DEVELOPMENT OF A BIOMASS GASIFIER STOVE

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ABSTRACT

The use of biomass in our local and primitive stove (three stone stove) has a negative impact on the health of household members especially women and children that are mostly exposed to the pollutants produced by this stove. Biomass combustion provides basic energy requirements for cooking and heating of rural households and for processes in a variety of traditional industries in the developing countries. A study was conducted to develop a biomass gasifier stove using locally available materials like mild steel, clay and wood to save the cost of production. It converts biomass fuel into a combustible wood gas or producer gas that is directly burn to produce luminous blue flame. The power supply unit is a rechargeable battery which provides 25.9KJ of energy to drive the fan assembly unit and forces air through the fuel column in the reactor. The performance of the stove was determined using water boiling test. The results show that the specific gasification rate (SGR), fuel consumption rate (FCR), combustion zone rate(CZR), percentage char produced, input power and output power to be 186.19kh/m^{2}hr, 5.85kg/hr, 0.67cm/m, 13%, 130kW and 29069.24kW respectively.

1. INTRODUCTION

Biomass combustion provides basic energy requirements for cooking and heating of households and for processes in a variety of traditional industries (Reric, 2003). Firewood and charcoal accounts for a major fraction of the total biomass used and this causes deforestation in the country. Apart from contributing to deforestation which endangers our environment, it also consumes time and labour in its collection (Yohannes, 2011). Currently in Nigerian, the high cost of fossil fuel prevent people from using other heat energy sources like kerosene stove, pressure stove, gas cooker and even electric stove is not reliable due to epileptic power supply. As we know, every home needs cooking to sustain life and the only alternative is this biomass as a renewable source of energy. Although, biomass offers itself as sustainable and carbon-neutral source of energy, its inefficient use in household cooking results in wastage, indoor air pollution and causes related respiratory and other health problems (Yohannes, 2011). More so, excessive use of fuel wood is exerting pressure on the regions forest cover and causing global warming. There are large quantities of surplus biomass residue such as rice husk, corn cob, cotton shell, palm kernel, plant straw etc. which their use has been severely restricted due to certain difficulties experienced in using them for cooking (Yohannes, 2011).

The biomass gasitier stove has the potential to replace Kerosene stove, gas cooker and old method of burning firewood for cooking that uses a lot of wood in an inefficient combustion that produce smoke and causes serious health hazard. It also reduces household expenditure on conventional fuel source, such as kerosene, gas, wood and wood charcoal. So, it substitute the expensive fossil fuel with wood and agricultural waste such as saw-dust, wood shaving, rice husk, corn cob, coconut shell, palm kernel, plant straw etc. It can provide employment opportunity and source of income for the country's unemployed youth if they engage in the production and marketing of the stove.
The use of biomass in our local and primitive stove (three stone stove) has a negative impact on the health of household members especially women and children that are mostly exposed to the pollutants produced by this stove. Such exposures are linked to acute respiratory infections, chronic obstructive lung disease, low birth weight, lung cancer and eye problems (Kaoma and Kasali 1994).

The most common pollutant produced from the combustion of biomass fuels are particulate matter, carbon monoxide, hydrocarbons, nitrogen oxides and sulfur oxides (Yohannes, 2011). The composition of the pollutants emitted during the combustion of biomass fuel depends on several factors; such as original compositions of the fuel, ambient and combustion temperatures, air flow into the fire, mode of burning and type of stove (Yohannes, 2011). Biomass combustion provides basic energy requirements for cooking and heating of rural households and for process in a variety of traditional industries in the developing countries (Reric, 2003). In general, biomass energy use in such cases is characterized by low energy efficiency and emission of air pollutants. Biomass fuels currently used in traditional energy systems could potentially provide a much more extensive energy service than at present, if these were used efficiently. For example, new stove design can improve the efficiency of biomass used for cooking by a factor of 2 to 3. (Reric, 2003).

According to Yohannes (2011), four different processes can be distinguished in gasification as illustrated in Fig. 1.

