A Rice Husk Fired Biomass Stove for Cooking, Water and Space Heating

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Abstract: Rice husk, a major by-product of the rice-milling industries, accounts for 20% by weight of rice paddy and is abundantly available in the rice processing industries. This potential energy source is usually burnt off in many rice industries to create space by farms that are in dire need of thermal energy for airand water heating as well asfor electricity generation.

A simple energy efficient rice husk fired stove was developed for space and water heating as well as for cooking.The stove consisted of three closed concentric cast iron cylinders with the innermost being the combustion chamber that supplies heat directly onto a cooking cast iron plate. Waste heat from the innermost cylinder is extracted from the second cylinder using a forced convection 12 volt powered compressor and transferred to the heating space. A stainless steel heat exchanger brings in cold water into the combustion chamber and conveys warm water away from the stove to a storage tank. The outermost cylinder is heavily lagged to prevent heat losses. Rice husk is introduced into the innermost cylinder through a rectangular supply port that has a cover. The inner most cylinder has a grate under for ash exit and anexhaust pipe for smoke exit;

Preliminary tests indicated that complete combustion of 1 kg of rice husk with calorific value of 12.6 MJ in the furnace of the stove took 30 minutes.The heat transfer through the cooking plate, the heat exchanger by water and air were 25513.33 J/s, 11486.45 J/s, and 10235.32 J/s respectively. Over 140g of the rice husk supplied 1.75 MJ of heat to the 3 sections. The maximum temperature reached in the furnace was 556.5 °C. The temperatures of the hot air and water from the stove rose up 116.5 °C and 105°C respectively. The burning rate of the husk in the furnace was 1.6 kg/hr. No pre-mechanical treatment of rice husk is required for the stove to function properly.

Keywords; *Biomass stoves, rice husk, water heating, space heating, agricultural waste.*

I. INTRODUCTION

Access to energy plays a key role in economic development and welfare throughout the world. Technological improvement has contributed in laying the foundation for today's society, industries and transportation growth (Vattenfall, 2011). It was estimated that about 2.6 billion of the world population in 2015 relied on biomass fuels. Without new policies, the number is expected to increase to 2.7 billion by 2030 due to population growth (Pongsak, 2015). IEA (2014), reported that the energy demand in sub-Saharan Africa grew by 45 % from 2000 to 2012. In sub-Saharan Africa, the lack of modern energy sources is a call for concern. The rapid increase in the population is complicating the situation, with poor or no maintenance of the existing energy infrastructures.

In Cameroon, the major energy sources include fuel wood, hydropower and petroleum. There are reserves of oil and natural gas. The annual production of petroleum products has gradually fallen. In 1999, the output was 100,000 barrels per and dropped to 76,600 barrels per day in 2001 (Nfor, 2011). Cameroon currently relies heavily on hydropower for its energy. AES SONEL generated 3,685 GWh electrical energy in 2009, from 435 MW of thermal and hydropower (Nfor, 2011). The completion of the LomPangar hydroelectric station will add 200 MW to the existing MW power (Tangka*et al*., 2016). In Cameroon 90 % of population use traditional solid fuels such as fuel-wood and charcoal in residential sector for heating, light and cooking (IREA, 2013). The highly used fuel is contributing greatly to deforestation and causing serious problems to the ecosystem (destruction of natural habitat). The inefficient use of the biomass has caused many respiratory and ophthalmological diseases to the users (Tangka*et al*., 2016). The present energy situation of many developing countries calls for need for alternative sources to complement the little available conventional sources.Most of these alternatives are cheap, affordable and environmental friendly compared with fossil fuels (Tangka*et al*., 2016). Cameroon has the third largest biomass potential in sub-Saharan Africa (IREA, 2013). Biomass forms the dominant source of energy accounting for 66.7 % of the total national energy consumption (Nfor, 2011). If modern and efficient technologies are used in this sector, it will greatly improve the living standards of the population.The country is known for its vast agricultural production. The processing of these agricultural products has left agro-industries with large quantity of residues. The residues are potential sources of energy that can be valorised. Rice processing produces rice husk as residue in rice mills.

