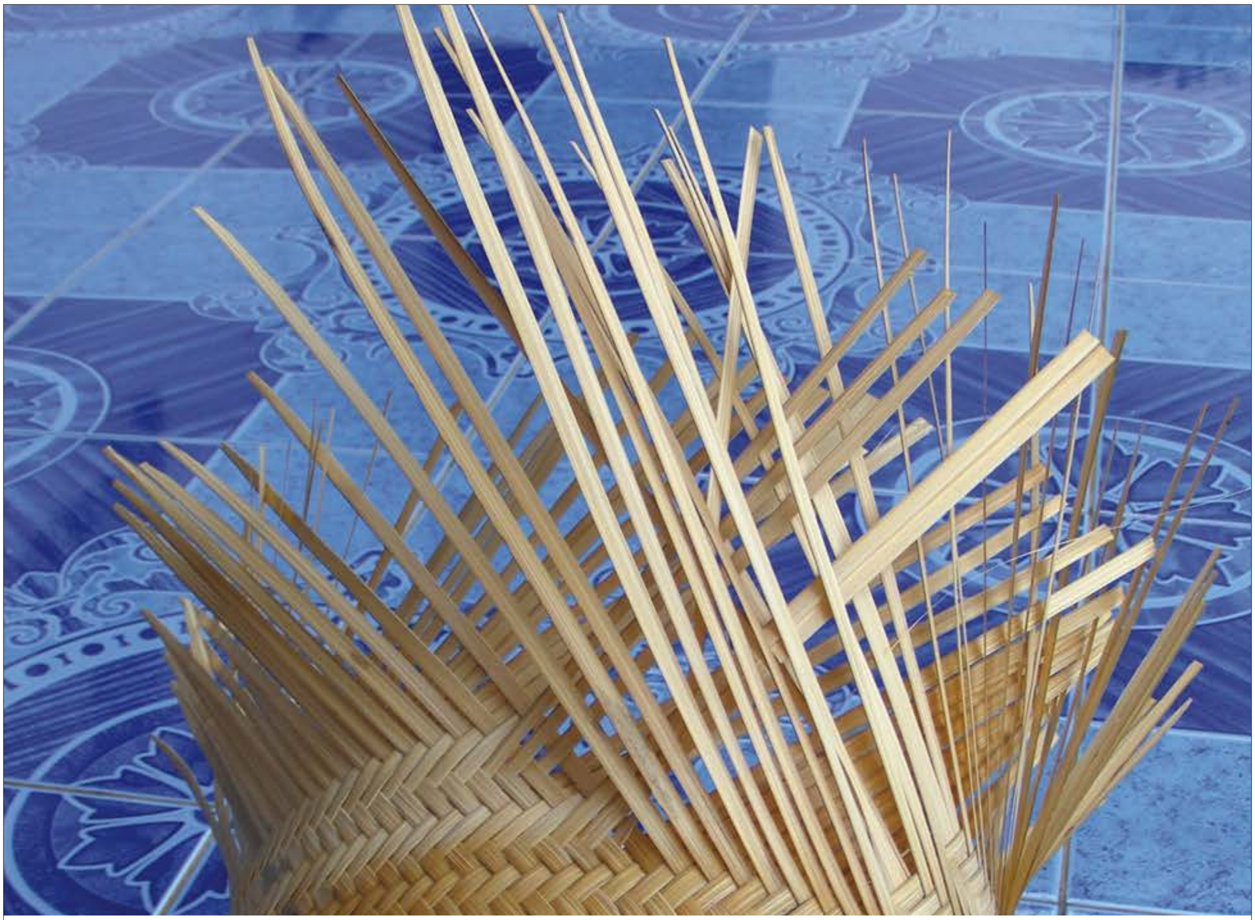

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Development of a Laboratory Scale Updraft Gasifier

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ABSTRACT

This study presented a designed and fabricated 11.19 kW laboratory scale updraft gasifier tested on sawdust and palm kernel shell as feedstock. The samples of the pulverized feedstock were analysed for their fuel characteristics. The results of the proximate analysis of the sawdust and palm kernel shell showed that the respective moisture content of 9.9 and 12% (dry basis) contains 4 and 3% fixed carbon, 82 and 55% of volatile matter and 4 and 30% of ash on dry basis. The Higher Heating Value (HHV) are 23.4 and 15.8 MJ kg^{-1} while the Low Heating Values (LHV) were 22.2 and 15.0 MJ kg^{-1}. The result of ultimate analysis validates both ash and moisture content which are found to be 4 and 30% and 9.9 and 12%, respectively. Other elemental compositions determined by the ultimate analysis are respectively carbon (66.964% and 45.19), hydrogen (5.71% and 3.85), nitrogen (0.822 and 0.558%) and oxygen (12.604 and 8.402%). The performance test carried out on both the sawdust and palm kernel shell indicates the heat energy input of 28,125 and 31,633.06 kJ, power input of 7.812 and 8.79 kW, power output of 5.47 and 6.15 kW and the respective gasifier efficiency of 93 and 67.4%. The study has identified that the sawdust and palm kernel shell are suitable for the designed and fabricated updraft gasifier. This gasifier has been made to meet various energy demands from the local readily available materials and can be developed for various applications of heating, electricity supply and can be used to generate the needed combustible gases during fuel scarcity.

Key words: Updraft, gasifier, feedstock, energy, design

INTRODUCTION

The high and rising demand for energy due to population growth and the high rate of industrialization has made it necessary to look beyond the conventional sources of energy. Nigeria has yet untapped a great potential for biomass which if developed will make a lot of impact on the development of its rural population.

In Nigeria, there are 774 local government areas, Akinbami and Momodu (2011) studied the potential (availability) of sawdust for heating and electricity generation purposes in 100 sawmills from four local government councils located in Ijebu area of Ogun State, Nigeria. The study estimated total volume of wood waste in excess of 212, 220 m^3 (about 66000 tons) per annum, with this, about 8.0 MW of electricity power will be generated with an annual electricity output of about 79,089.3 MWh, in monetary terms, diesel displaced by the sawdust based power plant is about US $1.3 million. In addition CO_2 emission that will be saved through the efficient use of the feed stock is in excess of 73,000 tons CO_2 year^{-1}.

Sawdust and palm kernel shell are by-products from wood and oil processing, respectively, these are produced in large quantities in Nigeria and are burnt directly as waste, creating environmental pollution into the atmosphere. Taking advantage of the energy potentials in biomass will help to meet part of the energy demand and assist in the socio-economic development of the end users (Joseph *et al.*, 2011). Generally, population and economic growth result in increase in the rate of energy consumed (Agbontalor, 2007). Biomass has been one of the main energy sources of mankind ever since the dawn of civilization, with about 14 per cent of the energy supplies worldwide (Anon, 2002; Syamsiro *et al.*, 2011). The global concerns for green environment has increased research on alternative sources of energy that are clean, available, affordable and sustainable for meeting energy demand. Biomass is one of the renewable energy resources, capable of replacing fossil fuels through a process known as gasification (Hassan *et al.*, 2011). The main applications of biomass are energy production and thermal applications (Yusof *et al.*, 2008).

