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Development of a Natural Cross Draft Gasifier Stove for Application in Rural Communities in Sub-Saharan Africa

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ABSTRACT

The study was to develop a natural cross draft gasifier stove for application in rural households and to determine the performance of the stove using rice husk briquette and also test the emission properties of the stove. The moisture content of the rice briquette was 8.5% on wet basis. The heat of combustion was 15641.4 kJ kg^{-1}. The efficiency of the stove was tested using Water Boiling Tests (WBT). The efficiency was 20.75 and 21.47% for high power cold start and high power hot start, respectively, which are the minimum and maximum efficiency of the stove. The average efficiency of the stove was 21.10%. The ignition duration and time required to boil 1.5 kg of water were 5.1 min for cold start test and 4.5 min for hot start test. The output power of the stove was observed to be range of 8.95-10.64 kW. The CO_2 and CO emission was 6.5 and 5.1 g L^{-1}. The Particulate Matter (PM) quantity was 3.02 g L^{-1}. The results are near standards and modification can be done to improve stove efficiency.

Key words: Gasifier, stove, briquettes, rice husk, rural communities

INTRODUCTION

Energy intervention, sustainability, availability and utilization are the driving force for urbanization and economic growth. Chum and Overend (2001) noted that in future our energy system will be derived from renewable and sustainable energy sources which are effective in cost and usage (Yusof *et al*., 2008). Energy plays a major role in the production of goods and services in the transport, agriculture, health and education sectors. The Nigeria Demographic Health Survey (NPC., 2013) contains information about household environment and energy which entails access to electricity and clean cooking. To improve health and economic power of rural dwellers, there is need to increase energy availability and sustainability which is part of the MDG 7. Increasing energy access especially in the area of household cooking has a direct impact to reduction of poverty. Rural cooking energy sources which is mainly from wood cause indoor pollution which can be hazardous and can cause cancer or related respiratory problems (NPC., 2013). The cooking methods utilized in most rural communities in Nigeria are not efficient and also contributes to increased household pollution. There are other major replacements for fuel wood as an energy source for household cooking. According to federal ministry of power and steel, animal waste availability is estimated to be 61 million t $year^{-1}$ and crop residue amounts to 8.3 million t $year^{-1}$ in Nigeria (Federal Ministry of Power and Steel Nigeria, 2006). Drawing from Federal Ministry of Power and Steel Nigeria (2006) solid fuels efficiently combusted should play an important role in making up for energy needs of rural communities in Nigeria. Therefore, the problem identified in this study is the non-availability of efficient cooking technology that reduces exposure to indoor pollution and indirectly reduces the propensity/incidence of cancer. This work is importance as Nigeria needs alternative energy sources that are environmentally friendly at reduced cost.

According to Pantuhan (2011), traditional wood stoves demanding larger logs, cause health problems and also air pollution, while gasifier stove is ideally suitable to burn fuels having smaller sizes. According to Kumar *et al*. (2008) gasifier stoves are viable alternative for producing heat and power with minimal adverse impact on the environment. Biomass gasification means incomplete combustion of biomass resulting in production of combustible gases consisting of carbon monoxide (CO), hydrogen (H_2) and traces of methane (CH_4) (Panwar, 2009). These fuels sources include wood chips, agricultural waste, forest residue, pellets etc. Gasifier stove utilizes combusting smoke, which gives control over combustion rate, hence minimize fuel consumption and realize clean combustion (Hassan *et al*., 2011). This mixture is called producer gas. The production of generator gas (producer gas) called gasification, is partial combustion of solid fuel (biomass) and takes place at temperatures ranging 600-1000°C (Rezaiyan and Cheremisinoff, 2005). The reactor is called a gasifier. Thus the key to gasifier design is to create conditions such that biomass is reduced to charcoal and charcoal is converted at suitable temperature to produce CO and H_2 (Sun *et al*., 2009). Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are: drying of fuel, pyrolysis (a process in which tar and other volatiles are driven off), combustion and reduction (Inayat *et al*., 2010). According to Gordillo and Belghit (2011), the design of a gasifier stove is based on energy requirement. Three types of gasifiers namely up-draft, down-draft and cross-draft are available as design options. Cross-draft gasifier is more efficient when compared to up-draft and down-draft as it has very fast response time to load, flexible gas production duration and short design height (Kumar *et al*., 2009). Solid fuels used for gasifiers range from rice husk, wood chips, charcoal, maize cob, sawdust and coal, thus forming the basis for this study. The major objective of the work was to design, construct and test the performance of a natural cross draft gasifier stove and determine emission properties of the gasifier using a local rice husk (Adani rice).