According to MINADER (2009), 100 000 tonnes of rice were produced on 44000 ha in Cameroon in 2008. The paddy production has increased by 23 % annually, i.e. from 68 000 tons in 2007 to 194 000 tons in 2013 (Akoa*et al*., 2016). When the rice is milled, 20 % of weight is the rice husk (Islam and Mondal, 2013). So at the rice mills lay these husks, which provide large quantity of biomass that can be used as an energy source. In some countries like India, Bangledesh, etc, the rice husks are used to generate electricity (Sadrul and Ahiduzzaman, 2013). Due to the availability of large quantities at any given location, rice husks can be put to use for comparatively larger energy applications, like generation of steam for process heating applications and cooking. The combustion temperature of rice husk can reach 800-1000 ℃, making it a good furnace combustion material (Sheng and Mins, 2015).

The main objective of this research was to design and develop a prototype of a simple rice husk fired stove for cooking, space and water heating. It was intended that there should be no pre mechanical treatment of the rice husk such as densification, briquetting or pelleting. This would ease the exploitation of this waste material for energy use as soon as it is developed in the rice mill.

II. MATERIALS AND METHODS

A. The Design of the System

The cooking surface was made of a cast iron plate.The energy required to heat the metal at the temperature that can be used for cooking was determined using the Equation 2.1 (Nelkon, and Parker,1988). The same equation was used to determine the energy that will be required to heat water and air.

$$Q = mcp(\Delta T) \quad (2.1)$$

Where:

- Q = the heat required (J);
- m = mass of the cooking plate or water or air to be heated (kg);
- cp = specific heat capacity of the metal plate or water or air ($kJkg^{-1}$ $°C^{-1}$)and
- ΔT = change in temperature °C.

The heat losses in the stove were assumed to be 50 % of the heat required. The losses were then determined and added to the total energy to give the final energy required to heat the metal plate of the stove, heat one litter of water and warm the volume of air in the system. Table 2.1 shows the design parameters and the assumption made during the design.

The furnace conducts the heat released from combustion by conduction. The air takes up the heat by convection. The equations of thermal conduction and convection were used to calculate the heat transferred by the furnace and air respectively.

Table 2.1: Design of components of the Rice husk fired biomass stove for cooking, water and room heating

Purpose	Parameter	Value	Assumption
Cooking surface	Heat required Q_c (J)	1.12 MJ	Initial temperature =22^{o}C, Final temperature = 200^{o}C, Mass of metal= 13.5 Kg
Water heating	heat needed Q_w (J)	0.22MJ	Initial temperature = 18^{o}C, Final temperature= 70 ^{o}C Mass = 1 kg
Air heating	Heat required Q_a (J)	0.0002MJ	Initial temperature= 15 ^{o}C Final temperature= 40^{o}C Mass 0.017kg Air volume air chamber 0.02 m^3
Insulation	Heat flux by Conduction (W/m2)	1.5 W/m2	Temperature 200 K = 42
	Heat flux by radiation (W/m2)	0.024 W/m2	Temperature 200 σ = 5.6704* 10-8 (Stefan-Boltzmann constant)
	Thickness (m)	0.04 m	ε is in the range 0.3 - 0.5 J Milicaet al., (2010)

From Table 2.1 the heat required will be the heat energy that a system or a substance needs to change the initial temperature to the final temperature. Thesum of all the heat required was evaluated at 1.14MJ. Considering losses from the system to be 50 %, which account for 0.57 MJ. The total heat required for the whole system was evaluated at 1.71 MJ. Assuming the minimum heat of combustion or the calorific value of rice husk to 12.6 MJ (Sheng and Mins, 2015), the quantity of husk that can supply the required heat was determined. The value obtained was 0.14kg;

The bulk density of rice husk was used to determine the volume to be occupied by 1 kg of the husk. The equation 2.2 was used to estimate the volume of the feed stock and this gave a value of 0.008m3. With this volume, different variations of the diameters of furnace were done. The diameter 30 cm gave a height 12 cm. It was based on these two values that the dimensions of the stove were made.

$$\rho_b = \frac{(W1-W2)}{V} \quad (2.2)$$

Where:

ρ_b= The bulk density of the sample (g/cm^3)
W 2 = the weight of the container and sample (g)
W 1 = the weight of the container (g)
V = the volume of the container (cm^3)

Transfer of heat rate through the design system

The transmission of heat through the metal plate by conduction was determined with the conduction equation 2.3 (Fourier's law). The water in the pipe takes up heat by convection. The Equation 2.3 was used to determine the heat transfer through the galvanized pipe. Equation 2.4 was then used to determine the energy flow through the water.