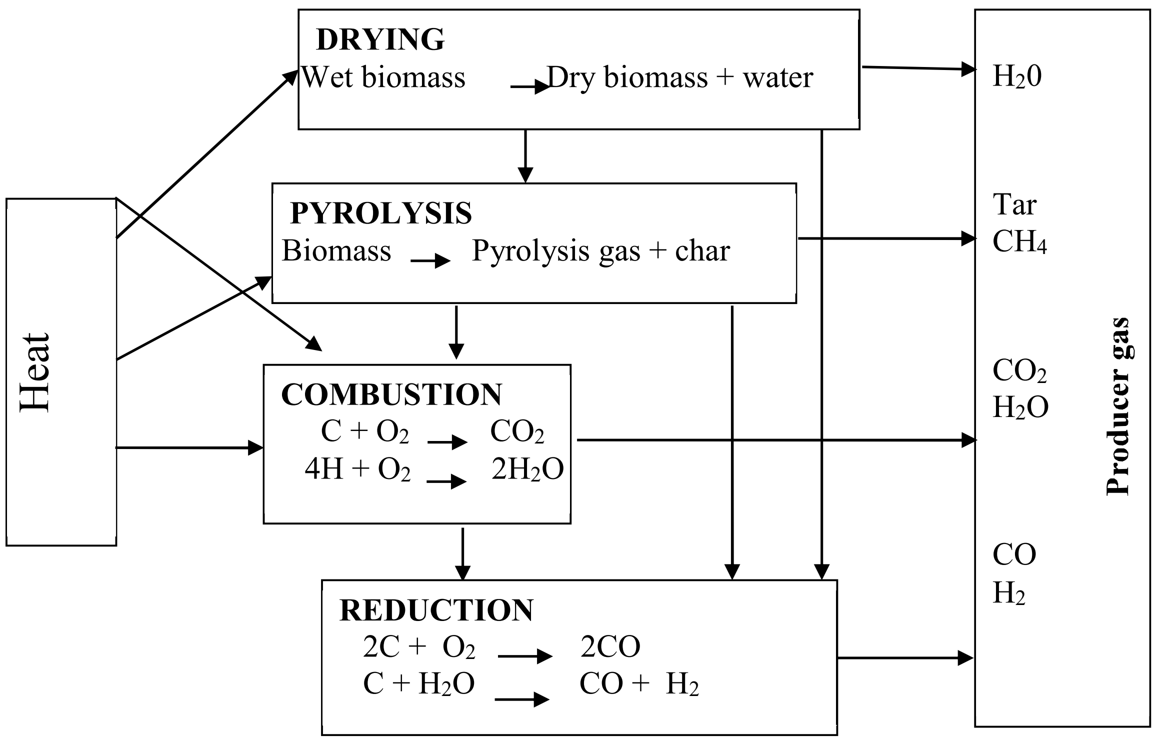

Fig. 1. The reaction mechanism of biomass gasification processes (Source: Yohannes 2011)

Several factors influence the gasification of biomass which include; energy content of the fuel, moisture content, size and form of fuel e.t.c. (Kaupp, 1984, Bellonio, 2005). Fuel with high energy content provides better combustion in biomass gasifier. The moisture content of biomass also affects gasification. Fuel with low moisture content can be properly gasified than that with high moisture content. The biomass fuel should be of a form that will not lead to bridging within the reactor. Bridging occurs when unscreened fuels do not flow freely axially downwards in the gasifier. Therefore, particle size is an important parameter in biomass gasification because it determines the bed porosity.

Therefore the objective of this project is to develop a stove that will burn biomass fuel in an efficient manner, and to carryout performance evaluation test so as to determine its usefulness.

2. METHODOLOGY

2.1 Functional Units of the Design

This stove consists of five functional units, which are burner assembly, reactor, ash chamber, fan assembly and the power supply or control units (Figs 2, 3, 4). Some of its parts are made up of mild steel sheet, refractory material, and wood. It's mode of operation is based on the principle of Top lit up-draft fan assisted method of gasification, burning different type of fuel such as rice husk, corn cub, wood shaving, saw dust, palm kernel, plant straw and other agricultural waste to produce luminous blue flame like that of gas cooker.

