

Optimization of Design and Operational Parameters of Horizontal Biomass Gasifier at Continuous Biomass Feeding Mode

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Abstract

Industries most of the products need continuous thermal energy to complete their process. Considering the Industries requirement, a continuous fed horizontal gasifier was successfully designed and tested. The design and operational parameters of gasifier were optimized. It was found that at L/D ratio of 1.2: 0.265 with the condition of air passes at the bottom at the velocity of 3.0 m/sec and generated gas outcome at axial was the best suitable air density for the design of continuous fed horizontal gasifier reactor. Likewise, operational parameters of continuous fed horizontal gasifier were also optimized. It works satisfactorily at Air/Fuel ratio of 2.5; biomass fuel size 2-4 cm and biomass feed rate 7.3 kg/h. At these conditions, the system generated 2.7 Nm³ producer gas from per kg of biomass, which has energy content about 1083 kCal/Nm³. It was also noted that generated producer gas has less tar content (91.4 g/Nm³) compared to vertical Updraft gasifier (100 g/Nm³) and have cold gas efficiency of the system is about 70%.

Keywords: ANSYS CFD Software; Biomass; Cold Gas Efficiency; Continuous Biomass Feeding Mechanism; Horizontal Gasifier

Introduction

Gasification of biomass in a fixed bed reactor is more suitable for small-scale heat and power applications and in general feature simple construction [1]. Characteristics of fixed bed gasification contain high carbon conversion, long solid residence time, low gas velocity, and low ash carry-over [2,3]. Although vertically oriented fixed-bed updraft gasification systems are well-established, however, due to the vertical orientation, the thermal zones of the gasifier are fixed, i.e. the residence time in a vertical gasifier is fixed, which sometimes creates clinkers of biomass materials having high ash content and are responsible for discontinuation of the gasification process. To overcome the problems of existing vertically oriented fixed-bed updraft gasification systems, it was decided to move the zones of the gasifier, instead of biomass. The zone of the gasifier changes due to change of temperature of the reactor. The concept of the horizontal gasifier for solid biomass was introduced by Balwanshi in 2016 [4]. A batch type 21 kW_{th} capacity horizontally oriented fixed-bed gasifier was successfully

design and development. Just due to change in orientation of Updraft gasifier, biomass gets better residence time with reactor temperature, and able to increase the conversion efficiency of solid biomass into gaseous fuel. Gasifier zones positions are changed depending upon the gasifier temperature rather than the biomass movement. Designed horizontal gasifier produces less tar and particulate matter compared to a vertical updraft gasifier. The developed gasifier worked satisfactorily, however being a batch types horizontal gasifier, its major limitation was working duration. In industries, most of the products need continuous thermal energy to complete their process. This limitation encourages us to design, and develop a lab-scale continuous fed horizontal gasifier.

Material and Methods

Design of Reactor

Basically, the horizontal gasifier is an Updraft gasifier, oriented horizontally. Less work has been reported in the literature. Singh et al. 2016 [5] worked on 21 kW_{th} batch type horizontal gasifier. The number of researchers worked on vertically oriented fixed bed gasifier using different biomass (wood saw dust, wood pallets, wood long sticks, wood chips, pine bark etc.). The working of this type of gasifier is simple; however, sometimes they have