MATERIALS AND METHODS

Design theory

Reactor diameter: This refers to the size of the reactor in terms of the diameter of the cross-section of the cylinder where briquettes are being burned and is a function of the amount of the fuel consumed per unit time (FCR) to the Specific Gasification Rate (SGR) of briquette, which is in the range of 100-210 or 5-130 kg m^{-2} h^{-1} as revealed by the results of several test on gasifier stoves. The reactor diameter can be computed using the formula (Belonio, 2005):

$$D = \left(\frac{1.27 \times FCR}{SGR}\right)^{0.5} \tag{1}$$

Where:
D = Diameter of reactor (m)
FCR = Fuel consumption rate (kg h^{-1})
SGR = Specific gasification rate of rice husk briquette, 100-210 kg m^{-2} h^{-1} (Bryden *et al*., 2005)

For a rice husk briquette gasifier stove with a required fuel consumption rate of 3 kg h^{-1}, the computed diameter for the fuel reactor using specific gasification rate of 160 kg m^{-2} h^{-1} will be:

$$D = \left(\frac{1.27 \times 3}{160}\right)^{0.5} = 0.195 \text{ m or } 19.5 \text{ cm}$$

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 stove be operated in on 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 rice husks briquette (ρ). The height the reactor can be computed using the formula (Belonio, 2005):

$$H = \frac{SGR \times T}{\rho} \tag{2}$$

Where:
H = Length of the reactor (m)
SGR = Specific gasification rate of rice husk briquette (kg m^{-2} h^{-1})
T = Time required to consume rice husk (h)
ρ = Rice husk briquette density (kg m^{-3})

If the desired operating time for the gasifier stove is 1 h and rice husk briquette density is 460 kg m^{-3} or 0.46 g cm^{-3}, Then the gasifier height will be:

H = [(100 kg m^{-2} h^{-1}×1 h)/460 kg m^{-3}] = 0.217 m or 21.7 cm
H = Length of the reactor = 22 cm

The engineering drawing of the cross-draft gasifier is shown in Fig. 1-3.

Materials dimension: The reaction chamber outside wall is made of 2 mm thick mild steel sheet and fabricated over an L-angle frame of outside dimensions 36×36×44 cm. The inside wall is a slotted mild steel cylinder with a refine clay placed in-between the two walls. The fuel chamber is made of 2 mm thick mild steel sheet and is located above the reaction chamber. Biomass briquettes from the fuel chamber enter into the reaction chamber by gravity. The primary air inlet is made of 2 mm thick mild steel sheet and is attached on one side of the reaction chamber. To reduce heat losses, the surfaces above and below the secondary air holes are insulated with refine clay and clad with a 1 mm thick Galvanized Iron (GI)

