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Design, Construction and Testing of an Improved Wood Stove

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Abstract

The design, construction and testing of an improved wood stove is undertaken in this work. The design improvement of the stove focused on the following areas: provision of insulation around the combustion chamber to reduce conduction heat loss across the walls of the chamber, incorporation of smoke rings at the top of the stove, provision of sizable and adjustable air inlet to ensure the availability of sufficient air for the complete combustion of the fuel wood, and the incorporation of chimney to convey flue gases away from the place of use. Performance test results show that the wood stove has a maximum thermal efficiency of 64.4% and power delivery of 2.52kW, but a minimum specific fuel consumption of 0.447. This indicates a better performance when compared to the average thermal efficiency value of 17.9% for traditional mud stove as reported by George (1997), or the Kilakala stove which has a fuel saving capacity of 30% (Crewe 1990, Otiti 1991). *The performance is also better when compared to the Improved Vented Mud stove (IVM) which has the average thermal efficiency values across fuels that vary from 10% to 23% which is comparable with the range of 10.8% to 19.6% reported by Pal and Joshi (1989). On smokiness, it was observed that virtually all the flue gases were conveyed out of the test area through the chimney.*

Keywords: *Wood stove, air inlets, combustion chamber, smoke rings, insulation, thermal efficiency, chimney, smokiness, fuel consumption.*

Introduction

Several sources indicate that wood is the most widely used domestic fuel. Hall *et al.* (1982) reported that about half of the world's population cooks with biomass fuel for all or some of their meals. The dependence on fuel wood by the rural dwellers of most developing countries including Nigeria is estimated at about 100%, while the annual consumption of fuel wood in Nigerian is estimated at about 70 million cubic meters. FAO has estimated that about two million people around the world use wood stove for their domestic cooking and for keeping their surroundings warm. The large preference for wood as fuel is predicated upon the fact that apart from wood and coal the other primary non-renewable sources of energy such as petroleum, natural gas and liquefied natural gas are no longer easy to come-by in terms of cost and availability. The lifetime for these other alternatives is estimated to range from 15 years for natural gas to nearly 300 years for coal (Yawas 2003). The demand for fuel wood will, therefore, continue to increase in response to the cost and availability factors stated above. This will in turn also continue to elicit innovations and improvements in the design of wood-burning stoves.

The development of wood-burning stove is not a recent development, several improvement works have been done on the stove design. Apart from the economic and environmental considerations, the other main issue which motivates the various developmental efforts of the wood stove is the health factor (Joseph *et al.* 1990, Karekezi 1992). The Kilakala stove, a mud stove built using locally available materials and developed at the Sokoine University, Tanzania, has a fuel saving capacity of 30% (Crewe 1990, Otiti 1991). One of the major disadvantages of the stove was that it did not provide sufficient illumination (Otiti 1991). The Kenya Ceramic Jiko (KCJ), one of the most successful urban stove projects in the Eastern African region, which is disseminated throughout Kenya (Kammen and Fayemi Kammen 1992) is reported to have a useful heat of about 25-40 % of the heat generated, which represents a significant increase from an open fire that directs only about 5-10% of the heat generated from the fire to the cooking pot. The Improved Vented Mud stove (IVM), a two-pot stove with chimney, also called the Nada Chula, developed in India has the average thermal efficiency values across fuels that varies from 10 to 23.5% which is comparable with the range of 10 to 19.6% reported by Pal and Joshi (1989). The version of (IVM), made of ceramic lining with mud coating and called the Improved Vented Ceramic (IVC), has higher efficiencies for all fuels except crop residues. George (1997) found the thermal efficiency of the traditional mud (TM) stove, which is a simple U-shaped heavy stove for a single pot made with locally available clay and coated with cow-dung clay mixture, to average 17.9%. The Angethi stove used for charcoal and char briquettes and fabricated with galvanized iron bucket, mud/concrete, and grate has a thermal efficiency of 17.5%, which is comparable with that (15.3%) quoted by Wazir (1981). However, in these various developmental efforts, the level of achievement of some of the objectives still leaves a lot of room for improvement.

The present work, thus, seeks improvement on the existing designs by making the following design considerations: enhancing the combustion process by providing for means of introducing sufficient air for combustion, further reducing the amount of heat loss from the combustion chamber by insulating with fiber glass, reducing the amount of heat loss by radiation by a careful design of the pot seat, and reducing the level of pollution of the kitchen environment with smoke emissions by the design of the pot seat and by incorporating a chimney.

