gasifier were 31 and 130 78 mm, respectively. The reduction zone was carefully designed to enhance the content of CO and H_2 in syngas. The gasifier was developed with SS 304 for longer life and to sustain exothermic reactions at the oxidation zone. The developed gasifier is beneficial to the environment as it can use biomass as the feedstock.

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