$$\text{For a rectangular surface,} q = k\frac{A}{\Delta x}(\Delta T), \quad (2.3)$$

$$\text{And for a cylindrical surface } q = \frac{2\pi kL(\Delta T)}{\ln(\frac{r_o}{r_i})} \quad (2.4)$$

Where;

q = the thermal energy (W)
k is the thermal conductivity (W/m °C)
A = the area, (m^2)
T_1-T_2 = the temperature difference (^{o}C)
x= the thickness of the wall (m)
L = length of pipe (m)
r_o = outside radius (m)
r_i = inside radius (m)

The cooking platewas made of cast iron with k-value of 43 Wm^{-1} $°C^{-1}$, thickness 2.4 cm (0.024m). The area A is 0.08m^2. The flow of heat through the cooking plate was computed with the conduction equation as in 2.3

$$q = 25.51 \text{ kW}$$

The pipe is galvanized with k-value = 52 Wm^{-1} $°C^{-1}$.

Length of pipe (L) = 0.45 m, Inside radius (r_i) = 0.001 m, Outside radius (r_o) = 0.013 m..Heat loss through the section of the pipe was assumed to be zero because of the thin section. A conservative temperature (200°C) of the furnace was used. Applying equation 2.4 gives

$$Q = 11486.45 \text{ W}$$

The rate of heat transfer through the pipe is 11486.45 J/s. The energy made available to water was then estimated at 11.49 kW. The water transfer heat at the rate 10235.32J/s.

The selection of the materials used in the fabrication

The selection of materials used in the fabrication of the heating surfaces, was made based on their thermophysical properties. This material would withstand temperatures of up to 1000 °C or the potential rice hush fired furnace temperature. The second property taken into consideration was the thermal conductivity (K-values) of the materials.

The design of the insulation system

The following equations as used by Milica*et al.*, (2010), were used to design the insulation system;

Fourier's law,

$$q_{1\to2\ cond}\,(T_1, T_2) = k(T_1, T_2)\frac{T_1 - T_2}{d} \qquad (2.5)$$

$$k(T_1, T_2) = k\frac{T_1 - T_2}{2} \qquad (2.6)$$

Where

$q_{1\to2cond}$ = heat flux due to conduction (W/m^2)
k = thermal conductivity (W/m°C)
d = thickness of the material (m)
T_1- T_2 or T = change in temperature (°C)
Stefan-Boltzmann law and Kirchhoff's law

$$q_{1\to2\ rad}\,(T) = \sigma\frac{T}{\frac{1}{\varepsilon}-1} \qquad (2.7)$$

where

$q_{1\to2rad}$ heat flux due to radiation ((W/m^2)
T = temperature (°C)
σ = 5.6704* 10^{-8} (Stefan-Boltzmann constant)
ε = emittance from the air heating container (mild steel)

Dimensions of the stove

The stove was drawn and dimensioned using AutoCAD. Figure 3shows the representation of the cross sectional view of furnace and air chamber.

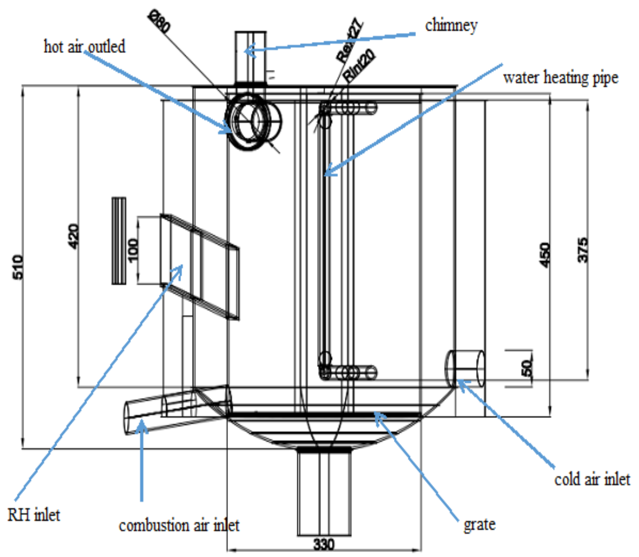

Figure 3.3: cross sectional view offurnace and air chamber

B. Fabrication of Stove

Combustion furnace and its components

The combustion furnace was made up of a cylindrical can opened at the two ends. It was 45 cm in height and with the diameter 33 cm. The volume of the furnace was calculated using the equation 3.5

$$C_v = \pi r^2 h \qquad (3.5)$$

Where

C_v = combustion chamber volume;
r = radius of furnace;
h = height of furnace; and
Cv = 38468.93 cm^3 ≈ 0.038 m^3