Design Description, Analysis and Calculation

Design Description

The wood stove (see Fig. 1) is circular in section and generally consists of a combustion chamber, a top section and a base. The hearth of the combustion chamber is made of clay the outside of which is lined with fiberglass and encased in a mild steel casing. The grate or fuel bed is at the base of the combustion chamber. The base of the stove consists of a door for loading fuel wood into the combustion chamber, and four openings which serve as combustion air inlets to the chamber. A drawer is incorporated at the base to facilitate the removal of ash which would have collected at the tray. The top of the stove consists of the pot seat, three refractory rings of different diameters to accommodate different sizes of pot, and a chimney. The pot seat is designed such that the pot sinks to a depth below the top-most level of the stove. The refractory ring to be selected for use is such that has the internal diameter equal to or closest to the external diameter of the cooking pot, thus ensuring that there is little or no clearance between the pot and the ring. The chimney is made of mild steel and incorporated at the periphery of the top of the stove to convey smoke and other by-products of combustion out of the kitchen.

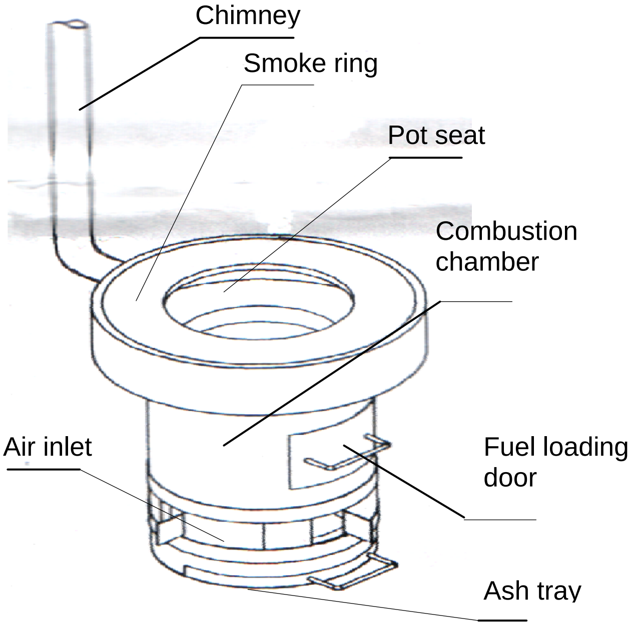

Fig. 1. The wood burning stove.

The diameter of the combustion chamber is such that it is smaller than the pot seat or the external diameter of the smallest pot that can be utilized on the stove. This is to ensure that the maximum amount of heat is transferred to the base of the pot before it proceeds to be ejected out through the chimney. The distance between the fuel bed and the pot seat is also selected to allow for enough time for the complete combustion of the burning fuel particles before it strikes the base of the pot mounted on the pot seat.

Design Analysis and Calculations

Design Specifications

Based on the choice of a domestic-size stove, the following parameters are selected for the design: height of the combustion chamber, L_{cc} = 210mm; internal radius of combustion chamber, r_1 = 90mm; internal radius of insulation lining, r_2 = 105mm; internal radius of mild steel casing, r_3 = 138mm; external radius of mild steel casing, r_4 = 139mm; height of side air vent, h = 50mm; height of stove base, H_{sb} = 150mm; external diameter of pot seat chamber, D_{ps} = 350mm; height of pot seat chamber, H_{ps} = 70mm; measured ext. temp. of comb. chamber, T_o = 32°C; measured Int. temp. of comb. chamber, T_i = 495°; thermal conductivity of clay, K_1 = 1.28W/mK; thermal conductivity of fiberglass, K_2 = 0.037W/mK; thermal conductivity of mild steel, K_3 = 39W/mK.

Combustion Air Requirement

Following Ramakrishna (1992), a typical fuel wood has the following ultimate analysis by mass as shown in Table 1.

Table 1. Mass analysis of a typical fuel wood.

C	H_2	O_2	N_2	H_2O	Ash
40.4%	4.2%	33.9%	0.3%	20%	0.2%

The combustion analysis based on the above mass composition gives a stoichiometric Air/Fuel ratio,

A/F = 4.6107 kg air/kg fuel.