2.2 Design Calculations

Some of the parameters required in determining the appropriate size and power of gasifier stove reactor are computed as follows:

Energy demand: This is the amount of heat energy required to be developed by the stove. This can be determined based on the amount of food and/or water to be boiled and their corresponding specific heat energy values (Yohannes, 2011).

The amount of energy required to cook food was calculated using equation 1

$$Q_n = \frac{M_f \times E_s}{T} \qquad (1) \qquad \text{(Yohannes, 2011)}$$

Where, Q_n - Energy needed, KJ/hr, M_f - Mass of food, Kg
E_s - Specific energy, KJ/Kg, T - Cooking Time, hr

Energy Input: It is the amount of energy to be supplied into the stove in terms of fuel. This stove can handle a variety of dry biomass of reasonable size that will allow the passage of primary air. Such biomass include saw dust, rice-husks, wood shaving, wood waste, plant straw and other agricultural residue. The fuel consumption rate is determined using equation 2

$$FCR = \frac{Q_n}{H_{vf} \times E_g} \qquad (2) \qquad \text{(Yohannes, 2011, Belonio, 2005)}$$

Where, FCR - Fuel consumption rate, Kg/hr, Q_n - Heath energy needed, Kg/hr
H_{vf} - Heating value of fuel, KJ/Kg, Eg - Gasifier Stove Efficiency, %

Reactor Diameter: This is the size of reactor in terms of the diameter of cross-section of the cylinder where biomass is being burned. It is a function of the amount of fuel consumed per unit time (FCR) to the specific gasification rate (SGR) of biomass material; which is in the range of 110 to 210 kg/m^2-hr or 56 to 130 as revealed by the results of several test on biomass material gas stoves (Belonio, 2005).
The reactor diameter is calculated using equation 3

$$D = \left(\frac{1.27 \times FCR}{SGR}\right)^{0.5} \qquad (3) \qquad \text{(Belonio, 2005, Yohannes 2011)}$$

Where, FCR - Fuel consumption rate, Kg/hr, SGR - Specific gasification rate of biomass material, Kg/m^2-hr, D - Diameter of reactor, m.

Height of the Reactor: This is the total distance from the top and the bottom end of the reactor and it determines the operation time of the stove. Basically, it is a function of a variables such as operating time (T), the specific gasification rate (SGR) and the density of the biomass material ρ (Yohannes, 2011). The height of reactor can be calculated using equation 4.

$$H = \left(\frac{SGR \times T}{\rho}\right) \quad (4) \quad \text{(Belonio, 2005, Yohannes, 2011)}$$

Where, H - Height of the reactor, m, SGR - Specific gasification rate of biomass fuel, Kg/m^2-hr, T - Time required to consumes the biomass fuel, hr
ρ - Biomass material density, Kg/m^3

Time to consume the biomass fuel: This is the total time required to completely gasify the biomass material inside the reactor. This includes the time to ignite the fuel, time to generate the gas, plus time to completely burn all the fuel in the reactor (Yohannes, 2011),
Time required to consumes the Biomass material, hr is calculated using equation 5

$$T = \frac{\rho \times V_r}{FCR} \quad (5) \quad \text{(Belonio, 2005, Yohannes, 2011)}$$

Where, T - Time required to consumes the Biomass material, hr
V_r - Volume of the reactor, m^3, ρ - Biomass material density, Kg/m^3
FCR - Fuel Consumption rate, Kg/m^3

Therefore, a cylindrical reactor made of clay material supported by mild steel cylinder of 1.2mm thick with the following configuration was selected for the stove

The parameters required in selecting the type and size of the fan is the amount of air Needed for Gasification, This is the rate of flow of air into the stove reactor. It helps in determining the size of fan or blower needed for the reactor in gasifying biomass material. It can be calculated using equation 6.

$$AFR = \frac{E \times FCR \times SA}{\rho_a} \quad (6) \quad \text{(Belonio, 2005)}$$

Where, AFR - Air flow rate, m^3/hr, E - Equivalence ratio, 0.3 to 0.4
FCR - Fuel consumption rate, Kg/hr, SA - Stoichiometric air of biomass fuel, 4.5kg air per kg of fuel., ρ_a - Air density, 1.25Kg/m^3

Superficial Air Velocity: This is the speed of air flow through the fuel bed as shown in equation 7.

$$V_s = \frac{4AFR}{\pi (D)^2} \quad (7) \quad \text{(Belonio, 2005)}$$

Where, V_s - Superficial gas velocity, m/s, AFR - Air flow rate, m^3/hr
D - Diameter of reactor, m.