flow problems of biomass, as biomass moved from top to bottom in the gasifier reactor. Working of vertically oriented updraft gasifier was found satisfactory at the reactor Length to Diameter ratio (L/D) varied from 1.27 – 8.00 [6,7], depending upon the size of the gasifier. Based upon the experience of batch type horizontal gasifier [5] and reported data for vertically oriented updraft gasifier, a 24 kW_{th} (batch mode capacity) continuous fed horizontal gasifier with L/D_{th} ratio of 4.36 (length of the reactor 1.2 m and diameter 0.265 m) was designed and developed. L/D ratio was kept higher side to accommodate the biomass moving arrangement inside the reactor and to have the scope for optimization of the driving mechanism of biomass. The reactor was fabricated with 0.0045 m thick mild steel maintaining reactor diameter 0.265 m and length 1.2 m. At the inner side of the reactor, provision was made to accommodate a curved shape MS-grate with 1.135 m length, 0.232 m wide and 0.004 m thick, which was placed at 0.008 m above from the bottom surface of the reactor. At a distance of 0.100 m from the air inlet, five air vent pockets (0.0381 m diameter each) with a spacing of 0.1727 m were provided at the circumference of the reactor (Figure 1). It is to be used to ignite the biomass evenly. Later four air vent pockets were closed except bottom one, which is used for the supply of gasification air from the blower. This air vent also has provision for control of air supplies (with the help of valve).

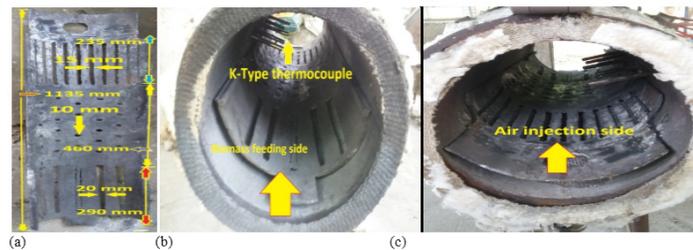


Figure 1: (a) Grate dimension (b) At biomass feeding side view (c) At air injection side view.

Design of Continuous Biomass Feeding System

To meet the continuous electrical/ thermal power requirement of Industries a manually operated continuous biomass feeding mechanism was designed & developed. The manual feeder is equipped with a perforated plate (0.245 m diameter and 0.003 m thickness) connected with a screw made of solid MS rod with 0.5 m length and 0.03 m diameter (Figure 2). Pitch length between two screw pitches was maintaining about 4 mm. Hence, one revolution of solid MS rod covered about 4 mm horizontal distance. The perforation in the plate was made in such a way that it can restrict the flow of gas from the upper side however, allow it to flow from the bottom portion of the plate. It helps to restrict the shortest path (axial exit) made by producer gas.

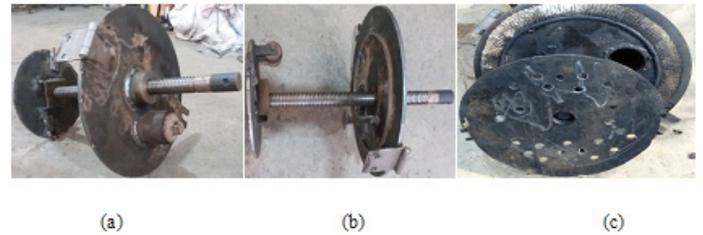


Figure 2: Biomass feeding assembly (a) with exit Producer gas, (b) Top view (c) with a perforated plate.

Design of Hopper

The hopper stores biomass feedstock. It has the provision for water seal at the top to avoid the leakage of producer gas as well as feeding of biomass in the hopper and sliding plate (0.003 m thick) shield with a rectangular box (0.6 × 0.3 × 0.045 m). The sliding plate can move horizontally in the rectangular box. When the sliding plate at the dead end of the rectangular box, it closed the supply of biomass from the hopper. And when it is opposite side, it allows the flow of biomass from the hopper to the reactor (Figure 3). Thus, by closing and opening the hopper with a sliding plate, biomass supply in the reactor could be made continuous without disturbing the operation of gasifier.