For an actual air supply which is 20% in excess of stoichiometry, actual air/fuel ratio,

A/F_{actual} = 5.53284 kg air/kg fuel.

Design of Combustion Air Inlet

Following Tran and White (1992), the burning rate, $\dot{m}''$, of a typical fuel wood based on mass loss rate is between 2.92 gm^{-2}s^{-1} and 9.80 gm^{-2}s^{-1}.

Assuming up to six layers of wood pieces each having a rectangular cross-section of dimensions 15 x 15 mm, the actual surface area of the wood pieces exposed to burning may be approximated to fourteen times the cross-sectional area of the combustion chamber.

The mass of wood burned per second may then be expressed as,

$$\dot{m} = 14\dot{m}''a \,. \tag{1}$$

Based on the maximum burning rate of the fuel wood then,

$$\dot{m} = 14 \times 9.8 \times \pi \frac{d^2}{4} = 3.4913 \text{ gs}^{-1}.$$

The actual air supply rate corresponding to the mass burning rate can also be expressed as,

$$\dot{m}_{air} = A/F_{actual} \times \dot{m}$$

= 5.53284 x 3.4913 x 10^{-3}

= 1.93 x 10^{-2} kgs^{-1} air.

This gives a volume rate of air supply based on air density of 1.23 kgm^{-3} ,

$$\dot{V}_{air} = 1.5691 \times 10^{-2} \text{ m}^3\text{s}^{-1}.$$

According to Parker *et al.* (1969), the area of air opening, A_{air}, is related to the volume flow rate, $\dot{V}_{air}$, as

$$\dot{V}_{air} = 23.6 A_{air} \sqrt{h} \,. \tag{2}$$

This gives an area of air opening,

A_{air} = 2.9734 x10^{-3} m^2,

for an air opening being rectangular in section with a vertical dimension, h = 50mm, and a horizontal dimension, l = 60mm.

Chimney Design

The design of the chimney is basically for the appropriate diameter of the chimney. In practice, the following inequality is used for the determination of the diameter of the chimney:

$a_c \leq 10A_{air}$,

where a_c = cross-sectional area of chimney.

Substituting for the area of side air opening in the inequality gives the diameter, d_c, of the chimney as follows:

$a_c \leq 29.734 \times 10^{-3}\ \mathrm{m}^2$
$d_c \leq 0.195$ m.
where: d_c = diameter of chimney.

Heat Loss across the Cylindrical Walls of the Heating Chamber

The radial conduction heat flow for a hollow cylinder is expressed by the Fourier's law as:

$$Q_r = -KA\frac{dT}{dr}, \qquad (3)$$

where: K is the thermal conductivity of the cylinder material; A is the area of the walls of the cylinder heating chamber across which heat transfer occurs; and dT/dr is the radial temperature gradient across the walls.

For a steady heat flow in which Q_r is independent of r and $T_i > T_o$, the equation can be integrated and rearranged to become

$$Q_r = \frac{T_i - T_o}{\frac{1}{2\pi LK}\ln\left(\frac{r_o}{r_i}\right)}, \qquad (4)$$

where the subscripts 'i' & 'o' define inside and outside surfaces of the cylinder respectively.

For a composite cylinder (see Fig. 2) with known inside and outside surface temperatures and having 'n' layers of different materials the form of Eq. (4) is

$$Q_r = \frac{T_1 - T_{n+1}}{\frac{1}{2\pi L}\sum_{i=1}^{n}\frac{1}{K_i}\ln\left(\frac{r_{i+1}}{r_i}\right)}. \qquad (5)$$

For the composite hollow cylinder consisting of three layers of materials: clay surrounding the fire box, insulating fiberglass and a steel casing, Eq. (5) becomes

$$Q_r = \frac{T_1 - T_4}{\frac{1}{2\pi L}\sum_{i=1}^{3}\frac{1}{K_i}\ln\left(\frac{r_{i+1}}{r_i}\right)}. \qquad (6)$$

Substituting for the various parameters gives, $Q_r = 80.50$ W.

Therefore, the heat transfer through the wall of the stove per second is determined to be 80.50 W.