This furnace was then incorporated with the water heater. A hole with diameter (Φ) 4 cm was drilled on the furnace. Two other holes with diameter as the external diameter of the bent pipe (water heater) were also drilled on the can. An inlet 10 x 10 cm was cut on the furnace which isused for feeding the rice husk into the furnace. The grate was formed from a mild steel sheet (0.2 cm thick) and its diameter was that of the combustion furnace (33 cm).

The cooking plate was made up of cast iron with the thickness of 2.4 cm and the diameter 32.5 cm. A chimney was coupled on it,to facilitate smoke exit.

The air heating container

The air-heating chamber was made up of a cylindrical drum. The same holes of the same sizes as on the furnace were drilled on the the drum. Two more holes were drilled on the tank for the cold and hot air with the diameter 4 and 6 cm respectively. A hole with diameter 8 cm was drilled at the bottom for the ash outlet. The angle of repose of rice husk and the right-angled theorem were used to calculate the angle of inclination rice husk supply inlet. The volume of air container was determined to be 0.56 m^3. By subtracting the volume of the combustion chamber (0.038 m^3), the volume of the air chamber was found to be 0.018 m^3. The mass of this volume of air is 0.02 kg (Ajay *et al.*, 2012).

The different parts of the heater were joinedby welding them together. The space between the furnace and the air-heating container formed the air-heating chamber. The water heating pipe was then fitted through the holes that were drilled on both the can and the tank. Four pieces of metal sheets 13 x 10 cm were welded at the rice husk supply inlet.

The cooking surface was welded on the top of the combustion chamber. The cover of the air chamber was fitted at its position.

Mounting the fan and the water control system

A 60W, 12 volts DC centrifugal fan was used. The fan was mounted at the inlet of cold air into the air chamber. At the exit of hot air, a muff was mounted. A 12 volts battery which supply powered to the fan was used. The battery was charged using a solar panel of 17 volts.

A support stand was made with angled bars to support the water reservoir. The stand was mounted on three legs of the stove by the use of two bracket angled bars. The reservoir was a home water heater tank. Two pipes (for cold and hot water) were connected from the reservoir to the heater. A valve was fitted at the water excite end of the heating pipe. A long pipe was mounted on the pipe supplying hot water to the tank. Two valves were mounted on the cold water pipe to control water circulation into the tank and water heater.

The fitting of the insulator

The protective layer was first made from aluminium sheet of height 45 cm. Holes were cut on the sheet to to make way for the pipes and rice husk inlet on the container. The insulating material used was the polystyrene foam. The polystyrene foam was chosen because of high R- and low K- value and because of it availability in the local market. The foam of 3cm thickness was fitted between the air-heating container and the protective layer.

Determination the moisture content MC of the rice husk.

MC of the rice husk was determined by using the standard oven drying method. Test sample of 21 g was kept for 2 hrs in a hot electric oven maintained at 105ºC. After 2 hours, the sample was removed from the oven. It was placed in a desiccator for cooling. After cooling, the weight of the sample was taken andthe MC was determined using equation 2

$$MC = \frac{WW - DW}{WW} * 100 \qquad (2)$$

Where:
MC = The moisture content wet bassis (%)
WW = The wet weight of the sample and dish (g)
DW = The dry weight of the sample and dish (g)

Test of the Heating Systems

The combustion behavior of the stove

The mass of rice husk used to observe the behaviour of the stove during combustion was 500 g. The fire was set using some waste papers. The fan was put on to activate the fire and to blow the heat in the air chamber as shown in fig 1.

Measuring temperature changes in the stove

Two different tests were carried out

- The first measurement was the combustion rate of a kg of rice husk in the furnace.
- The second test was done with variation in the quantity of the rice husk burnt

The temperature being an indispensible parameter of heat transfer, it was measured using and electronic thermometerof mark GENEQ Inc with a range of -200^{o}C – 1370 ^{o}C. The thermocouples had long sensors, which were inserted in different points of the system to measure the temperature. The temperatures of the water, the furnace, the cooking surface and the air were measured and the data analysed. The burning rate, R, corrected for the moisture content of the fuel was calculated using:

$$R = \frac{100(Wi - Wf)}{t(100 - M)}$$

Where: R = burning rate (kghr^{-1})
Wi= initial weight of fuel at start of test, kg;
Wf= final weight of fuel at end of test, kg;
M = moisture content of fuel, %;
t = total time taking for burning fuel, s.