Gasification is a Thermo-chemical process in which, chemical transformation occur along with conversion of energy. It is the production of combustible (synthetic) gases: CO, H_2, CO_2, H_2O and CH_4, from carbon-containing feedstock by the application of heat with limited air under intense pressure (Jenkins, 2008; Senapati, 2008; Babu, 2005). The complete gasification process consists of feeding, gasification, ash removal, heat recovery, gas clean-up, water treatment, utilization of combustible gas for electricity and heat generation and proper disposal of other by-products (Bridgwater, 2002). The gasification process occurs at temperatures between 600-1000 degrees Celsius and decomposes the complex hydrocarbons of wood (Rezaiyan and Cheremisinoff, 2005; Brown, 2005). When burning any biomass, various gases and vapour called “smoke” must be driven from solid fuel and then the smoke is burned. This initiates a series of reactions that produces a gaseous mixture composed primarily of carbon monoxide and hydrogen. This syngas can be burned directly or used as a starting point to manufacture fertilizers, pure hydrogen, methane or liquid transportation fuel (Jenkins, 2008).

A gasification reactor provides a method to provide gas-solid reactions in which a gas stream passes through a bed of particles. Gasifiers are viable alternative for producing heat and power with minimal adverse impact on the environment (Kumar *et al.*, 2008). The updraft fixed bed gasifier is the oldest form of gasifier and is still used for coal and biomass gasification (Brammer and Bridgwater, 2002; Lucas *et al.*, 2004; Ramana *et al.*, 2005). The Biomass is fed in at the top of the reactor and moves downwards as a result of the conversion of the biomass and the removal of ashes through a grate at the bottom of the reactor. The air intake is at the bottom and the gas leaves at the top. Air or oxygen and or steam are introduced below the grate and diffuse up through the bed of biomass and char. Complete combustion of char takes place at the bottom of the bed, liberating CO_2 and H_2O. These hot gases (~1000°C) pass through the bed above, where they are reduced to H_2O and CO and cooled to 750°C. Continuing up the reactor, the reducing gases (H_2 and CO) pyrolyze the descending dry biomass and finally dry the incoming wet biomass, leaving the reactor at low temperature (~500°C) (Reed and Siddhartha, 2001; Stultz and Kitto, 1992; Bridgwater and Evans, 1993). The updraft gasifier is also called a counter-flow gasifier. The major advantages of this type of gasifier are its simplicity, high biomass burn-out and internal heat exchange leading to low gas exit temperatures and high equipment efficiency, as well as the possibility of operation with many types of feedstock (sawdust, cereal hulls, etc.) (FAO, 1985).

This study examines the design, manufacture and performance test of a laboratory scale updraft gasifier, with sawdust and palm kernel shell as the feedstock and the biomass energy potentials.

THEORY OF GASIFICATION

The sequence of events occurring in the updraft gasifier are drying, pyrolysis and two distinct reactions namely oxidation and reduction.

Oxidation: Partial oxidation of wood fuel's carbon releases heat that helps feed the gasification reaction as shown in Eq. 1-4. The volatile products and some char produced are burned in a controlled manner to form CO_2 and CO in a process called oxidation as following:

Gasification oxidation reactions and change in enthalpy (Sun Grant Bioweb-gasification of biomass, Inayat *et al.*, 2010):

$$C + O_2 \rightleftharpoons CO_2, \qquad -394.4\,kJ\,mol^{-1} \tag{1}$$

$$C + H_2O \rightleftharpoons H_2 + CO, \qquad -131.4\,kJ\,mol^{-1} \tag{2}$$

$$H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O, \qquad -280.0\,kJ\,mol^{-1} \tag{3}$$

$$CO + \frac{1}{2}O_2 \rightleftharpoons CO_2, \qquad -251.0\,kJ\,mol^{-1} \tag{4}$$

where, ΔH is change in enthalpy.

Reduction: In the reduction stage, the carbon remaining in the char reacts with the CO_2 to produce CO and H_2, with some CH_4 which together are transformed to a gaseous mixture known as syngas. The high temperature in the gasifier converts the inorganic materials left behind by gasification and fuses them into a glassy material, generally referred to as slag. The slag has the consistency of coarse sand. It is chemically inert and may have a variety of uses in the construction and building industries. It is in this zone that the combustible gases are formed as following:

Gasification reduction reactions and change in enthalpy (Sun Grant Bioweb-gasification of biomass, Inayat *et al.*, 2010):

$$C + CO_2 \rightleftharpoons 2CO_2, \qquad -173.0\,kJ\,mol^{-1} \tag{5}$$

$$C + H_2O \rightleftharpoons H_2 + CO, \qquad -131.4\,kJ\,mol^{-1} \tag{6}$$

Equation 5 is known as the Boudouard reaction and Eq. 6 is the heterogeneous water-gas reaction. These reactions are related by the homogenous water-gas shift reaction:

$$CO_2 + H_2 \rightleftharpoons CO + H_2O, \qquad \Delta H = 18.2\frac{BTU}{lb-mol} \tag{7}$$

In addition, methane may be formed in the reduction zone by a variety of reactions, the simplest being:

$$C + 2H_2 \rightleftharpoons CH_4, \qquad \Delta H = -35.8 \frac{BTU}{lb-mol} \tag{8}$$

Studies have shown that there are a number of factors influencing the gasification reactions and influence the syngas composition and distribution these include the heat effect (Harris *et al.*, 2006; Scott *et al.*, 1988; Voloch *et al.*, 1983; Elliot and Sealock, 1985; Font *et al.*, 1988) temperature (Hobbs *et al.*, 1993), pressure (Nandi and Onischak, 1981; Plante *et al.*, 1988; Liinanki *et al.*, 1981; Richard *et al.*, 1985; McLendon *et al.*, 2004) and height of the reactor fuel bed (Font *et al.*, 1988; Beaumont and Schwob, 1984; Sadaka *et al.*, 1998), the air velocity (Raman *et al.*, 1981), the gasifying medium; the equivalent ratio (Schoeters *et al.*, 1989), the pressure of catalysts (Ergudenler and Ghaly, 1992) energy content, reactivity, bulk density, charring properties, size and size distribution, volatile matter and chemical composition (FAO, 1985) and the fuel moisture and particle (FAO, 1985; Elliot and Sealock, 1985; Raman *et al.*, 1981; Edrich *et al.*, 1985) and Ash content. Ash content is very important parameter that affects the composition and calorific value of the syngas (Iqbal *et al.*, 2010). Miskam *et al.* (2009) reported that the lower the ash content the better the producer gas.

