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Design and Development of a Laboratory Scale Biomass Gasifier

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Abstract: A laboratory scale downdraft biomass gasifier was designed to deliver a mechanical power of 4 kW and thermal power of about 15 kW. The gasifier was manufactured as a single piece having a water seal and cover. The gasifier was tested in natural downdraft and forced downdraft mode. Ignition of the fuel beneath the grate, during natural downdraft mode, using wood shavings as fuel, produced gas which burned with a blue flame for 15 minutes. Ignition at the throat, using either palm kernel shells or wood shavings, during the natural downdraft mode, the gasifier did not produce syngas. During the forced downdraft mode, fuel was ignited at the throat. Gasification was successful with the palm kernel shells, during forced downdraft, which produced gas which burned steadily with luminous flame for 15 minutes per kilogram of biomass fed. However, wood shavings experienced some bridging problems during the forced downdraft mode of operation. The fuel conversion rate of the gasifier, when using palm kernel shells as fuel in forced downdraft mode, was 4 kg/h. Forced downdraft mode of operation yielded better results and is the preferred operation of the gasifier.

Key words: Biomass, gasifier, design, downdraft, energy.

1. Introduction

Agriculture and energy have always been tied by close links, but the nature and strength of the relationship have changed over time [1, 2]. The linkages between agriculture and energy output markets weakened in the twentieth century as fossil fuels gained prominence in the transport sector. The use of renewable resources would contribute to a country's economic growth, especially in developing countries, many of which have abundant biomass and agricultural resources that provide the potential for achieving self-sufficiency in materials [3]. In most African countries, biomass continues to be the main energy source for subsistence activities such as cooking, heating and lighting. Solid biofuels such as fuel wood, charcoal and animal dung constitute by far the largest segment of the bioenergy sector, representing a full 99 percent of biofuels [4, 5].

Gasification means the transformation of solid fuels into combustible gases in presence of an oxygen carrier (air, O_2, H_2O, CO_2) at high temperatures. It is a process for converting carbonaceous materials to a combustible or synthetic gas like biomethane or producer gas [6]. Biomethane can be used like any other fuel, such as natural gas, which is not renewable [7]. The gasification process occurs at temperatures between 600-1,000 degrees Celsius and decomposes the complex hydrocarbons of wood [8]. The gasification process, with high temperature, produces ash and char, tars, methane, charcoal and other hydrocarbons. The corrosive ash elements such as chloride and potassium are removed, allowing clean gas production from otherwise problematic fuels [9]. Conversion of solid biomass into combustible gas has all the advantages associated with using gaseous and liquid fuels. Such

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advantages include clean combustion, compact burning equipment, high thermal efficiency and a good degree of control. Biomass is also economic in places where biomass is already available at reasonable low prices or industries using fuel wood [6].

Biomass gasifiers are reactors that heat biomass to produce a fuel gas that contains from one-fifth to one half (depending on the process conditions) the heat content of natural gas. A biomass gasifier converts solid fuel such as wood waste, saw-dust briquettes and agro-residues converted into briquettes into a gaseous fuel through a thermo-chemical process and the resultant gas can be used for heat and power generation applications [10, 11]. Biomass gasifiers have been classified based on their operation principles such as gasification and product temperature, oxygen requirements, product gas composition amongst others. The major types of gasifiers are updraught or counter current gasifier, downdraft or co-current gasifiers, cross-draft gasifier and fluidized bed gasifier [12]. The throated downdraft gasifier is suitable for biomass gasification, has a low tar yield, high carbon conversion, low ash carry over and simple construction and operation. However, it has a high gas exit temperature, requires uniformly sized feed stock and limited moisture content of feed.

This work presents the design of a laboratory scale biomass downdraft gasifier.

2. Theory of Gasification

The substance of a solid fuel is usually composed of the elements carbon, hydrogen and oxygen. In addition, there may be nitrogen and sulphur present in small quantities. Biomass gasification in air can be expressed in three stages which are oxidation or combustion, pyrolysis and reduction or gasification [12].