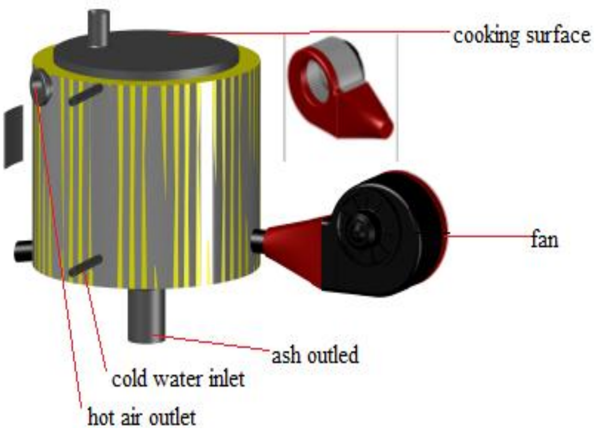

Fig 1. Operational diagram of the rice husk fired stove.

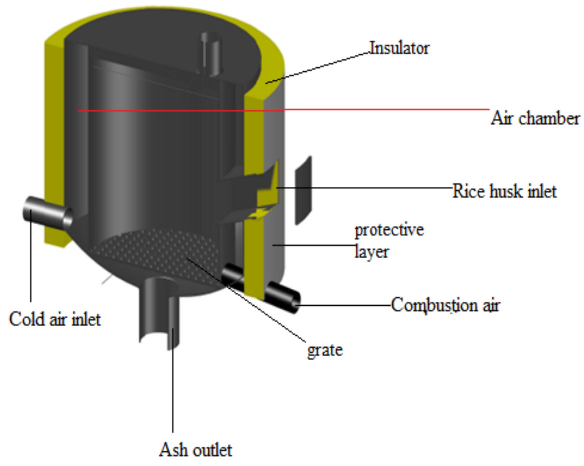

Fig. 2 the vertical cross section of the stove

Fig 3 Complete assembled rice husk fired stove

III. RESULTS AND DISCUSSIONS

The Energy flux in the stove

The total heat required in the system was 1.71 MJ.The quantity of rice husk to supply the heat required was 0.14 kg. The heat transfer rate through the cooking surface of the stove was 25513.33 J/s.The rate of heat transfer through the pipe is 11486.45 J/s. The energy made available to water will be 11.49 kW. The water transfer heat at the rate 10235.32J/s.The heat flux was found to be 1.8 W/m^2. The thickness of the insulator is 4 cm. When the temperature of a system was 200 °C, the insulator emittance factor was 0.3. This is in line with the findings of Milica*et al.*, (2010).

Presentation of the system of the stove and function

The heat exchanger in the furnace transfer heat by conduction and permitted the heating of water. The tank's support stand had a height higher than the stove. This enhancedthe flow of from the tank into the heater by gravity. The heated water left the stove through a thermo syphon mechanism and natural convection.

A pipe connected to the cold water pipe supplied water into the system from the network, The cold and hot water pipes are connected to the tank by flexible pipes. Proper pressure relief valves were installed at cold water entrance and the hot water exit to avoid explosion of the system. A grate located at the floor of the stove provides sufficient residence time for the rice husk before combustion. After combustion, the grate allows the ash to go out through the ash outlet. The rice husk is introduced into the furnace through the inlet port. It is also through the port that the fire is started with the aide of waste papers. The furnace forms the combustion chamber. It also serves as the surface where cold air exchanges heat. The furnace supports the cooking metal which form the stove.

The stove transfers heat to the pot for cooking by radiation and conduction as said by Orhevba and Chinedu (2015). The chimney on the cooking surface permits the evacuation of smoke.

Air chamber and fan

Waste heat is collected from the the surface of the inner cylinder to heat the air. The air is blown into the air chamber by a 12 volts DC centrifugal fan as shown in figures1 and 3 The capacity of the fan is 60 W. A 12 volts battery supply power to the fan. The hot air outlet has a muff on which a pipe can be connected and made to circulate in the room.