Resistance to Airflow: This is the amount of resistance exerted by the fuel and by the char inside the reactor during gasification. This is important in determining whether to use a fan or blower to supply the required air for the reactor. It can be calculated using equation 8.

$$R_f = T_f \times S_r \quad (8) \quad \text{(Belonio, 2005)}$$

Where, R_f - Resistance of fuel, cm of H_2O, T_f - Thickness of fuel column, m
S_r - Specific resistance, cm of water/m of fuel.

Power supply unit. Power requirement by the 2 fans is calculated using equation 9.

$$\text{Power, P} = \text{IV} \quad (9)$$

Where, P – Power in watt, I – current in A, V – Voltage in V

The specifications of the fan selected were 12V and 0.30A.

$$Power, P = IV = 0.30 \times 12 = 3.6W$$
$$\text{For the two fans, Power} = 2 \times 3.6\text{W} = 7.2\text{W}$$
$$Energy\ needed\ by\ the\ two\ fans = Power \times Time$$

The stove is to be operated for the maximum periods of one hour (Assumption)

$$Energy\ needed = 7.2W \times 3600\text{sec} = 25920\text{J} \quad = 25.\text{KJ}$$

For the power supply output power; Output voltage = 12V, Maximum current = 1A

$$Output\ Power = 1A \times 12V = 12W$$

The battery capacity is determined using equation 10:

$$Battery\ Power\ (Ah) = \frac{Load\ in\ watt}{Battery\ voltage \times Backup\ hour} \qquad (10)$$

(Electroschematics.com/5645/home/Inverter/)

$$\text{Battery power (Ah)} = \frac{7.2W}{12V \times 1hour} = 0.6Ah$$

According to the above calculation, a 12V battery with 1Ah capacity can supply the required current for the stove operation for one hour. But, in Nigeria there may be power failure for 2 or more days at times and cooking must be done. For this reason, two 6V batteries with 4.5Ah capacity were selected for the project and it was connected in series to give 12V, 4.5Ah. Backup time is expressed as follows:

Required Battery power for 1 hour = 0.6Ah

Selected Battery power for 1 hour = 4.5Ah

$$\text{Backup time} = \frac{\text{Selected battery power}}{\text{Required battery power}} = \frac{4.5\text{Ah}}{0.6\text{Ah}} = 7.5 \text{ hours} \qquad (11)$$

Backup time = 7 hours, 30 minutes.

Therefore, the power supply unit can supply the stove for up to 7 hours continuously before the battery run down.

2.3 Procedures for Testing and Performance Evaluation

The test equipment such as weighing scale, thermometer, measuring cylinder, weighing balance, pot, digital multi-meter and stop-watch were prepared. The stove was set up with the power supply unit connected. Measured weight of fuel (biomass) was loaded in batches till the stove reactor filled up and total weight of fuel loaded was recorded. Small amount of kerosene was poured on top of fuel bed and ignited with match stick and stop-watch started. Fire was fully established after about 1 minute. After this, the burner and stove cover put in place. Blue flame was fully established after about 5 minutes. 1 litre of water measured with volumetric cylinder and poured into the pot, covered and placed on the burner. The water boiled after about 3 minutes. This step was repeated three times using 1 litre of water and initial and final temperature of water, as well as weight of water left in each case was measured. Pot filled with 1 litre of water and placed on the stove without cover. Initial temperature of water and simmering water temperature was measured at 1 minute interval till the water boils. The stove was left in operation on till the fuel was completely gasified. Char was discharged from the ash chamber and measured with weighing balance.