Combustion/oxidation reactions provide the heat energy required to drive the pyrolysis and char gasification reactions:

$$C + \tfrac{1}{2}O_2 \leftrightarrow CO \qquad -111 \text{ MJ/kmol}$$

$$CO + \tfrac{1}{2}O_2 \leftrightarrow CO_2 \qquad -283 \text{ MJ/kmol}$$

$$H_2 + \tfrac{1}{2}O_2 \leftrightarrow H_2O \qquad -242 \text{ MJ/kmol}$$

The pyrolysis reactions involve the cracking of the heavier biomass molecules into lighter organic molecules and carbon monoxide:

$$C_6H_{10}O_5 + Heat \leftrightarrow C_xH_z + CO$$

$$C_6H_{10}O_5 + Heat \leftrightarrow C_nH_mO_y$$

The reduction/gasification reactions involve, mainly, the gasification of tar, depending on the technology used. They include:

The Boudouard reaction:

$$C + CO_2 \leftrightarrow 2CO$$

The water gas reactions:

$$C + H_2O \leftrightarrow CO + H_2$$

$$C + 2H_2O \leftrightarrow CO_2 + 2H_2$$

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Methane synthesis reactions:

$$C + 2H_2 \leftrightarrow CH_4$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O$$

3. Design of the Gasifier/Reactor

A laboratory scale biomass gasifier is for a micro scale application which is to produce mechanical power of about 1 to 7 kW. A mechanical power of 4 kW is assumed and the design of the gasifier is based on this. The design of the reactor is basically empirical, that is, implied from charts based on past experiences.

3.1 Power Consumption of the Gasifier

For an engine with a compression ratio of 9.5:1, the effeciency has been estimated to be 28 per cent [12]. Therefore, the thermal power in the gas can be estimated as

$$P_g = \frac{P_m}{\mu} \qquad [12]$$

$$P_g = \frac{4}{0.28} = 14.3\ kW$$

If the thermal effeciency of the gasifier is taken at 70 per cent, the thermal power consumption at full load can be estimated as

$$P_t = \frac{P_g}{0.7} \qquad [12]$$

$$P_t = 20.4\ kW$$

3.2 Biomass Consumption of the Gasifier

A heating value of biomass with 14% moisture content is taken to be 17,000 kJ/kg, according to Ref. [12]. The biomass consumption of a gasifier can be estimated as [12, 13].

$$Biomass\ consumption\ of\ gasifier = \frac{Tlermal\ power\ consumption}{Heating\ value\ of\ biomass}$$

$$Biomass\ consumption\ of\ gasifier = \frac{20.4\ kW}{17000\frac{kJ}{kg}} = 0.0012\frac{kg}{s} = \frac{4.32kg}{l}$$

3.3 The Hearth Load: Specific Gasification Rate and Specific Solid Flow Rate

The hearth load, B_g, is defined as the amount of producer gas reduced to normal (p, T) conditions, divided by the surface area of the throat at the smallest circumference and is expressed in $m^3/(cm^2 \cdot h)$ [12]. This may be referred to as the specific gasification rate (SGR), which is the volumetric flow rate of gas per unit area based on throat diameter, the gas volume being measured at the standard conditions [14, 15]. The hearth load can also be expressed as the amount of dry fuel consumed divided by the surface area of the narrowest constriction, B_s, and is expressed in $kg/(cm^2 \cdot h)$ [12]. This may also be referred to as the specific solid flow rate (SSR) which is the mass flow of fuel measured at throat [14, 15]. One kilogramme of dry fuel under normal circumstances produces about 2.5 m^3 of producer gas [12, 14, 16]. Thus

$$B_g = 2.5 B_s \quad [12, 14]$$

$$B_s = \frac{4.32}{Area\ of\ tlroat} \quad [12]$$

The recommended value for B_g falls in the range of 0.30 to 1.0 [12, 14, 16]. Taking the value of B_g as 0.3,

$$0.3 = \frac{2.5 \times 4.32}{S}$$

3.4 Throat Sizing

The cross sectional area of the throat is thus

$$S = \frac{2.5 \times 4.32}{0.3} = 36cm^2$$

The diameter of throat, d_t, can be calculated using

$$S = \frac{\pi}{4} d_t^2$$

$$d_t = 6.8\ cm = 68\ mm$$

Sivakumar et al. [17] discovered from their model that for throat angles of about 45°, the cumulative conversion effeciency is increased while larger angles of about 90° decrease the cumulative conversion effeciency because of a decreased temperature for larger throat angles due to the divergent effect and the reaction rate. Venselaar [18] also recommended, after comparison of the design characteristics of a number of gasifiers, that the throat inclination should be around 45° to 60°. A throat angle of 60° is used.