Design of the updraft gasifier/reactor: The design of the updraft gasifier involves determining the amount of power needed to generate electricity, the amount of fuel to be supplied to the gasifier needed to meet the energy required for application. It computes the size of the combustion chamber in terms of diameter and height of the reactor. Others are the amount of air and the amount of draft needed to gasify the fuel. These are important information in the selection of the fan or blower needed for the reactor.

Combustion equation: The equations for the complete combustion of the products of gasification with oxygen are given below from the reduction reaction (Eastop and McConkey, 1993).

For the incomplete combustion:

$$C + H_2O \rightleftharpoons H_2 + CO$$

For complete combustion:

$$CO + H_2 + O_2 \rightleftharpoons CO_2 + H_2O$$

Since, the O_2 is supplied as air, the associated N_2 must appear in the equation (Eastop and McConkey, 1993) i.e.:

$$CO + H_2 + O_2 + \frac{79}{21} N_2 \rightleftharpoons CO_2 + H_2O + \frac{79}{21} N_2$$

$$O_2 \text{ required kg}^{-1} \text{ of fuel} = \frac{32}{28} = 1.143 \text{ kg}$$

$$\text{Stoichiometric A/F ratio} = \frac{1.143}{0.233} = 4.905/1$$

Table 1: Ultimate analysis of wood (Yinesor, 2008)

	Range of values	
Ultimate analysis	Lower	Higher
C	50	53.0
H	5.8	7.0
N	0	0.3
Cl	0.0001	0.1
O	38	44.0
S	0	0.1
Ash	0.1	2.0

The calorific value of wood fuel: Table 1 presented ultimate analysis of wood with lower and higher range values.

Lower calorific value (LCV) (Singh, 2008):

$$\text{LCV} = \text{Higher calorigic value} - \text{heat caried by vapour formed kg}^{-1} \text{ of fuel burned}$$

Lower calorific value from the lower values of the ultimate analysis of wood:

$$\text{LCV} = 19001.5 - \frac{9}{100} \times 5.8 \times 2442 \text{ kJ kg}^{-1} = 17726.776 \text{ kJ kg}^{-1}$$

Lower calorific value from the higher values of the ultimate analysis of wood:

$$\text{LCV} = 19001.5 - \frac{9}{100} \times 7.0 \times 2442 \text{ kJ kg}^{-1} = 19165.7 \text{ kJ kg}^{-1}$$

Higher calorific value (HCV) (Singh, 2008):

$$\text{HCV} = \frac{1}{100}\left[35000\text{C} + 143000\left(\text{H} - \frac{\text{O}}{8}\right) + 91605\right] \text{kJ kg}^{-1}$$

Higher calorific value from the lower values of the ultimate analysis of wood:

$$\text{HCV} = \frac{1}{100}\left[35000(50) + 143000\left(5.8 - \frac{38}{8}\right) + 9160\right] \text{kJ kg}^{-1} = 19001.5 \text{ kJ kg}^{-1}$$

Higher calorific value from the higher values of the ultimate analysis of wood:

$$\text{HCV} = \frac{1}{100}\left[35000(53) + 143000\left(7.0 - \frac{44}{8}\right) + 9160(0.1)\right] \text{kJ kg}^{-1} = 20704.16 \text{ kJ kg}^{-1}$$

Fuel consumption rate: The mechanical power of the laboratory scale updraft gasifier is 11.19 kW. The design of the gasifier components is based on the mechanical power and various factors taken into consideration, the fuel consumption rate is obtained with the following calculations.

This is the amount of fuel consumed per hour at a particular density of the fuel. From Eq. 1-4 the lower calorific value (19165.7 kJ kg^{-1}) obtained from the higher value of the ultimate analysis of wood is used to calculate the fuel consumption rate with 8.8 according to Yinesor (2008). For this gasifier, the thermal efficiency of the engine is taken as 70%. Then the Fuel Consumption Rate (FCR) is calculated as (Singh, 2008):

$$\text{FCR} = \dot{m}_f = \frac{\text{BP}}{\text{LCV}\times\eta\text{th}}$$

$$\text{FCR} = \dot{m}_f = \frac{11.19\times10^{3}\ \text{kJ sec}^{-1}}{19165.7\ \text{kJ kg}^{-1}\times0.7}\ \text{kg sec}^{-1} = 8.341\times10^{-4}\ \text{kg sec}^{-1} = 3.00\ \text{kg h}^{-1}$$

The updraft gasifier dimensions

Reactor diameter (D): This refers to the size of the reactor in terms of the diameter of the cross-section of the cylinder where the fuel is being burned. This is a function of the amount of the fuel consumed per unit time (FCR) to the Specific Gasification Rate (SGR) of the fuel ranging from 100-250 kg m^{-2}-h.

The reactor diameter is computed using the formula (Belonio, 2005):

$$\text{D} = \left(\frac{4\times\text{FCR}}{\text{SGR}\times\pi}\right)^{0.5}$$

Where:

$$\text{SGR} = \frac{\text{Weight of the wood fuel used (kg)}}{\text{Reactor area m}^2\times\text{operating time (h)}}$$

$$\text{D} = \left(\frac{4\times3.00\ \text{kg h}^{-1}}{100\ \text{kg m}^{-2}\text{–h}\times\pi}\right)^{0.5} = 0.195\ \text{m}\approx0.2\ \text{m}$$

The power output of the updraft gasifier is highly dependent on the diameter of the reactor. The bigger the diameter of the reactor, the more energy that can be released by the gasifier. This also means more fuel is expected to be burned per unit time since the gas production is a function of gasification rate in kg of fuel burned per unit time per unit area of the reactor (Belonio, 2005).

Height of the reactor: This refers to the total distance from the top and the bottom end of the reactor. This determines how long would the gasifier be operated in one loading of fuel. Basically, it is a function of a number of variables such as the required time to operate the gasifier (T), the specific gasification rate (SGR) and the density of the fuel.