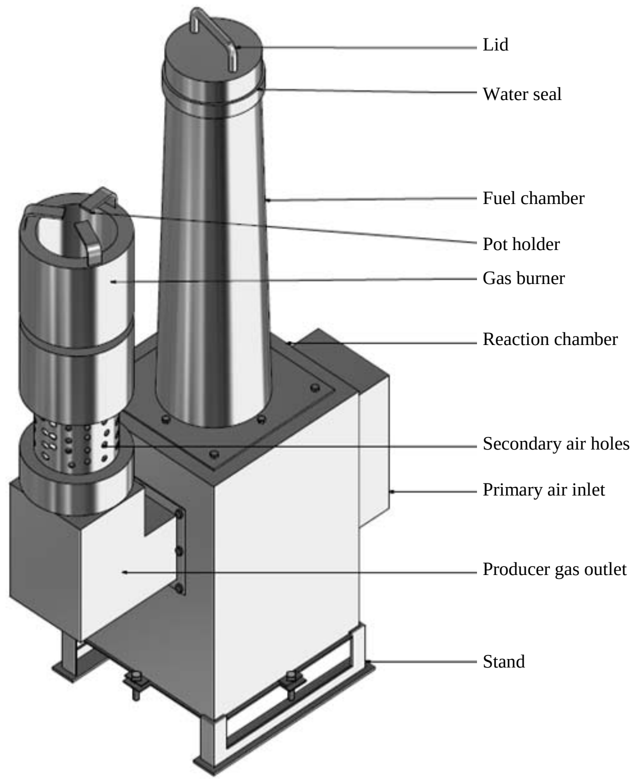

Fig. 1: 3-dimensional view of the cross-draft gasifier

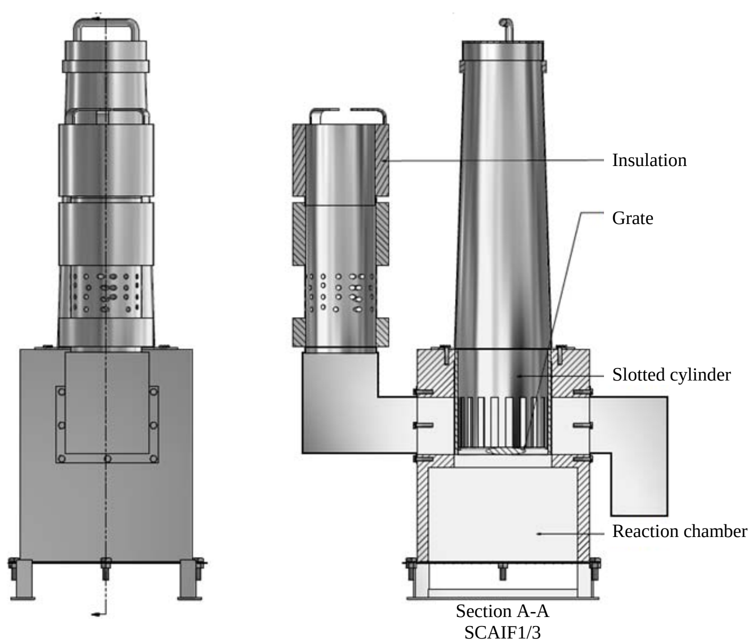

Fig. 2: Sectional view of the cross-draft gasifier stove

sheet. The top 1 cm of the burner pipe is left un-insulated so that it can fit into the pot support which will be placed over it. Asbestos gaskets are used while assembling the individual components together. Three gaskets, of size 30×30, 23.5×17.5 and 23×17 cm (outer dimensions), are used for connecting the fuel chamber, primary air inlet and the gas burner, respectively