3.5 Sizing of the Fire Box or Hearth

Diameter of the fire box or hearth, d_h is a function of throat diameter and can be estimated from Fig. 1a using

$$\frac{d_l}{d_t} = 3.5 \quad [12]$$

$$d_l = 3.5 \times 68 = 238\ mm$$

3.6 Nozzle Design and Air Blast Velocity

The height of nozzle plane above the smallest cross section of the throat is a function of the throat diameter and can be evaluated from Fig. 1b,

The ratio between the nozzle flow area and the throat area is a function of the throat diameter and is given from Fig. 1c as

$$\frac{A_n}{A_t} = 0.07 \quad [12]$$

Where, A_n is the total nozzle area. It is assumed that the gasifier will be equipped with 5 nozzles as recommended by Shrinivasa and Mukunda [19] for operating slow two-cycle engines. Hence,

$$d_n = 8\ mm$$

Sivakumar et al. [14] suggested optimum results are obtained when the angle of inclination of the nozzles is between 10° and 25°. An inclination of 15° is used.

The nozzle tip ring diameter d_{nt} is also a function of the throat diameter as seen in Fig. 1d. The ratio between the nozzle tip ring diameter and the throat diameter is

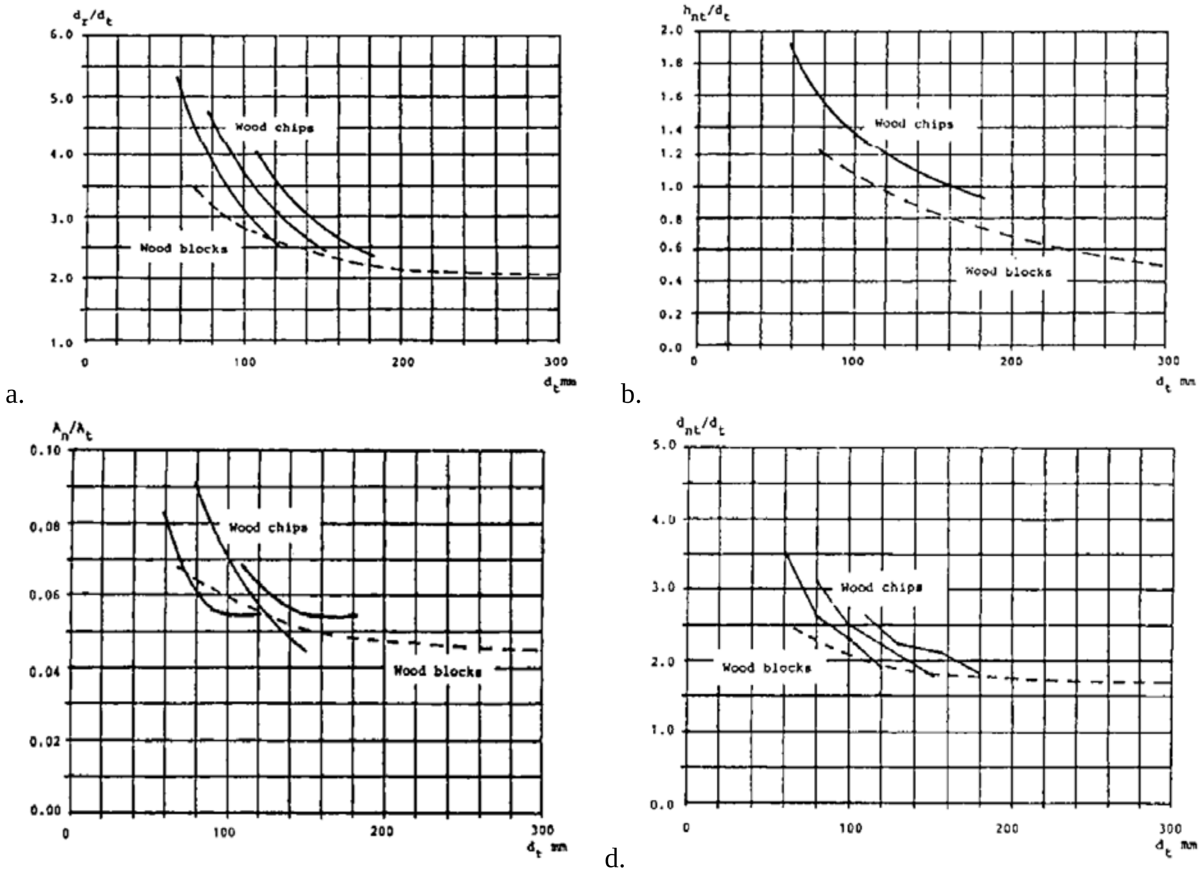

Fig. 1 a. Diameter of the fire box, d_r, as a function of the throat diameter, d_t ; b. Height of the nozzle plane above the throat, h_{nt}, as a function of the throat diameter; c. Ratio between nozzle flow area, A_n, and throat area, A_t, as a function of the throat diameter; d. Nozzle tip ring diameter, d_{nt}, as a function of the throat diameter, d_t [1].

$$\frac{d_{nt}}{d_t} = 3 \qquad [12]$$

$$d_{nt} = 204\ mm$$