Insulation

Polystyrene foam used as the insulator prevents heat losses from the system. It is a poor conductor of heat due to its low thermal conductivity (0.15 W/mK) and high resistance value (6.3) (Milica*etal*., 2010).

Moisture content of the rice husk

The moisture content was found to be 12.14 %. This value is greater than the value obtained by Ajay *et al*., (2012), which fell within the range 8-9 %. This value was within the range 11.5 -13 obtained by (Amzade*t al*., 2014). The variation in the value gotten and that of Ajay et al, 2012may be due to the relative humidity (Rh) of the environment. Areas with with higher relative humidity will have high MC compared to those with low relative humidity. This is because the husk turns to absorb water vapour from the air and increase its initial weight. When dried in standard oven drying conditions, more moisture is lost giving the difference in moisture content. Where it has fallen within the range we can simply say, the environmental conditions were the same. Thermal conversion technology requires biomass fuels with low moisture content (Kamruzzaman, 2011). He stated that for a good and efficient combustion moisture content should not be more than 30 %.

IV. PERFORMANCE OF THE RICE HUSK STOVE

Burning a fixed mass of rice husk

Using 1kg of rice husk, it was realised that complete combustion was attained after 30min and the maximum temperature was 556.5°C. Figures 4 and 5 give the variation of temperatures in the combustion chamber and hot air at the outlet with time as well as the variation of hot water with time respectively.

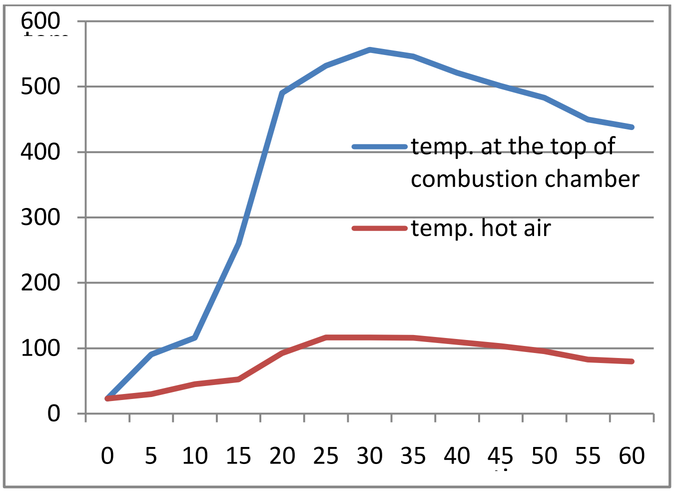

Figure 4.: the variation of combustion chamber and hot air temperatures with time

Temperature at the top of combustion chamber

At the interval 0 – 5 min the temperature in the furnace (top of combustion chamber) rose from 23.2 – 90.5 °C. This is because the rice husk has just started burning. From the 5th – 10th min, there is a gradual increase in temperature. This is because the rice husk is at it drying stage (Kamruzzaman, 2011 and Ahiduzzaman, 2013). During the drying stage, there is high release of smoke from the furnace. From the 10th - 20th min a sharp increase in temperature is noticed (116.2 – 490.5 °C). This is when complete combustion is taking place (Kamruzzaman, 2011 and Ahiduzzaman, 2013). At this time, the color of flame was blue-wish. The temperature continues rising from 490.5 -556.5 but at a decreasing rate. At this interval, the combustion is that of the chars. At the 30th min, the combustion of the char was over. This is shown by a decrease in temperature at the 35th min. This decrease would progress to the 60th and will continue until the ambient temperature is reach. Temperature keeping the inside of the furnace warm is from the heat in the ash and furnace wall.

Hot air temperature time

From the Fig 4, it is seen that as the rice husk burns progressively through 15 mins, there is an increase in the air temperature from the air chamber 52.7°C. This slow increase is due to the fact that the furnace has to first absorb heat before releasing it. A sharp increase in temperature is noticed from the 15th min up to the 25th min because the furnace has attained it maximum absorption capacity as postulated by Lienhard IV and Lienhard V, (2016). As such there is no heat retention thus all the heat is blown out as hot air. From the 25th min, rice husk has undergone complete combustion but since the furnace has the ability to store heat, the heat has been released at a constant rate to the 40th min where it start dropping as seen on Figure 5.