The results of the test are as presented in tables 1, 2 and 3. The summary of the stove performance was presented in table 4. The parameters in table 4 were obtained as stated below;

a) **Fuel Consumption Rate:** This is the amount of fuel used in operating the stove divided by the operating time.

$$Fuel\ Comsumption\ Rate, FCR = \frac{weight\ of\ fuel\ used\ (Kg)}{Operating\ Time\ (hr)} \quad (12) \quad \text{(Belonio, 2005)}$$

b) **Specific Gasification Rate, (SGR):** This is the amount of fuel used per unit time per unit area of the reactor.

$$\mathrm{SGR} = \frac{\text{weight of fuel used(Kg)}}{\text{Reactor area}(\mathrm{m}^2)\times\text{Operatingtime(Hr)}} \quad (13) \quad \text{(Belonio, 2005)}$$

c) **Combustion Zone Rate (CZR):** This is the time required for the combustion zone to move down the reactor.

$$\mathrm{CZR} = \frac{\text{length of the reactor (m)}}{\text{operating time (hr)}} \quad (14) \quad \text{(Belonio, 2005)}$$

d) **Power Input P_{in}:** This is the amount of energy supplied to the stove based on the amount of fuel consumed.

$$\mathrm{p_{in}} = 0.0012 \times \mathrm{FCR} \times \mathrm{HVF} \quad \text{(kW)} \quad (15) \quad \text{(Belonio, 2005)}$$

Where, FCR – Fuel consumption rate, KJ/Kg

e) **Power Output P_{out}:** This is the amount of energy released by the stove for cooking.

$$P_{out} = FCR \times HVF \times TE \quad \text{(kW)} \quad (16) \quad \text{(Belonio, 2005)}$$

Where, FCR – Fuel consumption rate, Kg/hr, HVF – Heating value of fuel, KJ/Kg, TE – Thermal efficiency, %

f) **Percentage Char Produced:** This is the ratio of the amount of char produced to the amount of fuel used.

$$\%\ \mathrm{Char} = \frac{\text{Weight of Char,Kg}}{\text{Weight of Fuel used,Kg}} \times 100 \quad (17) \quad \text{(Belonio, 2005)}$$