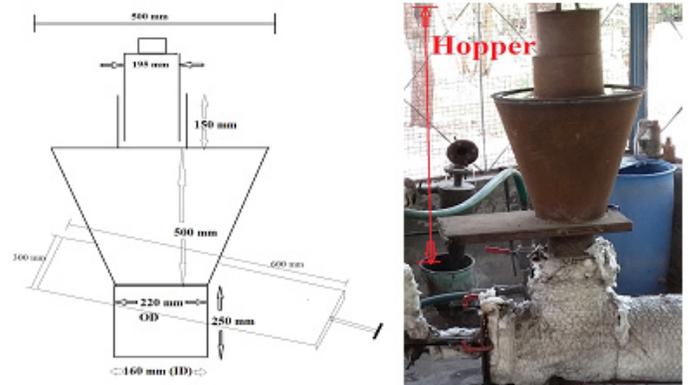


Figure 3: Biomass Hopper.

Design of Grate

A curved shape grate is placed at the bottom of the reactor about 0.008 m above from the bottom curvature of the gasifier reactor (Figure 1). For easy installation and maintenance, the whole grate was made in three compartments. The first compartment is comprising of a perforated strip (0.29 m length x 0.02 m wide), which is located below the hopper. The second compartment of grate situated at the center of the reactor and comprised with a 0.01 m perforated strip (0.46 m length x 0.232 m wide). The third

compartment of the grate is located neared the air injection points and comprised with a perforated strip of 0.235 m length x 0.015 m width. The spacing between the grate and bottom curvature of the gasifier reactor could be used for storage of ash.

Tar Removal and Water Sealing

Basically, the horizontal gasifier is an updraft gasifier except for the orientation. Updraft gasifier is known for higher Tar generation if operated by fresh biomass [8]. Thus, provision was made in the gasifier reactor (bottom side before gas outlet) to remove the tar by providing the 0.038 m dia. pipe sealed with water. Since Tar has the highest energy content among the byproducts of producer gas [9], thus removal of tar may give additional income; otherwise, even it may create problems during applications.

Air Flow Rate (AFR)

Air Flow Rate (AFR) refers to the rate of flow of air needed to gasify the fuel. This is very important parameters; it helps in proper size selection of blower needed for the supply of air during gasification of the fuel. This can be determined by using the rate of consumption of the fuel (FCR), the Stoichiometric Air of the fuel (SA), the density of air (ρ_a) and the recommended equivalence ratio (ϵ) for gasifying the fuel. Shelke, at al. 2014 [10] suggested that the highest gas yield and lowest tar content is obtained when the Equivalence Ratio (ER) = 0.32. Similarly, Mason, 2009 suggested that for complete combustion of 1 kg solid biomass (wood), 6.5 kg air is required. Therefore, at gasification mode to maintain 0.32 equivalence ratio, the requirement of air per kg of fuel (wood) would be $(0.32 \times 6.5) = 2.08$ kg. Knowing the equivalence ratio, fuel consumption rate, stoichiometric air of the fuel and density of air, the air flow rate was calculated as 3.67 m³/hr [11]. Similarly, for complete combustion of producer gas 1.1 -1.2 (average 1.15 kg air /kg of P gas) is required. Gas produced from gasifier per hour = $6.9 \times 2.9 = 20.01$ Nm³/h. Therefore, for the complete combustion of producer gas air requirement would be 23.01m³. Total air required for gasification as well as combustion of producer gas would be 26.68 m³/h ($3.67 \text{ m}^3 + 23.01\text{m}^3$), which is equivalent to 15.7 CFM (1 CFM = 1.699 m³ / hr). To reduce the cost of a blower, single blower with the capacity of 20 CFM and 0.56 hp was selected.

Design of Gas Outlet Pipe

For small capacity gasifiers (9-10 kWth) most of the researchers used producer gas velocity in the range of 4.5-5 m/s for deciding the size of producer gas outlet pipeline [12]. According to Kaupp & Goss, 1984 [13] generally 2.5-3 Nm³ producer gas is generated from per kg of dried biomass (12-15% moisture content). Balwanshi 2016 [4] found 6.5-6.9 kg/h biomass consumption rate during his study on design, development, and evaluation of horizontal gasifier for biomass material. This information was used for estimation of pipe diameter for producer

gas exists from gasifier. It was a workout as 2.16 inch (55 mm). Since 2.16 inch (55 mm) pipe diameter, pipe is not available in the open markets, thus the nearest diameter pipe size 0.05 m (2-inch) was selected [14,15]. At bottom of the producer gas exist pipeline, provision has been made for removal of tar, however, at the same place and the upper side of the pipeline provision for measurement of gas flow rate and gas sampling was made. Gas outlet pipeline is connected with cyclone and further connected with producer gas burner (Figure 4).