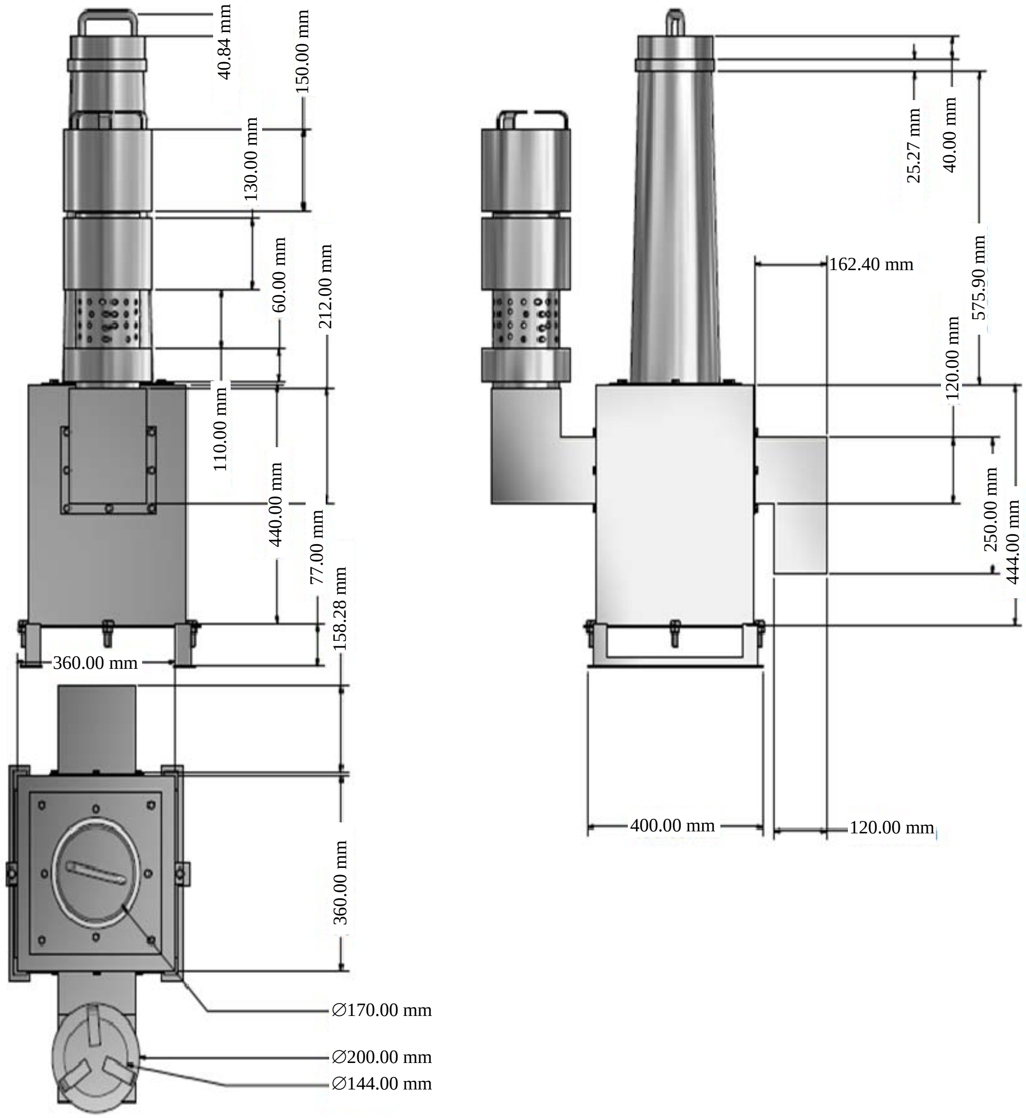

Fig. 3: First angle projection of the cross-draft gasifier stove

to the reaction chamber. A fourth gasket, of size 26×26 cm is used to connect the two parts of the gas burner together.

The fuels used for the rice husk were rice husk briquettes and saw dust briquettes which were highly available. The briquettes were made from a locally fabricated screw briquetting machine at the Department of Agricultural and Bioresources Engineering, University of Nigeria. The briquettes were reduce to experimental size of 25.4-38 cm. Fuel is first loaded in the fuel hopper and the lid is closed. Water is filled in the water seal. The fuel is then ignited from below the grate using a flame torch introduced through the ash pit door. About 5 min later, the torch is removed and the ash pit door is bolted. The stove warms up slowly and it takes about 15 min to generate combustible gas at the gas burner side. The gas is then ignited in the gas burner by introducing a flame through the secondary air holes in the burner. Once the gas gets ignited, its flow becomes smooth. The stove can operate continuously until the fuel in the fuel chamber is used up. Additional fuel can be loaded through the top of the fuel chamber to further extend its operation. The sample of the briquettes used is shown in Fig. 4.

Evaluation of the gasifier stove: The stove was evaluated using combustion property of briquette, water boiling test, thermal efficiency specific fuel consumption, power output, burning rate, degree of stove efficiency and emission properties. The combustion property of the biomass briquettes used for the testing of the stove was determined by the using a bomb calorimeter (state the part number and location).

Fig. 4: Fuels used in the gasifier stove (rice husk briquette)

The water boiling test method is comprised of "High power test with cold start, high power test with hot start and simmering test. Simmering test involves the quantifying of the amount of fuel required to keep a measured amount of water just below boiling point for about 45 min (Bailis et *al*., 2007). This step simulates the long cooking of legumes. The material used for the water boiling test include pot, water, fuel (rice husk briquette), weighing balance, thermometer, stopwatch, measuring cylinder, hand glove and lighter.

