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Development of an Inverted Downdraft Biomass Gasifier Cookstove

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Abstract
About eighty percent of Nigerians and sixty percent of Africans live in rural communities most of who utilize biomass for cooking. The benefits of improved cookstoves coupled with the perennial fuel crisis have led to intensified research into the development of the biomass cookstoves. This work aims to develop a biomass cookstove for use in developing countries. The biomass cookstove working with an inverted downdraft gasifier was developed and evaluated at Lagos State University, Nigeria. The biomass used was wood shavings with bulk density of about 0.05 g/cm^3 and with a moisture content of about 19.2% on dry basis and 16.2% on wet basis. The fuel conversion rate is 1.89 kg/h and it has a thermal effeciency of about 10.6%. The heating rate of the biomass cookstove was higher than the kerosene stove but less than the electric stove. While further work on the cookstove is recommended and proposed, the present and subsequent works can be adapted to suit rural applications where biomass is the major source of fuel but used inefficiently. The biomass cookstove cost $70 for a single unit but can be cheaper when mass produced.

Keywords: biomass, inverted downdraft, gasifier, cookstove

INTRODUCTION

In Nigeria, and indeed globally, the type of fuel used depends on the household income or revenue. Whilst the urban dwellers, assumed to earn more, utilize kerosene – a derivative from the fossil fuels, others who live in the rural regions utilize biomass in the form of fuel wood and agricultural wastes. About Sixty percent of the population in Africa live in rural communities – and in Nigeria, the estimate is about eighty percent – most of who utilize biomass for cooking. Issues associated with low technology, inefficient cook stoves, majorly the three stone stoves in Nigeria, are deforestation, land degradation and soil erosion, unnecessarily high fuel costs, global warming, deleterious indoor air quality, poor outside ambient quality visibility degradation and respiratory disease.

Benefits of improved cookstoves have been outlined by FAO (1993) and includes saving of fuels and, directly or indirectly, saving time due to the stoves' higher thermal effeciency; more complete combustion which makes the kitchen a healthier place in which to work; and reduction in safety hazards such as less exposure to heat resulting in a better work environment.

The emergence of perennial fuel crisis has drawn attention to the need for energy experts to concentrate on producing viable alternatives and/or compliments to kerosene and cooking gas for domestic cooking (Olorunsola, 1999). Also, interests in improvement of biomass cookstoves are developed to improve the health of women who are usually the users of the inefficient biomass cookstoves. This work aims to develop a biomass cookstove for use in developing countries and was carried out at the Lagos State University, Nigeria.

Design Specifications for the Biomass Cookstove

The cookstove was conceived to operate as to operate with the principle of gasification. The gasifier type is an inverted downdraft gasifier. The cookstove is designed to consist of a blower, a reactor/gasifier, a burner, a grate and insulation. Figure 1 shows the biomass cookstove. The design of the components is presented as follows.

Design of the Reaction Chamber

The energy needed for the reaction chamber can be determined from the specific energy which corresponds to the quantity of food to be cooked and/or water to be boiled. Where M_f is the mass of food, E_s is the specific energy of the food and t is the time, the energy, Q, required to cook food is estimated using (Belonio, 2005)

$$Q = \frac{M_f \times E_s}{t} \quad (1)$$

Assuming a kilogram of rice is cooked within fifteen minutes (0.25h), the energy required is estimated, taking the specific energy of rice as 1700kJ/kg, to be

$$Q = \frac{1kg \times 1700kJ/kg}{0.25h} = 6800kJ/h \quad (2)$$

The energy input, taken as the fuel consumption rate, FCR, refers to the energy/fuel quantity to be fed into

the stove. Where H is the heating value of fuel and γ is the gasifier stove effeciency, then FCR can be estimated using (Belonio, 2005)

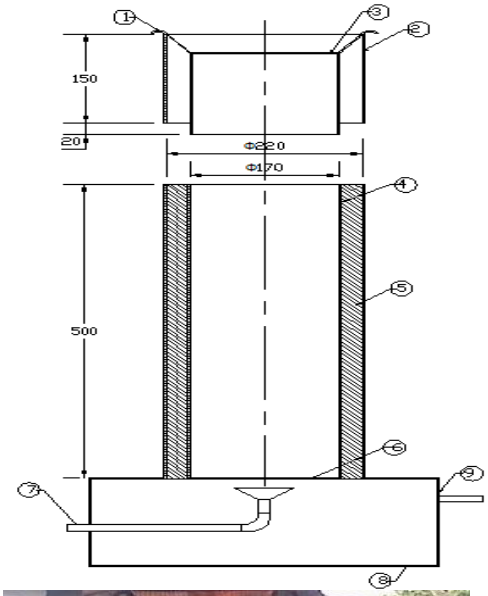

Figure 1: The biomass cookstove *(1-Pot carrier; 2-Burner shield; 3-Burner holes; 4-Reactor; 5-Insulation; 6-Grate; 7-Air inlet; 8-Ash tray; 9-Ash tray door)*

$$FCR = \frac{Q}{H \times \gamma} \quad (3)$$

Using products from wood as design basis which have an average heating value of about 17000kJ/kg and assuming a gasifier stove effeciency of 24%, the fuel consumption rate is estimated as

$$FCR = \frac{6800kJ/h}{17000kJ/kg \times 0.24} = 1.7kg/h \text{ of biomass} \quad (4)$$