As shown below, the height of the gasifier is computed using the formula (Belonio, 2005):

$$\text{H} = \frac{\text{SGR}\times\text{T}}{\rho_f}$$

For a desired operating time of the gasifier of 2.5 h, assuming the density of the fuel is 300 kg m^{-3} (Singh, 2008):

$$\text{The height of the reactor (H)} = \frac{(100\ \text{kg m}^{-2}-\text{h}\times 2\ \text{h})}{300\ \text{kg m}^{-3}} = 0.67 \approx 0.7\ \text{m}$$

The working height of the reactor is fixed 37.75% more in order to:

- Socket and plug
- Accommodate grate
- Provide space for ash collection at the bottom:

$$\text{H} = 1.3775\times 0.7\ \text{m} = 0.964.25\ \text{m}$$

The total height of the gasifier (from the top of the square plug) to the base of the ash collector is now taken as (H) = 964.25 mm.

The height of the fuel hopper (h_f):

- This is the distance from the top of the reactor to the top of the grate
- The height of the fuel hopper (h_f) = 0.7 m = 700 mm
- The height (h_f) is the same for both the inner and the outer fuel hopper
- The height of the ash container h_{ac} = 0.15 m

Time to consume the fuel: This refers to the total time required to completely gasify the fuel inside the reactor. This includes the time to ignite the fuel and the time to generate gas, plus the time to completely burn all the fuel in the reactor (Belonio, 2005). The density of the fuel (ρ_f), the volume of the reactor (V_r) and the Fuel Consumption Rate (FCR) are the factors used in determining the total time to consume the fuel in the reactor. This is computed using the formula (Belonio, 2005):

$$\text{T} = \frac{\rho_f \times V_r}{\text{FCR}}$$

Where:

$$\text{T} = \frac{300\ \text{kg m}^{-3}\times\pi\ (0.2\ \text{m})^2\times(0.7\ \text{m})}{4\times 3.00\ \text{kg h}^{-1}} = \frac{26.4}{12.00} = 2.2\ \text{h}$$

Amount of air needed for gasification-air flow rate (AFR): This refers to the rate of flow of air needed to gasify the fuel. This is very important in determining the size of the fan or of the blower needed for the reactor in gasifying the fuel. This can be simply determined using the rate of consumption of the fuel (FCR), the stoichiometric air of the fuel (SA), density of air (ρ_a) and the recommended equivalent ratio (ε) for gasifying wood fuel of 0.3-0.5. This is obtained using the formula (Belonio, 2005):

$$\text{AFR} = \frac{\varepsilon \times \text{FCR} \times \text{SA}}{\rho_a}$$

Where:

$$\text{AFR} = \frac{[0.3 \times (3.00 \text{ kg h}^{-1}) \times (4.905 \text{ kg air kg}^{-1} \text{ of fuel})]}{1.25 \text{ kg m}^{-3}} = 3.53 \text{ m}^3 \text{ h}^{-1}$$

Superficial air velocity (V_S): This refers to the speed of the air flow in the fuel bed. The velocity of air in the bed of the fuel will cause channel formation which may greatly affect gasification. The diameter of the reactor (D) and the Air Flow Rate (AFR) determine the superficial velocity of air in the gasifier. This is computed using the formula (Belonio, 2005):

$$V_S = \frac{\text{Air flow rate}}{\text{Area of the reactor}}$$

Where:

$$V_S = \frac{4 \times \text{AFR}}{\pi D^2} = \frac{4 \times 3.53 \text{ m}^3 \text{ h}^{-1}}{\pi \times (0.2 \text{ m})^2} = \frac{14.12}{0.126} = 112.06 \text{ m h}^{-1} = 3.11 \text{ cm sec}^{-1}$$

Resistance to air flow: This refers to the amount of resistance exerted by the fuel and by char inside the reactor during gasification. This is important in determining whether a fan or blower is needed for the reactor. The height of the fuel hopper (h_f) and the specific resistance (S_r) of the fuel which is 0.65 cm water per meter depth of fuel (Belonio, 2005):

$$R_f = h_f \times S_r$$

Where:

$$R_f = [0.75 \text{ m} \times 0.65 \text{ cm water m}^{-1} \text{ depth of fuel}] = 0.455 \text{ cm}$$

Determination of the thickness of insulation: The insulating material is fibre glass. Figure 1 shows the conduction and convection of heat flow through the gasifier walls, the suitable thickness and the location of the insulating material. The heat flow by conduction takes place between three layers of two different materials (the inner and outer mild steel and the fibre glass). The heat flow by convection takes place at the hot fluid inside the gasifier and the atmospheric condition. The heat is transferred from the hot fluid inside the fuel hopper to the external walls. Fibre glass is used because is a poor conductor of both heat and electricity and therefore useful for thermal insulation. This is to reduce the heat loss from the inner material of the fuel hopper to the outer material of the Mild Steel. The inner and outer temperatures have been chosen to represent the maximum temperature in the gasifier and atmospheric temperature, respectively.

Allowing 15% of the total power generated to be loss through the walls of the gasifier. Then, the allowable heat loss (Rajput, 2004):

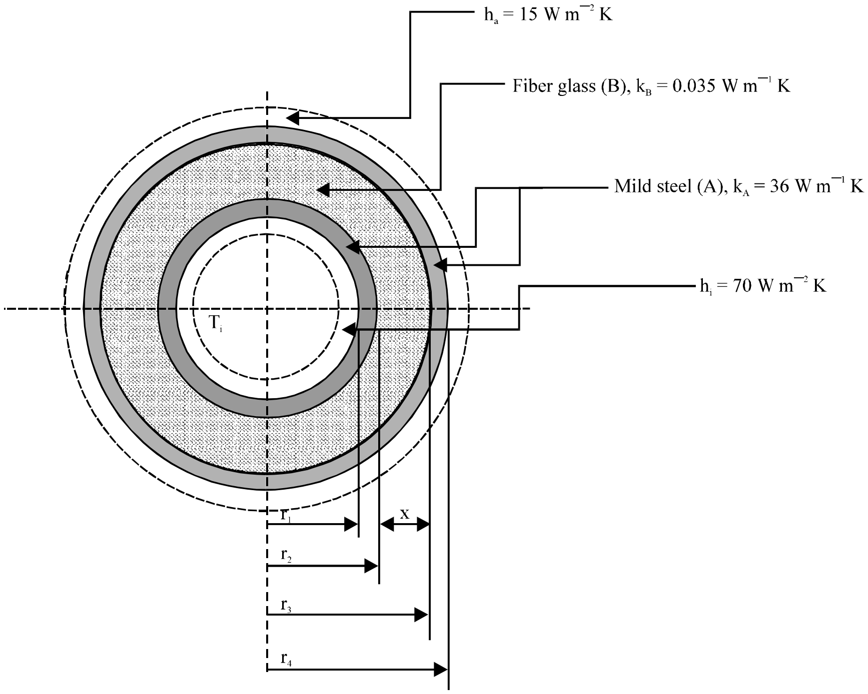

Fig. 1: Heat flow through the fuel hopper, r_1: Inner radius of the inner mild steel = 0.10 m, r_2: Outer radius of the inner mild steel = $(r_1+0.002)$ m = (0.0+0.002) m = 0.102 m, r_3: Inner radius of the outer mild steel = (r_2+x) m = (0.102+x) m, r_4: Outer radius of the outer mild steel = $(r_3+0.002)$ m = (0.102+0.002+x) = (0.104+x) m, x: Minimum thickness of insulation (m), L: Height of the reactor, θ_i: Maximum temperature in the gasifier = 700°C and θ_a: Atmospheric temperature = 30°C. The following values were extracted from [36]: h_1; Heat transfer coefficient of the synthetic gas = 70 W m^{-2} K, h_a: Heat transfer coefficient of atmospheric air = 15 W m^{-2} K, k_A: Thermal conductivity of mild steel = k_A = 36 W m^{-2} K and k_B: Thermal conductivity of fiber glass = 0.035 W m^{-2} K