The data collected during the water boiling test was used in determining percentage heat utilized which was calculated using Eq. 3 (Belonio, 2005):

$$PHU = \frac{mv\ Cp(Tb - To) + mcl}{mf \times Ef} \times 100 \quad (3)$$

Where:
PHU = Percentage heat utilized
mw = Mass of water in the pot (kg)
Cp = Specific heat of water ($kJ\ kg^{-1}$°C)
To = Initial temperature of water (°C)
Tb = Boiling temperature of the water (°C)
mf = Mass of fuel burnt (kg)
Ef = Calorific value of the fuel ($kJ\ kg^{-1}$)
mc = Mass of water evaporated (kg)
L = Latent heat of evaporation ($kJ\ kg^{-1}$)

Power output determines the available amount of energy released from the fuel in a given time. It was calculated using Eq. 4 (Belonio, 2005):

$$p = \frac{mf \times Ef}{t} \quad (4)$$

Where:
p = Power output
mf = Mass of fuel burnt (kg)
Ef = Calorific value of the fuel ($kJ\ kg^{-1}$)
t = Time taken to burn fuel (sec)

Specific fuel consumption: Is defined as the amount of solid fuel equivalent used in achieving a defined task divided by the weight of the task and was calculated using Eq. 5 (Belonio, 2005):

$$SFC = \frac{mf}{mc} \quad (5)$$

Where:
SFC = Specific fuel consumption
mc = Mass of water evaporated (kg)
mf = Mass of fuel burnt (kg)

Burning rate determines the rate at which a certain mass of fuel is combusted in air. It was evaluated using:

$$BR = \frac{mf}{t} \quad (6)$$

Where:
BR = Burning rate
mf = Mass of fuel burnt (kg)
t = Time taken to burn fuel (sec)

Stove efficiency: The Eindhoven formula was employed to determine the degree of stove efficiency. Water-boiling tests were conducted to measure the efficiency of the gasifier stove and only rice husk briquette is used for this test. A known quantity of water was taken in both the pots, which were then placed on the gasifier stove. The quantity of fuel consumed the amount of water evaporated and initial and final temperatures during a test run were used to calculate the efficiency.

The Eq. 7 express efficiency (nf) of stoves as:

$$nf = \frac{MwCp(Tb - To)}{Mf \times Ef} \times 100 \quad (7)$$

Where:
nf = Stove efficiency
Mw = Initial mass of water in the pot kg
Mf = Mass of water evaporated during the experiment (kg)
Cp = Specific heat capacity of water ($kJ\ kg^{-1}$ °C)
To = Initial temperature of water (°C)
Tb = Final temperature of water (°C)
L = Latent heat of vaporization of water ($kJ\ kg^{-1}$)
Ef = Calorific value of fuel ($kJ\ kg^{-1}$)
Mc = Mass of water evaporated (kg)

Emission test: The emission test was carried out using Aprovecho IAP meter for emission test. The IAP meter has the following specifications: Carbon Monoxide Sensor, Type: Electrochemical cell, range: 0-1000 ppm, repeatability: 2%, resolution: 1 ppm, response time: T90 = 30 sec. Particulate Matter Sensor, Type: Red laser scattering photometer, range: 0-60,000 ug m^{-3}, resolution 25 ug m^{-3}, response time: 1 sec. According to Jetter and Keriher (2009), emissions from cook stoves contribute to pollution and cancer related diseases increasing worldwide. They further analyzed the emissions of selected cook stoves and compared with United States Environmental Protection Agency (EPA) standards.