Figure 4: Experimental setup of continuous fed horizontal gasifier.

Result and Discussions

Optimization of Design and Operational Parameters of Continuous Fed Horizontal Gasifier

Design and operational parameters of continuous fed horizontal gasifier were optimized using ANSYS CFD software simulation [16] as well as experimentally. ANSYS CFD software was used to optimize the inlet airflow distribution inside the reactor for gasification, the position of producer gas outlet, Length to Diameter ratio (L/D) of horizontal gasifier and residence time of producer gas across the reactor. The ANSYS CFD model was simulated for three lengths to diameter ratio (1: 0.32; 1.2: 0.27 and 1.34: 0.82 respectively). However, the thickness of the reactor in all models was maintained as 0.005m. L/D ratio of 1.2: 0.27 at the condition of air pass at the bottom at the speed of 3.0 m/sec and generate a gas outcome at axial was found the best suitable streamline for the design of gasifier reactor. As it will give maximum air swirls and eddy turbulence inside the reactor. Due to turbulence, the residence time of generated producer gas would be more which would improve the quality of producer gas in the reactor. Similarly, biomass size, Biomass feeding rate, and Air to Fuel ratio were also optimized experimentally. The number of permutation and combination were tried for the optimization of these parameters and results are tabulated in Table 1& Table 2.

Sr. No	Biomass size (diagonal length & dia./width),cm	Biomass feeding rate, kg/h	P gas generation (Nm ³ /kg)	P gas Energy (kCal/ Nm ³)	η _{CGE} (%)
1	6-May	6.2	2.3	996	54
2	5-Mar	6.7	2.6	1003	59
3	2 – 4	7.8	2.7	1083	68

P gas = Producer gas; η_{CGE} = Cold Gas Efficiency (%).

Table 1: Effect of Biomass size and Biomass feeding rate on performance of horizontal gasifier.

Sr. No.	Air/Fuel ratio	Producer gas generation per kg of biomass (Nm ³ /kg)	Producer gas energy content (kCal/ Nm ³)	ER (equivalence ratio)
1	1.6	2.2	996	0.25
2	1.8	2.3	1000	0.3
3	1.9	2.4	974	0.33
4	2.1	2.5	971	0.36
5	2.3	2.6	1003	0.38
6	2.4	2.7	1040	0.39
7	2.5	2.7	1083	0.39
8	2.8	2.6	912	0.48

Table 2: Effects of air fuel ratio on performance of horizontal gasifier.

Critical analysis of Table 1& Table 2 indicates that at optimized conditions (Biomass size 2-4 cm; Biomass feeding rate 7.8 kg/h and Air/Fuel ratio 2.5) on an average 2.7 Nm³ producer gas per kg of biomass was obtained. Generated producer gas has energy content 1083 kCal/Nm³.

Performance of Horizontal Gasifier at Optimized Conditions

At optimized conditions, horizontal gasifier performance was evaluated as per the method suggested by MNRE, New Delhi for the thermal application [17] for short duration (5-6) (Aharwal & Singh, 2018) [18] followed by long duration (45 cumulative hours). Characteristic of biomass used for performance evaluation of gasifier was already available before in hand (Table 3).

Proximate analysis		Ultimate analysis	
Moisture content (% wb)	3.9	C %	48.64
Volatile matter (% db)	76.83	H %	5.92
Fixed carbon (% db)	22.3	O %	44.86
Ash content (% db)	0.87	N %	0.47
Calorific value (kCal/kg)	4203	S %	0.11
Physical Properties			
Biomass size (diagonal length & diameter/width), cm			2 – 4

Table 3: Proximate and Ultimate analysis of Babul wood (*Acacia nilotica*).