The air blast velocity (V_b) can be estimated by equating the volumetric flow rate of the producer gas through the throat to the volumetric flow rate of air through the nozzle.

$$Q = Av$$

The volumetric flow rate of producer gas through the throat is estimated using

$$Q = 2.5\frac{m^3}{kg} \times 4.32\frac{kg}{l}$$

Using this flow rate as the flow of air through the nozzle,

$$\frac{Q = \frac{10.8}{60\ \times 60}m^3}{s} = 9 \times \frac{\pi(0.006)^2}{4} \times v_b$$

$$v_b = 11.79\frac{m}{s}$$

3.7 Air Inlet and Outlet

The general range for air inlet velocity is 6 m/s to 10 m/s [17]. The dimensions for the air inlet can be obtained using the continuity equation. By taking the velocity of air to be 6 m/s,

$$\frac{Q = \frac{10.8}{60\ \times 60}m^3}{s} = A_i \times 6$$

$$A_i = 0.0005\ m^3$$

For a circular opening, the diameter is $d = 0.025\ m = 25\ mm$. The gas inlet is taken to be 25 mm. The gas outlet is taken to be 20 mm.

3.8 Length of Reduction Zone

Sivakumar et al. [17] proposed that for a throat diameter of about 100 mm and for a throat angle of between 45 and 90 degrees, the reduction zone with a length above 150 mm gives an optimum cumulative conversion effeciency. However, SERI [20] proposes that the height of the reduction zone should equal the diameter of the throat. The reduction zone is designed with a length of 80 mm.

3.9 Height of the Hoper

The height of the hoper is decided on the basis of the feedstock which it will be required to hold within the period of operation. The period of operation is taken to be 2 hours since it is laboratory scale. Therefore, given the biomass consumption rate as 4.32 kg/h, the total biomass consumption estimated to be consumed in 2 hours is 8.64 kg.