$$Q_L = 0.15\times 11.19\times 10^3 = 1698.5 \text{ W}$$

Where:

$$QL = \frac{\ln\left(\frac{0.102+x}{0.102}\right)}{0.035} + \frac{\ln\left(\frac{0.104+x}{0.102+x}\right)}{36} + \frac{1}{15(0.104+x)} = 1.76 - 0.143 = 1.61$$

Performance calculation

Fuel consumption rate (FCR): This is the amount of fuel used in operating the gasifier divided by the operating time. This is computed using the formula (Belonio, 2005):

$$FCR = \frac{\text{Weight of the fuel used (kg)}}{\text{Operating time (h)}}$$

Specific gasification rate (SGR): This is the amount of fuel used per unit time per unit area of the reactor. This is computed using the formula (Belonio, 2005):

$$\mathrm{SGR} = \frac{\text{Weight of the fuel used (kg)}}{\text{Reactor area m}^2 \times \text{operating time}}$$

$$\mathrm{SGR} = \frac{\text{Weight of the fuel}}{\frac{\pi D^2}{4} \times T_o}$$

Combustion zone rate (CZR): This is the time required for the combustion zone to move down the reactor. This is computed using the formula (Belonio, 2005):

$$\mathrm{CZR} = \frac{\text{Length of the reactor (m)}}{\text{Operating time (h)}}$$

Heat energy input: This is the amount of heat energy available in the fuel. This is computed using the formula (Belonio, 2005):

$$\mathrm{QF} = \mathrm{WFU} \times \mathrm{HVF}$$

Power input: This is the amount of energy supplied to the gasifier based on the amount of fuel consumed. This is computed using the formula (Belonio, 2005):

$$\mathrm{P1} = \mathrm{FCR} \times \mathrm{HVF}$$

Thermal efficiency: ηth = 70% (as used in the design).

Power output: This is the amount of energy released by the gasifier. This is computed using the formula (Belonio, 2005):

$$\mathrm{P0} = \mathrm{FCR} \times \mathrm{HVT} \times \mathrm{TE}$$

Percentage char produced: This is the ratio of the amount of char produced to the amount of fuel used. This can be computed using the formula (Belonio, 2005):

$$\%\mathrm{Char} = \frac{\text{Weight of the char produced (kg)}}{\text{Weight of the sawdust used (kg)}}$$

Gasifier efficiency:

$$\eta_g = \frac{\mathrm{HVH} \times \rho_g \times Q_g}{\mathrm{LHV} \times \dot{m}_f} \times 100\%$$

Drawing of the updraft gasifier: Figure 2 shows the two dimensional projection views of the laboratory scale updraft gasifier (all dimensions in millimeter). This was drawn using Autodesk Inventor 2010.

Preliminary test and evaluation: Sawdust and palm kernel shells were used as the feedstock for testing the performance of the of the manufactured updraft gasifier as in Fig. 3. Figure 3 shows the picture of the fabricated laboratory scale updraft gasifier.

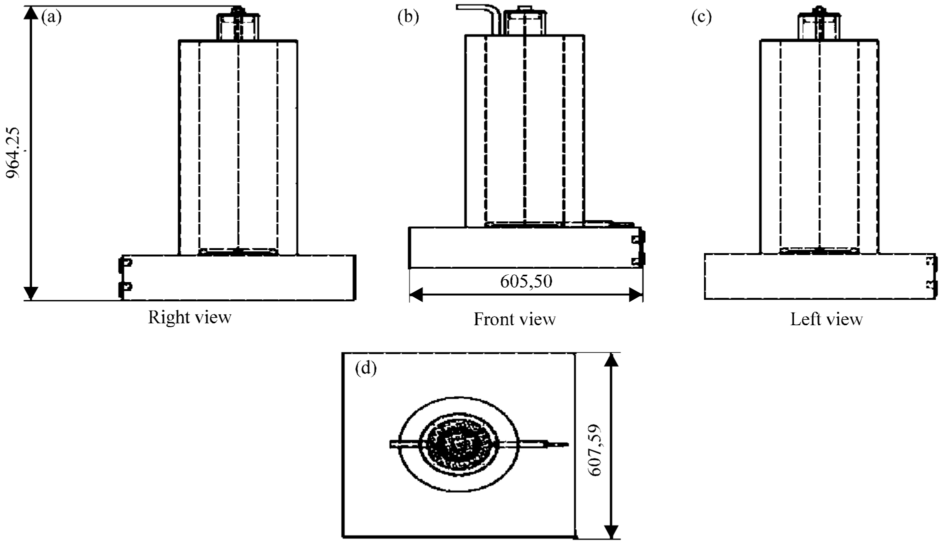

Fig. 2(a-d): Projection views of the laboratory scale biomass gasifier, (a) Right, (b) Front, (c) Left and (d) Plan view

Fig. 3: The fabricated laboratory scale updraft gasifier

Proximate analysis of the feedstock: Proximate analysis was carried out based on (FAO, 1985) to determine the following important properties of the feedstock. They are moisture content, volatile content (when heated to 600°C), the free carbon remaining at that point, the ash (mineral) in the sample and the High Heating Value (HHV) based on the complete combustion of the sample to carbon dioxide and liquid water. (The low heating value, LHV, gives the heat released when the hydrogen is burned to gaseous water, corresponding to most heating applications and can be calculated from the HHV and H_2 fraction).

The quality of the fuels (saw dust and palm kernel shell) was tested following the America Society for Testing Materials. These tests included: Moisture content, volatile and fixed carbon and ash content.

Determination of the moisture content of the feedstock: The heating value of the gas produced by any type of gasifier depends at least in part on the moisture content of the feedstock.

Moisture content can be determined on a dry basis as well as on a wet basis (FAO, 1986; Miskam *et al.*, 2009).