The reactor diameter is a function of the fuel consumption rate and the specific gasification rate, SGR. Kumararaja et al. (2010) found that the specific gasification rate for wood pieces to be 75kg/m^{2}h with the producer gas to wood ratio being 2.39 at an optimum equivalence ratio of 0.3. Hence, the diameter is estimated as (Belonio, 2005)

$$D = \left[\frac{1.27FCR}{SGR}\right]^{1/2} = \left[\frac{1.27 \times 1.7kg/h}{75kg/m^2h}\right]^{1/2} = 17cm \quad (5)$$

The height, H, of the reactor determines how long the stove would operate in one loading of fuel. Where T is the time the reactor will be required to operate assumed to be 3 hours and ρ being the bulk density taken to be 450kg/m^3, the height of the reactor can be estimated using (Belonio, 2005)

$$H = \frac{SGR \times T}{\rho} = \frac{75kg/m^2h \times 3h}{450kg/m^3} = 0.5m \quad (6)$$

The specifications for the reactor include 170mm internal diameter and a height of 0.5m and fabricated with mild steel.

Design of Burner

The burner is designed to receive gas produced from the reactor and allow passage of the gas through holes of about 5mm drilled at the top of the burner close to the circumference. A vertical shield was designed with the aim of acting as a shield for the flames. The shield also acts as part of the support of the pot.

Grate, Ash Tray and Insulation

The grate is made from mild steel which is net-shaped and covers the entire circumference at the bottom of the reactor. The grate acts as a support for the biomass in the reactor and allows passage of ash during operation. The ash tray lies beneath the grate and has the shape of a cuboid with dimensions $0.25m \times 0.25m \times 0.2m$. The ash from the gasification process drops into the ash tray from where they are collected. The insulation for the reactor is made from fibre glass and has a thickness of 20mm.

Preliminary Tests on the Biomass Material

Wood shavings were used as the biomass material for the biomass cookstove. Initial tests were carried out on the biomass material – wood shavings – utilized for operating the cookstove and the material was tested to determine the operation of the biomass cookstove. The properties of the biomass material determined include moisture content, bulk and apparent densities.

Moisture Content

The test to determine the moisture content of the wood shavings was carried out by heating the biomass material in an oven at about 110^{o}C with the initial and final weights being recorded. The moisture

content determined on dry basis (MCD) and wet basis (MCW) were obtained using:

$$\text{MCD} = \frac{(\text{wet mass} - \text{dry mass})}{\text{dry mass}} \quad (7)$$

$$\text{MCW} = \frac{(\text{wet mass} - \text{dry mass})}{\text{wet mass}} \quad (8)$$

Determination of Bulk Density

The bulk density of the wood shavings was determined by weighing a quantity of wood shavings in a beaker noting the volume the wood shavings occupied in the beaker. The value of bulk density was obtained using:

$$\rho_b = \frac{mass\ of\ biomass}{volume\ filled\ by\ biomass} \quad (9)$$

Evaluation of the Biomass Cookstove

A weighed quantity of biomass was fed into the reactor with the biomass being lit from the top. The blower which was to force air through the reactor was powered using direct current from a battery after which the burner was placed on top of the reactor. The gas from the burner holes was ignited and the times taken to start up and operate the reactor were noted. From these the fuel conversion rate, combustion zone rate.

The fuel conversion rate was estimated using (Belonio, 2005)

$$\text{fuel conversion rate} = \frac{\text{mass of biomass fed into the gasifier}}{\text{total operation time of steady state period}} \quad (10)$$

The combustion zone rate (CZR) was obtained using (Belonio, 2005)

$$\text{CZR} = \frac{\text{length of reactor (m)}}{\text{Total operating time (hr)}} \quad (11)$$

Boiling Test

A boiling test was performed using the biomass cookstove to compare the performance with a kerosene stove and electric stove which were also used to perform similar tests. In performing the test, a litre of water was poured into a pot with a diameter of about 20mm with the initial temperature of the pot with water taken. The pot was placed on the cookstove and the temperature taken at intervals until boiling. The test was repeated for the kerosene and electric stoves.