The bulk density of wood is between 300 and 550 kg/m^3 depending on the moisture content. Assuming the value of the bulk density is taken to be 500 kg/m^3, the total volume of the hoper is estimated as:

$$Volume = \frac{mass}{density}$$

$$Volume = 0.01728\ m^3 = 17280\ cm^3$$

The height of a cylindrical reactor is

$$Height = \frac{Volume}{Cross - sectional\ area}$$

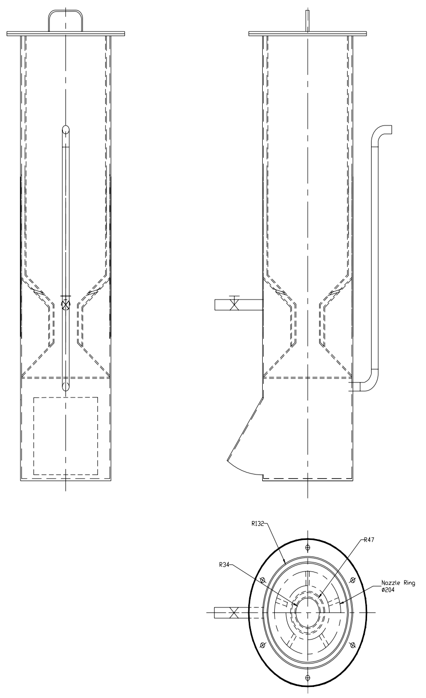

Fig. 2 Orthographic views of the laboratory scale biomass gasifier.

Fig. 3 The laboratory scale biomass gasifier.

$$Height = \frac{4 \times 17280}{\pi \times 23.8^2} = 38.8\ cm = 388\ mm$$

A height of 400 mm is taken. The biomass gasifier is shown in Fig. 2. Fig. 3 shows the picture of the gasifier.

4. Preliminary Tests Carried Out on the Biomass Fuels

Wood shavings and palm kernel shells were used as the biomass fuel/feedstock for testing the performance of the manufactured biomass gasifier. Preliminary experiments were carried out on the biomass fuels to determine some of their properties which are critical to the operation of the gasifier. The properties that were determined include the moisture content, bulk and apparent densities and bed voidage.

4.1 Determination of Moisture Content of Biomass

The moisture content determined on dry weight basis (MCD) and wet basis (MCW) were estimated using

$$MCD = \frac{(wet\ mass - dry\ mass)}{dry\ mass}$$

$$MCW = \frac{(wet\ mass - dry\ mass)}{wet\ mass}$$

4.2 Determination of Bulk Density

The bulk densities of the wood shavings and the palm kernel shells were determined using

$$\rho_b = \frac{mass\ of\ biomass}{volume\ filled\ by\ biomass}$$

4. 3 Determination of Apparent Particle Density

The apparent particle density is the density of a biomass particle with the pore inherently present in it. The apparent densities were determined using

$$\rho_p = \frac{mass\ of\ eacl\ piece}{volume\ of\ eacl\ piece}$$

4.4 Determination of Bed Voidage

The bed voidage is the ratio of the inter-particle void space to the total volume. The bed voidage was determined using [21]

$$\epsilon_B = 1 - \frac{\rho_b}{\rho_p}$$

4.5 Tests Carried Out on the Gasifier

The performance of the laboratory scale biomass gasifier was tested using the biomass fuels and in natural- and forced-draft modes.

4.5.1 Natural Downdraft Mode

During operation of the gasifier in the natural convection mode, the fuel wood shavings was fed into the gasifier until it reached above the throat level. It was ignited from the bottom of the grate using a torch. Air was allowed to flow through the air inlet by natural convection. The gas produced was ignited. The properties of the gas and the flame were observed. In another experiment, the fuel was fed to the hearth level and the ignition was carried out by introducing a flame in the throat. The operation of the gasifier was also observed. The second experiment was repeated for the palm kernel shells.

4.5.2 Forced Downdraft Mode

During operation of the gasifier in the forced down-draft mode, a blower with power rating of 3.5 kW was attached to the gasifier's inlet to introduce air into the air jacket which delivers it to the nozzles. The fuel was fed to the throat level and was ignited at the throat while the blower was operating. After sufficient temperature was reached, the fuel was loaded in multiples of 1 kg. The gas produced was ignited and the characteristic of the gas and flame were observed. The consumption rate of biomass was also observed. The experiment was carried out for both the wood shavings and palm kernel shells.

The fuel conversion rate was estimated using

$$Fuel\ conversion\ rate = \frac{mass\ of\ biomass\ fed\ into\ the\ gasifier}{total\ operation\ time\ of\ steady-state\ period}$$

5. Results and Discussions

5.1 Determination of Biomass Properties

The results for the determination of the properties of the biomass fuels are given in Table 1.