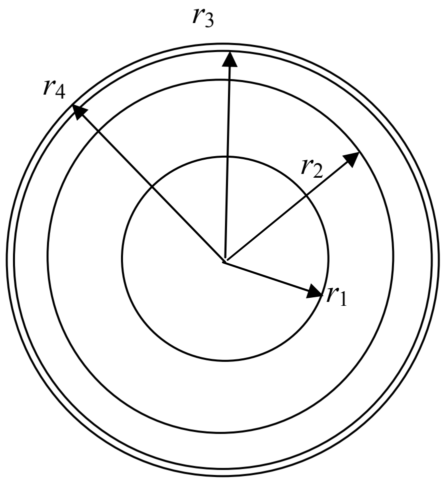

Fig. 2. A composite hollow cylinder.

Performance Testing of the Biomass Stove

The tests conducted on the biomass stove included water boiling test and simmering test. The tests were conducted with the air opening fully opened.

Test Procedures

Water Boiling Test

The stove and pot were thoroughly cleaned and dried. The test was conducted in an enclosed kitchen environment. A measured amount of fuel wood was weighed out for each test. The same type of wood was used for the series of tests, it was therefore ensured that there was sufficient fuel wood available for the tests, stored in the same place so as to have uniform moisture content. The pot, lid, and thermocouple were weighed, and then a measured amount of water by volume (about two-thirds the pot capacity) was added to the pot and weighed again to determine the weight of the water. This was repeated for each test

The already weighed fuel wood was introduced into the combustion chamber and about 15ml of kerosene was sprinkled on it to initiate burning. The pot was placed on the stove the moment the sprinkled kerosene got burnt out. The time of the day, the environmental conditions (ambient temperature) and the initial temperature of the water were recorded. Thereafter the commencement of the test the temperature of the water was recorded at intervals of five (5) minutes until the moment the water came to a vigorous boil. The pot was then removed from the stove and the fire immediately put out with the help of dry sand. The final weight of the remaining water, charcoal and the final temperature of water were then measured and recorded. The tests were carried out on the 30th of September, 2006 starting at about 10am in the morning.

Simmering Test

Simmering involves the heating of boiling water at a constant temperature for about thirty minutes. The procedure for the test is the same as that for the boiling test. At the end of the test, measurements are taken and recorded accordingly.

Test Results for Boiling and Simmering of Water

The test results for boiling and simmering of water are shown in Table 2.

The temperature variation during boiling is shown in Table 3.

Table 2. Test results for boiling and simmering of water.

Ambient temperature	32°C
Initial water temperature, T_i	32°C
Final water temperature, T_f	98°C
Time spent to boil	17Mins.
Weight of empty pot, M_P	0.54Kg
Initial weight of fuel wood, M_F	1.5Kg
Average weight of charcoal recovered after boiling, M_{CB}	0.1Kg
Average weight of fuel wood consumed in boiling	0.5Kg
Average weight of charcoal recovered after simmering, M_{CS}	0.08Kg
Average weight of fuel wood consumed in simmering	0.3Kg
Initial weight of water, M_W	2.5Kg
Average weight of water evaporated during boiling, M_{VB}	0.02Kg
Average weight of water evaporated during simmering, M_{VS}	0.4Kg
Total weight of water evaporated, M_V	0.42Kg
Final weight of water	2.08Kg

Table 3. Temperature variation during boiling.

Time (Min.)	Temperature (°C)
0	32
5	55
10	79
15	91
17	98

Analysis of Test Results

Thermal Efficiency of the Stove

The thermal efficiency of the stove can be expressed as

$$\textit{Thermal Efficiency}(\eta_T) = \eta_C \times \eta_{HT}, \qquad (7)$$

where:

η_c is combustion efficiency;

η_{HT} is heat transfer efficiency.

But thermal efficiency is also related to percentage heat utilized as

$$\textit{Thermal Efficiency} = \textit{Burning Rate} \times \textit{PHU}. \qquad (8)$$

The percentage heat utilized (*PHU*) is expressed as

$$PHU = \left[\frac{(M_W C_W + M_P C_P)(T_f - T_i) + M_v L_V}{M_F C_F - M_C C_C}\right] \times 100, \qquad (9)$$

where:

C_W is specific heat capacity of water;

C_P is specific heat capacity of pot;

L_V is latent heat of evaporation of water;

C_F is specific heat capacity of fuel wood;

C_C is specific heat capacity of charcoal.

Substituting for the various parameters, the percentage heat utilized is obtained as follows, *PHU* = 72.84%.