Accurately measured 1 g of each of the fuel (saw dust and palm kernel shell) samples was measured and dried in an electric oven at a temperature of 105°C for one hour (Koledzi *et al.*, 2011).

The moisture content of the sawdust on the wet basis is defined as:

$$\text{MC}_{\text{dry}}\ (\%) = \frac{\text{W}_{\text{sb}} - \text{W}_{\text{sa}}}{\text{W}_{\text{sb}}} \times 100 = \frac{1 - 0.89\ \text{g}}{1\ \text{g}} \times 100 = 11$$

The moisture content of the sawdust on the dry basis is defined as:

$$\text{MC}_{\text{dry}}\ (\%) = \frac{100 \times \text{MC}_{\text{wet}}}{100 + \text{MC}_{\text{wet}}} = \frac{100 \times 11}{100 + 11} = 9.9$$

The moisture content of the palm kernel shell on dry basis was obtained as follows:

$$\text{MC}_{\text{dry}}\ (\%) = \frac{\text{W}_{\text{pb}} - \text{W}_{\text{pa}}}{\text{W}_{\text{pa}}} \times 100 = \frac{1 - 0.89\ \text{g}}{0.89\ \text{g}} \times 100 = 12$$

The moisture content of the palm kernel shell on the wet basis is defined as:

$$\text{MC}_{\text{wet}}\ (\%) = \frac{100 \times \text{MC}_{\text{dry}}}{100 + \text{MC}_{\text{dry}}} = \frac{100 \times 12}{100 + 12} = 10.7$$

According to FAO (1985), high moisture contents reduce the thermal efficiency since heat is used to drive off the water and consequently this energy is not available for the reduction reactions and for converting thermal energy into chemical bound energy in the gas. Therefore high moisture contents result in low gas heating values. When the gas is used for direct combustion purposes, low heating values can be tolerated and the use of feedstocks with moisture contents (dry basis) of up to 40-50% is feasible, especially when using updraft gasifiers.

Determination of the volatile matter content of the fuels: The fuel samples were crushed to powdered form, 1 g of each of the crushed samples was place in different porcelain crucibles. They were each covered with a lid with little opening left and placed on hot plates at a temperature of 500-600°C to drive off the volatiles. The heating continued until the flame coming out through the holes have ceased. This indicates that all volatile matter has been driven off. After this, the weight of each of the heated samples was taken:

- The volatile content of the sawdust = W_{sb}-W_{sa} = 1 g-0.18 g = 1.82 g
- Percentage of the volatility for sawdust = W_{sb}-W_{sa}/W_{sb} = 0.82 g/1 g = 82% volatile matter by weight
- The volatile content of the palm kernel shell = W_{pb}-W_{pa} = 1-0.45 g = 0.55 g
- Percentage of the volatility for palm kernel shell = W_{pb}-W_{pa}/W_{pb} = 0.45 g/1 g = 55% volatile matter by weight

Determination of the ash content: The ash content test of the fuel samples was carried out by crushing the samples and accurately weighed 1 g in a porcelain crucible with a lid. The samples were heated to temperature of 500-600°C on an hot plate. After two hours, the weight of the samples was taken and given as follows:

$$\text{The ash content of the sawdust (\%)} = 100 - \frac{\text{Initial weight of the sewdust} - \text{weight afer combustion}}{\text{Initial weight of the sawdust}} \times 100 = 100 - \frac{1 - 0.04\text{ g}}{1\text{ g}} \times 100 = 4$$

$$\text{The ash content of the palm kernel shell (\%)} = 100 - \frac{\text{Initialweight of palm kernel shell} - \text{Weight afer combustion}}{\text{Initial weight of thepalm kernel shell}} \times 100$$

$$= 100 - \frac{1 - 0.30\text{ g}}{1\text{ g}} \times 100 = 30 \text{ after 2 h of combustion}$$

According to FAO (1986), ashes can cause a variety of problems particularly in up or downdraught gasifiers. Slagging or clinker formation in the reactor, caused by melting and agglomeration of ashes, at the best will greatly add to the amount of labour required to operate the gasifier. If no special measures are taken, slagging can lead to excessive tar formation and/or complete blocking of the reactor. A worst case is the possibility of air-channelling which can lead to a risk of explosion, especially in updraft gasifiers.

Determination of the fixed carbon: The value of the fixed carbon is calculated as follows:

$$\text{C (\%)} = 100\text{-(\%moisture+\%volatility+\%ash)}$$

For the sawdust:

$$\text{C (\%)} = 100\text{-}(9.9+82\text{-}4) = 4$$

For the palm kernel shell:

$$\text{C (\%)} = 100\text{-}(12+55+30) = 3$$

Ultimate analysis of the produced synthetic gases: The "ultimate analysis" gives the composition of the sawdust and palm kernel shell in wt.% of carbon, hydrogen and oxygen (the major components) as well as sulphur and nitrogen. The expressions by Nowling (2000) are used for the analysis.

The sawdust:

- Calculation of the percent fixed carbon on a dry, mineral-matter-free basis:

$$\text{DMMFFC (\%)} = \frac{\text{FC}}{\text{FC} + \text{VOL}} \times 100 = \frac{4}{4 + 82} \times 100 = 4.65$$

- Calculation of the percentage volatile matter on dry, mineral-matter basis:

$$\text{DMMFVOL } (\%) = \frac{\text{VOL}}{\text{FC}+\text{VOL}}\times 100 = \frac{82}{4+82}\times 100 = 95.35$$

- Calculation of the weight percent of carbon in the fuel:

$$\text{C } (\%) = \frac{[(\text{DMMFFC} + 0.9\ (\text{DMMFVOL} - 14)\times(\text{VOL}\times\text{FC})]}{100} = 66.964$$

- Calculation of the weight percent of nitrogen in the fuel:

$$\text{N}_2\,(\%) = \frac{[(2.1 - 0.012\times\text{DMMFVOL})\times(\text{VOL}\times\text{FC})]}{100} = 0.822$$

- Calculation of the weight percent hydrogen in the fuel:

$$\text{H}_2\,(\%) = \frac{\left\lfloor\left(\frac{\text{DMMFVOL}\times 7.35}{\text{DMMFVOL}+10}\right) - 0.013\times(\text{VOL}\times\text{FC})\right\rfloor}{100} = 5.71$$

- Calculation of the weight percent of oxygen in the fuel:

$$0_2\ (\%) = 100 - \text{Ash} - \text{S} - \text{H}_2 - \text{C} - \text{Moisture} - \text{N}_2 = 12.6041$$

For the palm kernel shell:

- Calculation of the percent fixed carbon on a dry, mineral-matter-free basis:

$$\text{DMMFFC } (\%) = \frac{\text{FC}}{\text{FC}+\text{VOL}}\times 100 = \frac{82}{4+82}\times 100 = 95.35$$