During long-duration trial, the system was operated cumulatively about 45 hours without any changes made in the setup. Data such as fuel consumption rate, gas generation per kg of biomass, reactor temperature, flame temperature, producer gas temperature, the supply of gasification air, Tar content in producer gas, producer gas composition est. were recorded and tabulated in Table 4 & Table 5.

Component	Operation Conditions
Type of biomass	babul wood
Total weight of biomass consumed	331 kg
Time take to get combustible producer gas	12-13 minutes
Total operating time of gasifier (Cumulative)	45 hours
Fuel consumption rate	7.2-7.6 kg/h
Combustion zone temperature	750-980 °C
Producer gas temperature (at end of the reactor)	200-350 °C
Generate producer gas per kg of biomass	2.4 to 2.6 Nm ³ /kg
Tar content in producer gas	84 ~99 g/Nm ³
Calorific value of producer gas	1093kCal/Nm ³
Cold gas efficiency of the system	65 – 70 %

Table 4: Performance of continuous fed biomass horizontal gasifier.

S. No.	CO %	H ₂ %	CH ₄ %	CO ₂ %	N ₂ %	O ₂ %	Energy content of Producer gas in kCal/Nm ³
1.	14.8	11.1	2.9	14.4	54.7	Balance	1098
2.	14.3	10.8	3.4	14.2	55.5	Balance	1123
3.	14.6	10.9	3.2	14.3	55.4	Balance	1115
4.	14.2	10.4	3.1	13.7	57.0	Balance	1077
5.	13.9	10.3	3.5	13.2	57.5	Balance	1104
6.	14.3	10.5	3.4	14.0	56.2	Balance	1113
7.	13.9	10.1	3.3	13.5	57.6	Balance	1078
8.	14.1	10.2	3.0	13.4	57.7	Balance	1058
9.	14.3	10.1	3.1	13.9	57.0	Balance	1071
Avg.	14.3	10.5	3.2	13.8	56.5	Balance	1093

Table 5: Composition of producer gas taken at every day.

Critical analysis of Table 4 clearly indicates that the system is not able to maintain the cold gas efficiency constant throughout the long-term trials. It varied from 65 to 70%. It may be due to variation in producer gas generation rate with per kg of biomass (2.4 – 2.6 Nm³/kg). Cold gas efficiency is directly proportional to producer gas generation per kg of biomass [19].

Conclusion

A continuous fed horizontal gasifier has been successfully designed and tested. It has a hopper with a sliding plate, continuous biomass feeding mechanism, and grate as the major components. The design and operational parameters of gasifier were optimized. Numbers of permutation and combination were tried with the help of ANSYS CFD software. It was found that at L/D ratio of 1.2: 0.265 with the condition of air passes at the bottom at the

velocity of 3.0m/sec and generate a gas outcome at axial was the best suitable air density for the design of continuous fed horizontal gasifier reactor. Likewise, operational parameters of continuous fed horizontal gasifier were also optimized. It works satisfactorily at Air/Fuel ratio of 2.5; biomass fuel size 2-4 cm and biomass feed rate 7.30 kg/h. At these conditions, it generates about 2.7 Nm³ producer gas from per kg of biomass and has energy content about 1083 kCal/ Nm³. Long run trials (about 45 cumulative hours) of continuous biomass fed horizontal gasifier was also performed successfully. On an average from per kg of biomass, the system was able to generate 2.4 – 2.6 Nm³ producer gas with the energy content of 1093 kCal/ Nm³. It was also noted that generated producer gas has less tar content (91.4 g/Nm³) compared to vertical Updraft gasifier (100 g/Nm³). Cold gas efficiency of the system was about 70%.

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