5.2 Results of Experiments Carried Out on the Gasifier Operation in Natural Downdraft Mode

The operation of the gasifier with wood shavings in the natural downdraft mode took about 35 minutes for the initial start up and production of combustible gas when ignited from under the grate. The gas burned with a blue flame similar to the butane gas for a short period of about 10 minutes before the production of the syngas was stopped. The pressure at which the gas exited the outlet was low. It was observed further that the heat remained in the reduction zone and thus the oxidation zone at the throat did not combust the biomass wood

Table 1 Properties of the biomass fuels.

Property	Palm kernel shell	Wood shavings
Moisture content (dry weight basis) (%)	9.8	19.3
Moisture content (wet basis) (%)	8.9	16.2
Bulk density (g/cm^3)	0.5	0.05
Apparent particle density (g/cm^3)	0.82	0.3
Bed voidage	0.39	0.83

Table 2 Results from the operation of the gasifier using palm kernel shells.

Start up time	10 minutes
Mass of biomass consumed	2 kg
Time taken to operate steadily	30 min
Fuel conversion rate	4 kg/h

shavings in the zone. There was, in addition, no observable decrease in the bed height during the process.

Syngas was not produced when wood shavings were ignited at the throat. Instead, the biomass only burned but did not gasify. A lot of smoke was also produced before the wood shavings began to burn. Palm kernel shells also burned but did not gasify when operated in the natural draft mode. It was noticed that the ignition from the bottom of the grate was not an efficient method of ignition. Also, the gasifier could not operate by natural draft and it needed a source of forcing air through the bed.

5.3 Operation in Forced Downdraft Mode

The operation of the gasifier in forced downdraft mode using wood shavings as fuel produced combustible gases, but a bridging was noticed which was caused by the char produced from the wood shavings which did not allow the gas produced to flow through the bed to the outlet. The bridging problem has been observed for fluffy or loose biomass by Kumararaja [22] for gasification of groundnut shells and Rudakova [23] for sawdust. In addition to the bridging problem, it was observed that there was no free flow of biomass within the gasifier into the throated region. The possible cause for the hindered flow is the inherent properties of the biomass as observed also by Kumararaja [22]. The operation of the gasifier in forced downdraft mode using palm kernel shells as fuel produced the results in Table 2.

During the gasification of the palm kernel shells, the start up time was about 10 minutes. A lot of smoke was produced during the start-up after which combustible gases were produced steadily. The gas produced, when ignited, burned a luminous flame as that obtained during the flaring of natural gas. Unlike the wood shavings, the palm kernel shells flowed freely. There were no bridging problems observed. It was also observed that a lot of smoke and tar oil was produced initially when the gasifier is loaded with fuel.

6. Conclusions

A laboratory scale downdraft biomass gasifier was designed to deliver a mechanical power of 4 kW and thermal power of about 15 kW. The design was largely empirical, that is, based on past experience. The biomass gasifier was manufactured as a single piece having a water seal and cover. The laboratory scale biomass gasifier has a capacity of holding 8.64 kg of feedstock. The hearth and throat diameter are 238 mm and 68 mm respectively. It had five nozzles, 10 mm diameter, for the injection of air. The gasifier is lagged along its length and throat using fibre glass material.

Palm kernel shells had moisture content of between 8% and 10% while wood shavings had moisture content between 16% and 20%. The bulk density of palm kernel shells is estimated to be 0.5 g/cm^3. Palm kernel shells also have an apparent density estimated as 0.82 g/cm^3 and with a bed voidage of 0.39. Wood shavings have a bulk density estimated to be 0.05 g/cm^3. The apparent density of wood shavings is 0.3 g/cm^3 and the bed voidage is 0.83. The biomass fuel conversion rate is 4 kg/h. The gasifier was suitable for gasifying palm kernel shell, but bridging problems were experienced during gasification of wood shavings. Forced downdraft mode of operation yielded better results and is the preferred operation of the gasifier.

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