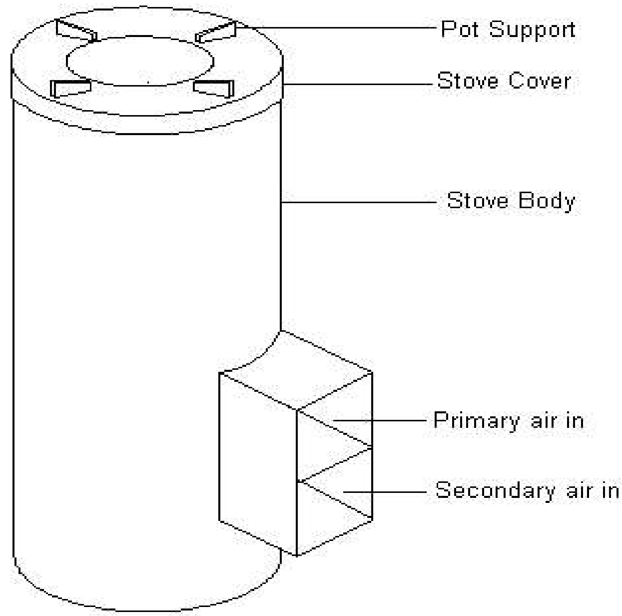

Fig 2: Isometric View of the Gasifier stove

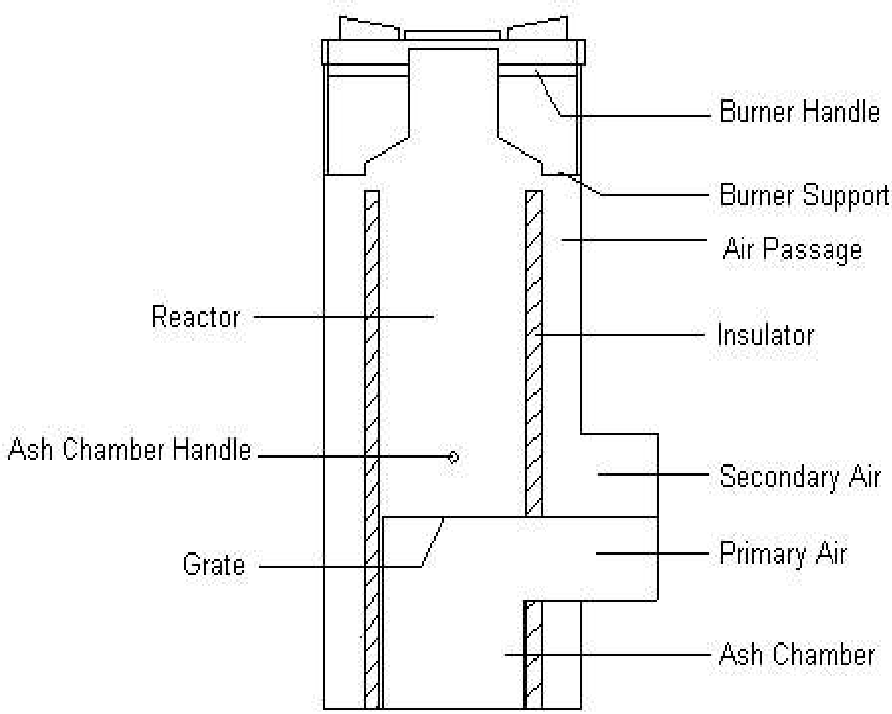

Fig 3: Sectional View of the Gasifier stove

Fig. 4. Completed Stove and Power Supply Unit

3. RESULTS AND DISCUSSIONS

The results of the tests carried out on the stove are as shown in Tables 1, 2, 3 and 4. Table1 shows the change in weight of water as its temperature rises from room's to boiling point. About 300g of water is lost as its temperature rises by 74^{o}C (4g/^{o}C). Table 2 shows the water simmering test. The table shows that it takes the stove an average of 5 minutes to boil a litre of water. About 15^{o}C/min. rise in temperature of water was recorded throughout the test period. Table 3 shows the performance of the stove in terms of fuel consumption rate, specific gasification rate, combustion zone rate, input and output power and thermal efficiency. The ratio of output to input power of 223.6 shows that the power output was very high.

Table 1: Water Boiling Tests

S/NO	WATER PARAMETERS	TEST 1	TEST 2	TEST 3	AVERAGE
1	Initial weight	1000g	1000g	1000g	1000g
2	Final weight	700g	680g	690g	690g
3	Initial temperature	26^{0}C	27^{0}C	27^{0}C	26.7^{0}C
4	Final temperature	100^{0}C	100^{0}C	100^{0}C	100^{0}C

Table 2: Water Simmering Tests

	WATER	TEMPERATURE		
TIME	TEST 1	TEST 2	TEST 3	AVERAGE
0	26^{0}C	27^{0}C	29^{0}C	27.3 ^{0}C
1	35^{0}C	38^{0}C	37^{0}C	36.7^{0}C
2	41^{0}C	42^{0}C	42^{0}C	41.7^{0}C
3	54^{0}C	54^{0}C	55^{0}C	54.3^{0}C
4	73^{0}C	76^{0}C	75^{0}C	74.7^{0}C
5	98^{0}C	100^{0}C	100^{0}C	99.3^{0}C
6	100^{0}C	100^{0}C	100^{0}C	100.0^{0}C

Table 3: Stove Operating Parameters.

S/NO	Parameters	Value
1	Weight of fuel	5.85Kg
2	Weight of ash	0.76Kg
3	Ignition time	1 minute, 12 seconds
4	Time when blue flame begins	2 minutes, 43 seconds
5	operating time	58 minutes, 7 seconds
6	Total operating time	1 hour, 2 minutes

The stove performances are summarized in Table 4 below:

Table 4; Summary of stove performance

S/N	Parameters	Values
1	Fuel consumption rate	5.85kg/hr
2	Specific gasification rate(SGR)	186.19kg/m^{2}hr
3	Combustion zone rate (CZR)	0.67cm/m
4	Power input	130kW
5	Power output	29069.24kW
6	Percentage Char produced	13%

4. CONCLUSIONS AND RECOMMENDATIONS

A biomass gasifier stove has been design and constructed using locally available materials to minimize cost. It makes use of agricultural and wood waste as fuel to produce luminous blue flame like that of gas cooker. The stove was equipped with power supply unit that has a battery backup for up to 7 hours in case of power failure which helps in supplying the air needed for gasification.

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