Temperature of hot water

From the Figure 6, as the rice husk burnt, there was a steady increase in the temperature of water up to the 10th min. as complete combustion phase was reached, temperature of water was 90°C. As the rice husk burnt completely, the temperature started falling.

Continues burning of rice husk

Rice husk was continuously fed into the combustion chamber and variation in temperature of both the combustion chamber and the cooking surface was taken with respect to time as seen on Figure 6

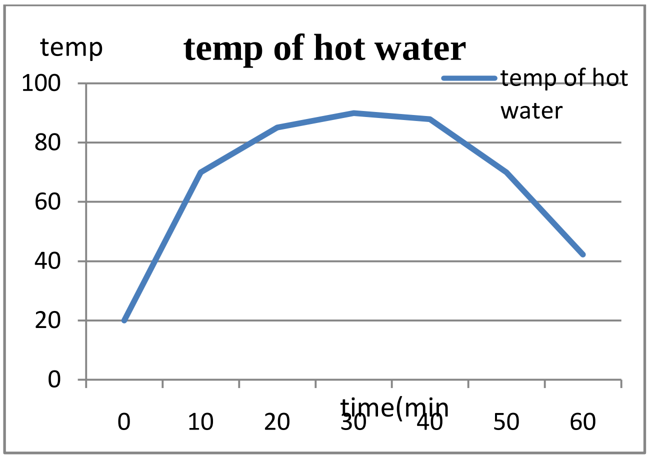

Figure 5: Variation of hot water temperature with time

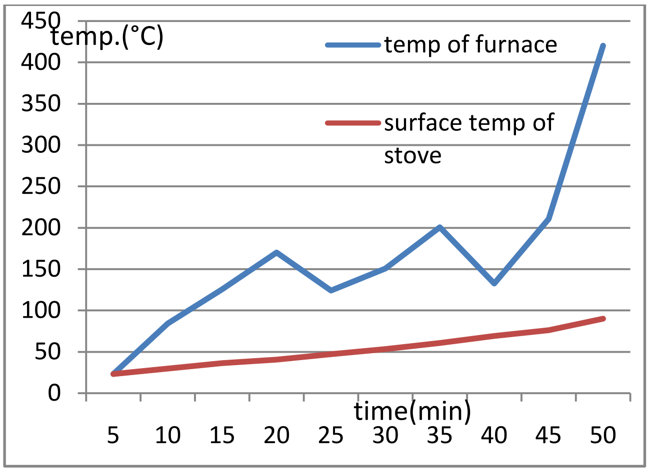

Figure 6: Furnace/ cooking surface temperatures plotted against time

Variation of temperature of furnace

From the Figure 6, as the rice husk is fed into the combustion chamber, there is an increase in temperature and as the combustion chamber is re-fed, there is a drop in temperature for a short while before the temperature increases again. This is because as the husk is fed into the system, the new husk absorbs heat to dry up before initializing the burning process again.

Surface temperature of stove

From Figure 6, it is seen that there is a steady increase in the temperature of the cooking surface despite the drops in the temperature of the combustion chamber. This is because the material of the stove has the ability to store heat due to it thickness (2.4cm) as such the drop in temperature of the furnace does not influence the temperature of the stove.

The burning rate (R) of the rice husk

The burning rate of the RH was found to be 1.6 kg/hr. This rate gave a maximum temperature of 420 °C. This is far less compare to maximum temperature of 1,000 °C , at husk feeding rate of 30 kg/hr and an air flow rate of 2.80 m^3/min flue gas as obtained by Herzog et al, (2000).

CONCLUSIONS AND RECOMMENDATIONS

A rice husk fired biomass stove was successfully designed fabricated and tested. The temperature reached during combustion of rice hush was at 200°C. The heat required by the system was determined to be 1.71 MJ. The quantity of rice husk to supply this energy was 140 g. To fabricate the rice husk stove two cylinders were used as the furnace and an air chamber. A metal of 2.4 cm thick provide a surface for cooking. A water heat exchanger was inserted into the furnace where the heating of water takes place. A 12 volts DC centrifugal fan of 60 W made stove less energy demanding.

The temperature inside the furnace goes up to 556.5 °C and the hot air temperature rising when 1 kg of rice husk is burnt. Time taken to combust a kg of rice husk is 30 minutes. The variation of quantity fed into the furnace has the temperature rising up to 420 °C.

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