- Calculation of the percentage volatile matter on dry, mineral-matter basis:

$$\text{DMMFVOL } (\%) = \frac{\text{VOL}}{\text{FC}+\text{VOL}}\times 100 = \frac{55}{3+55}\times 100 = 94.83$$

- Calculation of the weight percent of carbon in the fuel:

$$\text{C } (\%) = \frac{[(\text{DMMFFC} + 0.9(\text{DMMFVOL} - 14)\times\text{VOL}\times\text{FC})]}{100} = 45.19$$

- Calculation of the weight percent of nitrogen in the fuel:

$$\text{N}_2\ (\%) = \frac{[(2.1 - 0.012\times\text{DMMFVOL})\times(\text{VOL}\times\text{FC})]}{100}\ 0.558$$

- Calculation of the weight percent hydrogen in the fuel:

$$H_2\ (\%) = \frac{\left[\left(\left(\frac{\text{DMMFVOL} \times 7.35}{\text{DMMFVOL} + 10}\right) - 0.013\right) \times (\text{VOL} \times \text{FC})\right]}{100} = 3.85$$

- Calculation of the weight percent of oxygen in the fuel:

$$O_2\ (\%) = 100 - \text{Ash} - \text{S} - H_2 - \text{C} - \text{Moisture} - N_2 \quad 8.402$$

RESULTS AND DISCUSSION

Proximate analysis of the feedstock: The results of the proximate analysis carried out on the properties of the feedstock (sawdust and palm kernel shell) are presented in Table 2. This analysis gives the suitability of the feedstock for use in a particular application, this includes moisture content, volatile content, the fixed carbon and ash content in the both the sawdust and palm kernel shell. The two feedstocks considered have very low moisture content and ash content. The moisture content of the feedstock was reduced by sun drying to obtain a high gasification temperature which results in the high energy values obtained. The results reveal the abundant biomass energy potentials available in the feedstock considered.

Ultimate analysis of the feedstock: The results of the ultimate analysis carried out on the properties of the feedstock (sawdust and palm kernel shell) and the heating values as obtained from (Singh, 2008) are presented in Table 3. The ultimate gives the weight percentage of carbon, hydrogen, nitrogen, oxygen and sulphur. The results of the ultimate analysis were used to obtain both higher and lower heating values of the two biomasses considered. These heating values show the abundant energy potentials in the feedstock for various applications as heating and small scale power generation.

Table 2: The laboratory proximate analysis of 1 g of each of the fuel samples

Proximate analysis	Sawdust	Palm kernel shell
Volatile matter (%)	82.0	55
Fixed carbon (%)	4.0	3
Ash (%)	4.0	30
Moisture content (%)	9.9	12

Table 3: The ultimate analysis of the fuel samples

Ultimate analysis	Sawdust	Palm kernel shell
Carbon (%)	66.964	45.190
Hydrogen (%)	5.710	3.850
Nitrogen (%)	0.822	0.558
Oxygen (%)	12.604	8.402
Sulphur (%)	0.000	0.000
Higher heating value (MJ kg^{-1})	23.400	15.800
Lower heating value (MJ kg^{-1})	22.200	15.000

Table 4: The weight of the sawdust used for the test

	Weight of sawdust (kg)			
Item	1	2	3	Total
Weight	0.4	0.4	0.4	1.2

Table 5: Temperature readings (saw dust)

		Temperature (°C)				
S. No.	Time (min)	Oxidation (T_1)	Reduction (T_2)	Pyrolysis (T_3)	Drying (T_4)	Syngas (T_5)
1	0	35	35	35	35	35
2	3	44	52	69	84	39
3	10	109	83	75	62	85
4	23	470	192	161	209	83
5	30	473	194	179	209	120
6	37	475	196	162	193	103
7	43	376	198	154	177	99
8	52	448	189	142	171	100
9	58	600	336	240	300	157
10	63	685	391	236	294	252
11	69	629	360	228	222	279
12	73	486	422	223	272	209
13	81	476	364	224	278	218

Results of the performance test carried out on the updraft gasifier: The quantities of both sawdust and palm kernel shell fed into the gasifier during the performance testing are shown in Table 4 and 6. At the beginning of the test after fire has been introduced into the reactor, white smoke was observed to be emitted, the gasifier started to produce a brown smoke which in the indication of the combustible gases been formed. During this time, the brown smoke was ignited, gradually; the production of the combustible gases began to be noticed through the production of yellow flame at the outlet of the gasifier at about 23 and 28 min for the sawdust and palm kernel shell, respectively and continued until the experiment lasted. The colour of the produced flame indicating the production of synthetic gases and the energy content in sawdust correspond to the tests that were carried by Yinesor (2008) and Belonio (2005) on wood chips and the energy content in the palm kernel shell is close the work of Azali *et al.* (2005).

Results of the test parameters for sawdust:

- Start-up Time = T_S = 21 min
- Operating time = T_0 = 60 min
- Total operating time = T_{to} = T_S+T_0 = 21+60 min = 1.35 h

The temperature readings obtained from the experiment conducted on the suitability of Sawdust for gasification is shown in Table 5. These values were obtained from the five different thermocouples inserted at the oxidation, reduction, pyrolysis, drying and syngas zones in the gasifier. The highest temperature reading of 685°C with sawdust as the feedstock was obtained in the oxidation zone.

The graph of the temperature distribution in the gasifier with sawdust as fuel against time is plotted in.

Table 6: Weight of the sawdust used

	Weight of palm kernel shell (kg)			
Item	1	2	3	Total
Weight	1	1	0	2

Table 7: Temperature readings (palm kernel shell)

		Temperature °C				
S/N	Time (mins)	Oxidation (T_1)	Reduction (T_2)	Pyrolysis (T_3)	Drying (T_4)	Syngas (T_5)
1	0	36	36	36	36	36
2	5	250	420	251	328	93
3	17	323	403	273	361	144
4	28	438	447	281	383	135
5	36	334	390	285	351	159
6	41	283	344	243	319	158
7	47	379	324	208	266	129
8	52	403	302	196	248	131
9	57	723	329	199	249	91
10	64	525	298	235	232	98
11	73	360	310	250	262	99