RESULTS AND DISCUSSION

The available biomaterial for testing the gasifier stove was rice-husk briquette. The properties of the briquette as determined are shown in Table 1. These properties contribute to the combustion rate of the fuel, especially the heating value of the fuel which is shown to be 15641.4 kJ kg^{-1}. The results of the cold start test for the gasifier stove are shown in Table 2. The calculated Percentage Heat Utilized (PHU), power output (kW), specific fuel consumption, burning rate (kg h^{-1}) and stove efficiency under cold start scenario are 20.72, 8.95, 1.16, 2.81 and 20.72, respectively. The results of the hot start test for the gasifier stove are shown in Table 3. The calculated Percentage Heat Utilized (PHU), power output (kW), specific fuel consumption, burning rate (kg h^{-1}) and stove efficiency under hot start scenario are 21.47, 10.64, 1.09, 3.35, 21.47, respectively. Figure 5 shows the rate of increase in temperature with respect to time for the cold start and hot start test. It is observed that the water start boiling at 4.5 min at temperature of 100°C for hot start. It is observed that the water start boiling at 5.1 min at temperature of 100°C for cold start test. Figure 6-9 show a pictorial view of the gasifier at the stage of construction, the briquettes used and the testing. The CO_2 and CO average emission was 6.5 and 5.1 g L^{-1}, respectively for cold start and hot start scenario, as against United States Environmental Protection Agency (EPA) standard of 5 g L^{-1} for eco stoves. The Particulate Matter (PM) quantity was 3.02 g L^{-1} as against EPA standard of 4.5 g L^{-1}. Chawdhury and Mahkamov (2011) reported percentage heat utilization, power output (kW) and stove efficiency value of 33.21, 10.45 and 60.2, respectively for woodchip fired downdraft gasifier which was higher than the present work's value of 20.72. This difference may be attributed to difference in biomass used as woodchips would have higher heat of combustion than rice husk. MacCarty *et al*. (2010) reported percentage heat utilized and stove efficiency value of 15.71 and 18.2 for a cross draft gasifier stove utilizing maize straw as biomass source. This value was lower than the values reported in this work and suggests that the designed stove for this study was within performance range. Ojolo *et al*. (2012) reported a high efficiency of 76 for producer gas type down draft gasifier which was used for powering a diesel engine. A proper comparison may not exist with the work reported by Ojolo *et al.* (2012) due to the fact that it was not a cook stove. Baredar *et al.* (2013) reported a percentage heat utilized, specific heat consumption, power output (kW), burning rate (kg h^{-1}) and stove efficiency value of 20.4, 9.2, 0.98, 3.35, 21.1%, respectively. These values were close to the ones reported in this study due to the fact that the biomass utilized was rice husk and therefore validated the work as having much significance. Azam *et al*. (2007) reported a specific heat consumption of 8.9 for a cross draft gasifier stove built for laboratory scale study. Inference made from all of the reported

Table 1: Result of rice husk briquette properties

Parameters	Values
Lower heating value (kJ kg^{-1})	11444.37
Higher heating value (kJ kg^{-1})	19838.40
Ash content (%)	20.20
Volatile matter (%)	71.40
Moisture content (%)	8.70
Fixed carbon (%)	5.40
Binding ratio (%)	0% mass of binder to fuel mass

Table 2: Properties of the gasifier stove under high power test with cold start

Parameters measured	Values
Cp = Specific heat of water (kJ kg^{-1} °C)	4.187
To = Initial temperature of water (°C)	28
Tb = Boiling temperature of the water (°C)	100
mf = Mass of fuel burnt (kg)	1.1
Ef = Calorific value of the fuel (kJ kg^{-1})	11444.37
mc = Mass of water evaporated (kg)	0.95
L = Latent heat of evaporation (kJ kg^{-1})	2270
t = Time taken to burn fuel (sec)	1407
mw = Mass of water in the pot (kg)	1.5
T = Ignition time (min)	18
Mass of fuel (kg)	2.5
Mass of ash (kg)	1.4
Mass of pot without lid (kg)	0.9
PHU = Percentage heat utilized (%)	20.72
p = Power output (kW)	8.95
SFC = Specific fuel consumption	1.16
BR = Burning rate (kg h^{-1})	2.81
nf = Stove efficiency (%)	20.72

Table 3: Properties of the gasifier stove under high power test with hot start

Parameters measured	Values
Cp = Specific heat of water (kJ kg^{-1} °C)	4.187
To = Initial temperature of water (°C)	28
Tb = Boiling temperature of the water (°C)	100
mf = Mass of fuel burnt (kg)	1.2
Ef = Calorific value of the fuel (kJ kg^{-1})	11444.37
mc = Mass of water evaporated (kg)	1.1
L = Latent heat of evaporation (kJ kg^{-1})	2270
t = Time taken to burn fuel (sec)	1290
mw = Mass of water in the pot (kg)	1.5
T = Ignition time (min)	14.5
Mass of fuel (kg)	2.5
Mass of ash (kg)	1.3
Mass of pot without lid (kg)	0.9
PHU = Percentage heat utilized (%)	21.47
p = Power output (kW)	10.64
SFC = Specific fuel consumption	1.09
BR = Burning rate (kg h^{-1})	3.35
nf = Stove efficiency (%)	21.47