The thermal effeciency, γ_c, of the cookstove was obtained from a relation between the sensible (SH) and latent (LH) heats, and the weight (m_f) and heating value (H_f) of fuel used. The thermal effeciency of the cookstove was obtained using (Belonio, 2005)

$$\gamma_c = \frac{SH + LH}{H_F \times m_F} \quad (12)$$

Where m_w is the mass of water, c_p is the specific heat of water taken to be 4.2kJ/kg-K, T_f is the temperature of water at boiling point which is 100°C and T_i is the initial temperature of water, the sensible heat was estimated using

$$SH = m_w \cdot c_p \cdot (T_f - T_i) \quad (13)$$

Also, where m_e is the mass of water evaporated and H_f is the specific latent heat of water, the latent heat was estimated using

$$LH = m_e \cdot H_f \quad (14)$$

RESULTS AND DISCUSSION

The results for the determination of properties of wood shavings used as biomass fuel for the gasifier are presented in table 1. The moisture content of the material was about 19.3% on dry basis and 16.2% on wet basis. The bulk density was about 0.05g/cm^3.

Table 1: Properties of biomass materials (wood shavings)

Property	Value
Moisture content on dry weight basis (MCD)	19.3%
Moisture content on wet basis (MCW)	16.2%
Bulk density (ρ_b)	0.05 g/cm^3

Table 2: Results from evaluation of biomass cookstove

Parameter	Value
Mass of biomass used	0.53kg
Start-up time	5.8 min
Operating/steady-state time	16.8 min
Total operating time	22.6 min
Fuel conversion rate	1.89 kg/h
Combustion zone rate	1.32 m/h

The results for the operation of the biomass cookstove are presented in table 2. The mass of biomass (wood shavings) used during the operation of the cookstove was 0.53 kg. The start up time of the gasifier was about 5.8 minutes and the time of operation of the gasifier in steady state was 16.8 minutes which gives a total operating time of 22.6 minutes. The fuel conversion rate was estimated to be 1.89 kg/h and the combustion zone rate was 1.32 m/h.

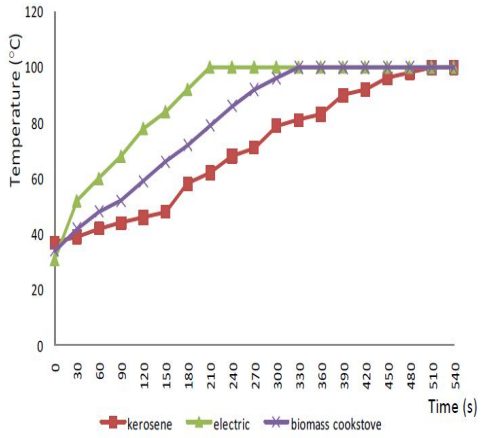

Figure 2: Results of boiling test with kerosene and electric stoves compared with the biomass cookstove.

Ojolo and Orisaleye (2010) have reported reported problems of bridging using wood shavings in the throated downdraft gasifiers; Kumararaja (2009) reported similar problems with groundnut shells and Rudakova (2009) with sawdust. The inverted downdraft gasifier performed better when fluffy biomass – sawdust – was used as fuel. Also, the start-up time improved. The gas produced had similar properties as reported for other gasifiers being a thick brownish gas which when ignited had similar flame/flaring properties as natural gas. The fuel conversion rate was not as high as that obtained by the throated downdraft gasifier designed by Ojolo and Orisaleye (2010).

The results from the boiling tests carried out are shown in figure 2 and table 3. It was observed that the heating rate gas produced by the biomass cookstove was higher than that of kerosene but not as high as the electric stove. The thermal effeciency of the biomass cookstove was estimated to be about 10.6% which is lower than the coal stove designed by Bolaji and Olalusi (2009) which may be improved by improving the design of the burner which did not operate quite satisfactorily.

Table 3: Results from the boiling test

Parameter	Value
Sensible heat (SH)	277.2 kJ
Latent heat (LH)	678 kJ
Thermal effeciency (γ_c)	10.6%

CONCLUSION

A biomass cookstove working with an inverted downdraft gasifier has been developed and evaluated. The biomass used was wood shavings with bulk density of about 0.05 g/cm^3 and with a moisture content of about 19.2% on dry basis and 16.2% on wet basis. The fuel conversion rate is 1.89 kg/h and it has a thermal effeciency of about 10.6%. The heating rate of the biomass cookstove was higher than the kerosene stove but less than the electric stove. While further work on the cookstove is recommended and proposed, the present and subsequent works can be adapted to suit rural applications where biomass is the major source of fuel but used inefficiently. Future work will also include evaluation of the cookstove using various biomass resources available locally. The biomass cookstove cost $70 dollars for a single unit but can be cheaper when mass produced.

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