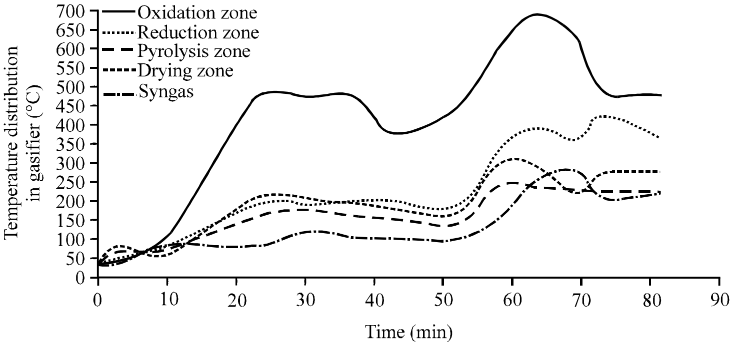

Fig. 4: Temperature distribution graph in the gasifier against time (when gasifying sawdust)

Performance calculation for palm kernel shell:

- Start-up time = 28 min
- Operating time = 45 min
- Total operating time = $T_{to} = T_S+T_0$ = 28+45 min = 1 h, 1.3 min

The temperature readings obtained from the experiment conducted on the suitability of Palm kernel shell for gasification is shown in Table 7. These values were obtained from the five different thermocouples inserted at the oxidation, reduction, pyrolysis, drying and syngas zones in the gasifier. The highest temperature reading of 723°C with sawdust as the feedstock was obtained in the oxidation zone.

Figure 4 and 5 illustrate temperature distribution during the gasifier's performance test operation. The highest temperatures obtained during the operation of the gasifier were found to be closer to the designed temperature. This indicates the suitability of the insulation thickness used for the fuel hopper.

Table 8: Summary of the experimental and performance of the gasifier with the fuel samples

Parameters	Units	Sawdust	Palm kernel
Start-up time	Min	21	28
Operating time	Min	60	45
Total operating time	Min	81	73
Weight of fuel consumed	kg	1.2	2
Fuel consumption rate	kg h^{-1}	1.2	2.67
Specific gasification rate	kg mW^{-2}-h	38.2	84.88
Combustion zone rate	m h^{-1}	0.7	0.93
Heat energy input	kJ	28,125	31633.06
Power input	kW	7.812	8.79
Power output	kW	5.47	6.15
Thermal efficiency	%	70	70
Gasifier efficiency	%	93.0	63.4
Percentage of char produced	%	4.2	20
Maximum temperature in the gasifier	°C	685	723

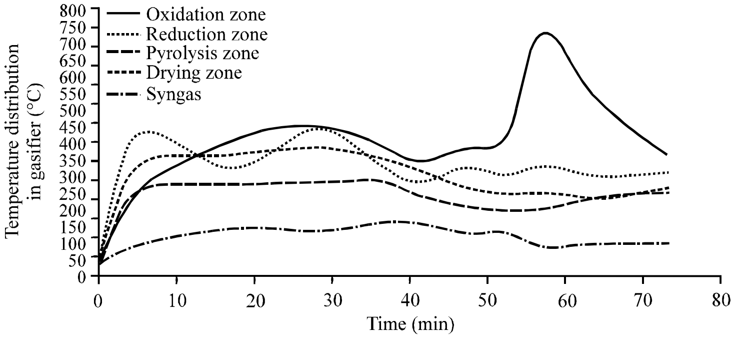

Fig. 5: Temperature distribution graph in the gasifier against time (when gasifying palm kernel shell)

Result of the experimental and performance: The performance result of the laboratory scale updraft gasifier for the two carbon containing feedstock (sawdust and palm kernel shell) considered is summarized in Table 8.

CONCLUSION

A 11.19 kW capacity thermal power consumption laboratory scale updraft gasifier was designed, fabricated and tested in this study with readily available materials for sawdust and palm kernel shell as feedstock. The gasifier volume is designed to hold enough biomass with density of 300 kg m^{-1} to run for at least 2.2 h without refuelling. The height of the fuel hopper is at a distance of 0.7 m above the grate. The proximate and ultimate analyses of these fuels are obtained from the test carried out. The synthetic gases were noticed to be produced after igniting the gases. A yellow flame was observed indicating the production of these combustible gases. Ash was also produced during the gasification process. From the test carried out on the fuel samples, the production of the combustible gases in the 1.2 kg of sawdust lasted 60 min while in 2 kg of palm kernel shell, the synthetic gases lasted 45 min. The results of the both the proximate and ultimate analysis carried out indicate that higher and lower heating value of both the sawdust and the palm kernel shell are 23.4, 22.2, 15.8 and 15.0 MJ kg^{-1}, respectively. There is enormous energy content in the feedstock under study, available to be used for meeting the present energy challenges. This technology should be further supported and encouraged to be used in the domestic and industrial operations where combustion is needed.

NOMENCLATURE

LCV = Lower calorific value (kJ kg^{-1})
HCV = Higher calorific value (kJ kg^{-1})
HHV = Higher heating value (kJ kg^{-1})
m_N = Mass of water vapour formed per kg of fuel burned
C, H, O, S = Percentages of carbon, hydrogen, oxygen and sulphur, respectively
FCR = Fuel consumption rate (kg h^{-1})
D = Diameter of the reactor (m)
SGR = Specific gasification rate (kg h^{-1})
H = Height of the reactor (m)
T = Operating time of gasifier (h)
h_f = Height of the fuel hopper (m)
h_{as} = Height of the ash container (m)
V_r = Volume of the reactor (m^3)
AFR = Air flow rate (m^3 h^{-1})
SA = Stoichiometric air-fuel ratio
V_S = Superficial velocity
R_S = Resistance to air flow,
S_R = Specific resistance
r = Radius
h = Heat transfer coefficient (W m^{-2} K)
k = Thermal conductivity (W m^{-1} K)
x = Thickness of insulation (m)
CZR = Combustion zone rate (m h^{-1})
QF = Heat energy input (kJ)
PI = Power input (kW)
PO = Power output (kW)
WFU = Weight of fuel used in the gasifier (kg)
W_{sb} = Weight of the sawdust before drying in the oven (g)
W_{pb} = Weight of the palm kernel shell before drying in the oven (g)
W_{sb} = Weight of the sawdust after drying in the oven (g)
W_{pa} = Weight of the palm kernel shell after drying in the oven (g)
FC = Fixed carbon, from fuel analysis (% by weight)
VOL = Volatile matter, from fuel analysis, (% by weight)
DMMFFC = Dry mineral matter free fixed carbon (% weight)
N_2 = Elemental carbon in the fuel (% by weight)
H_2 = Elemental hydrogen in the fuel (% by weight)
O_2 = Elemental oxygen in the fuel (% by weight)

Greek symbol

η = Efficiency
ρ = Density

ε = Equivalent ratio
θ = Temperature (°C)

Subscript

w = Water
f = Fuel
th = Thermal
ac = Ash container
a = Air
r = Reactor
s = Superficial
i = Synthetic gas
A = Mild steel
B = Fibre glass
g = Gasifier

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