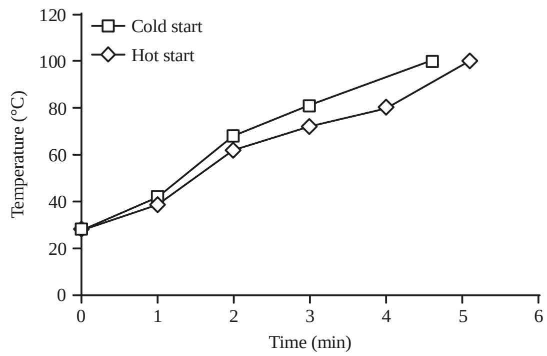

Fig. 5: Temperature change with time for high power cold start and hot start

Fig. 6: Gasifier stove under construction

Fig. 7: Finished gasifier stove without pot stand

Fig. 8: Gasifier stove under water boiling taste

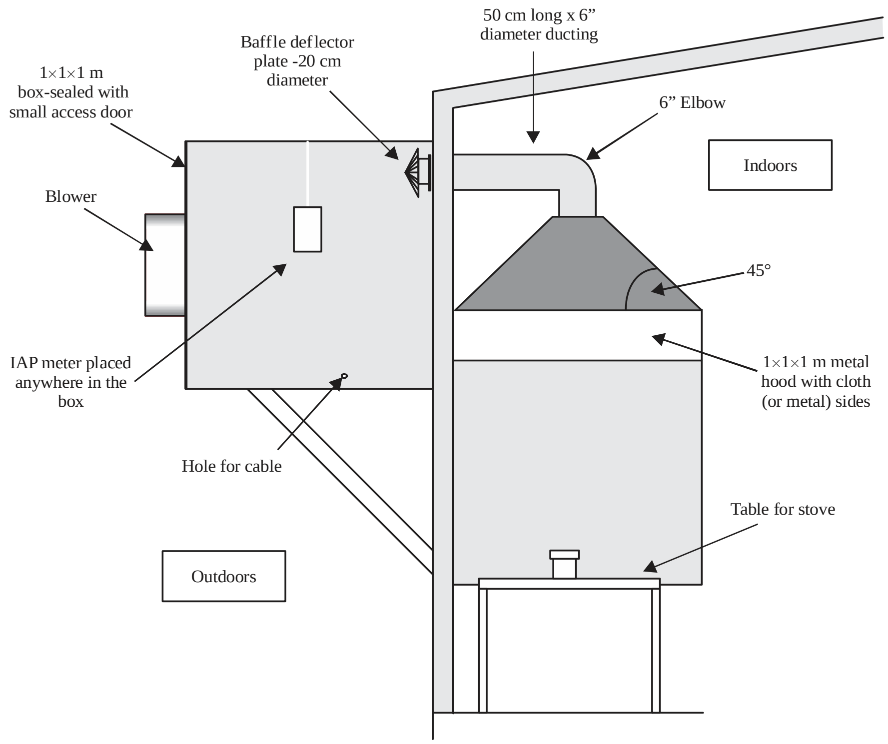

Fig. 9: IAP-in-a-box setup (source: www.aprovecho.org)

works that the characteristics of a down draft gasifier stove is different from that of the down draft and consequently varies with the type of biomass utilized. This was the major reasons for the variation notice. It was also deduced that no gasifier stove have the same properties.

CONCLUSION

The following are the conclusions drawn from this study:

- The Cross-draft gasifier stove was developed and tested
- The heating value of the rice husk used in testing the gasifier was 15641.4 kJ kg^{-1}
- The average Percentage Heat Utilized (PHU) was 21.095%
- The average power output was 9.795 kW which is significant for cross draft gasifier
- The average specific fuel consumption rate (SFC) and average burning rate were 1.125 and 3.08 kg h^{-1}
- The average stove efficiency was 21.11% which was within the range or gasifier stoves

In general, the developed stove will assist in improving the cooking conditions around the rural house holds in the South-East part of Nigeria with potential for adoption across Sub-Saharan Africa. The emission properties can be improved to meet United States Environmental Protection Agency (EPA) standards.

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