Burning Rate

The burning rate of the fuel wood can be expressed as

$$F = \frac{1}{t}\left[\left(\frac{100 \times M_W}{100 + X}\right) - \left(\frac{M_C \times H_C}{H_W}\right)\right], \qquad (10)$$

where:

X is moisture content of fuel wood;

H_C is calorific value of charcoal;

H_W is calorific value of fuel wood;

t is the time to boil.

Specific Fuel Consumption

The specific fuel consumption (*SFC*) is expressed as

$$SFC = \left[\frac{M_F(1-X)-1.5M_C}{M_W} \right], \qquad (11)$$

where the various parameters are as defined previously.

Substituting for the various parameters in Eq. (11) gives, $SFH = 0.447$.

Power Consumed for Boiling or Simmering

The power consumed (*PC*) for boiling or simmering can be expressed as,

$$PC = \left[\frac{M_F(1-X)-1.5M_C}{60t} \right] C_F, \qquad (12)$$

where the various parameters are as defined previously.

Substituting for the various parameters in Eq. (12) gives, $PC = 2.52$kW. Substituting for the various parameters in the expression for thermal efficiency (η_T) of the stove as expressed by Eq. (8) gives, $\eta_T = 64.4\%$.

The results of the analysis may be tabulated as shown in Table 4.

Table 4. Results of the analysis.

Parameter	
Wood consumed for boiling	0.5kg
Wood consumed for simmering	0.3kg
Total wood consumed	0.8 Kg
PHU for boiling	72.84%
PHU for boiling and simmering	78.81%
Thermal Efficiency	64.4%
Specific fuel consumed	0.447
Power consumed for boiling	2.52kW
Power consumed for simmering	0.69kW

Discussion of Results

The results show that the biomass stove has a maximum thermal efficiency of 64.4% and power delivery of 2.52kW, but a minimum specific fuel consumption of 0.447. This indicates a better performance when compared to the average thermal efficiency value of 17.9% for traditional mud stove as reported by George (1997), or the Kilakala stove which has a fuel saving capacity of 30% (Crewe 1990, Otiti 1991).

The performance is also better when compared to the Improved Vented Mud stove (IVM) which has the average thermal efficiency values across fuels that varies from 10% to 23% which is comparable with the range of 10.8% to 19.6% reported by Pal and Joshi (1989).

Furthermore, the thermal efficiency of the wood stove is higher when compared to the thermal efficiencies of petroleum based fuel stoves such as the LPG stove, the kerosene wick stove, and the kerosene pressure stove with thermal efficiencies of 53.6%, 50% and 47%, respectively (TERI 1987).

The enhanced performance can be attributed to a number of factors. The first is the insulation provided round the combustion chamber. This minimizes the rate of heat loss across the wall of the combustion chamber by conduction and radiation, and ensures that a good proportion of heat is conserved within the chamber and directed towards the top of the chamber. The second is the smoke rings provided which eliminate the horizontal clearance between the pot and the pothole. This minimizes heat loss by radiation through the annulus between the pot and the pothole. The third factor is the design of the pot seat and the position of the flue gas exit port This ensures that the base of the pot sinks to a depth inside the pothole such that there is no vertical clearance between the pot base and the top of the stove, and that there is longer interaction between the flame and the pot base, bringing about maximum heat transfer to the pot, before the flue gases exit into the chimney. There is also the factor of availability of sufficient air that ensures the complete combustion of the fuel wood.

On smokiness, it was observed that virtually all the flue gases was conveyed out of the test area through the chimney. The very small quantity of smoke noticed might have escaped as a result of construction inaccuracy in the roundness of the smoke rings leaving a very small gap between the pot and the ring. The escaping smoke, however, quickly diffuses into the air, causing insignificant fouling and irritation effects.

Conclusion

It would be seen that the modifications made in providing insulation around the combustion chamber and sizable air inlet to admit adequate quantity of air for combustion, incorporating smoke rings to seal the annulus between the pot and the pothole, and redesigning the configuration of the pot seat and the position of the flue gas exit port, have served to increase the thermal efficiency and therefore the percentage heat utilization of the stove. There has also been a drastic reduction in the smokiness of the stove, making it to be more user-friendly in health, comfort and convenience. Further modifications focused at redesigning the pot seat vis-à-vis the flue gas exit port in such a way that will minimize heat loss by radiation and convection, and ensure maximum heat transfer to the base of the pot can be pursued in future.

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