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### Design and construction of an improved-wood-burning stove

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#### ABSTRACT

An improved wood-burning stove was designed and constructed with a view to conserving heat and minimizing losses. A 2-mm mild steel sheet was used for the two-layer body. The cavity between the walls was filled with fibre glass for heat conservation. From the tests carried out on the constructed stove, time for boiling water was 6.1 min/kg; time for cooking food (rice) was 25.7 min/kg; the specific fuel consumption was 0.543 kg of wood/kg of food cooked, and the efficiency in terms of percentage heat utilized was 22.08%. Every year, especially in Nigeria more land is lost to desertification partly due to felling of trees for fuel wood. An improved wood-burning stove efficiently utilizing fuel wood would contribute significantly in reducing these problems.

#### Introduction

Within the last few decades, there has been a renewed interest in the development of improved wood-burning stoves for greater heat utilization with minimal loss. This has been especially so with the growing awareness of the devastation resulting from desertification caused, among other factors, by the felling of trees for fuel wood. The on-going research for development of improved wood-burning stove has also been due to the fact that most of the heat generated from burning of fuel wood is lost in the traditional wood-burning stoves. Many of these researches, like those by Akinbode, (1991); Danshehu, Atiku, and Tambuwal, (1996); Maishanu, Danshehu, and Sambo, (1990); Fapetu, and Oke, (2003); and Ali, and Diso, (2008), all focused on improving the efficiency by which heat energy is utilized. Wood-burning stoves have always

been in use for many centuries and their use cuts across all economic statuses but particularly where access to petroleum-based fuels is limited.

According to Douglas (1994), wood fuels were relatively cheap during the greater part of the past century, so efficiency was not an important factor in the design of wood-burning stoves. However, as the demand for wood fuel increased due to increasing urbanization and increasing processes, supplies became more distant from the markets, and some stove makers began more intensive efforts to improve their models and make it more efficient. Douglas (1994) stated that, with higher oil prices, increasing deforestation, and talk of an impending “fuel wood crisis”, government donors and non-governmental organizations (NGO's) started to finance and develop stove programs.

In the traditional open-hearth stoves much heat is lost; the efficiency of many improved wood stoves does not exceed 35% (Akinbode, 1991; Danshehu et al, 1996; Garba and Atiku, 1997; Fapetu and Oke, 2003, Obi et al, 1991) from a base of between 5 to 10% using wood from different species of tropical trees, (Garba and Atiku, 1997).

The traditional open-hearth wood stove is generally made from sheet metal or bricks with designs largely on trial and error. They lack satisfactory fuel-to-air ratios for complete combustion and thus producing excessive smoke. It has been estimated (Danshehu et al, 1996) that in open fire cooking methods only 5 to 10% of the fuel wood energy is utilized. It is in the light of all these that improved wood-burning stoves like those by Akinbode (1991) and Maishanu et al (1990) were developed.

Recent surveys in urban areas indicate that the lowest 20% of the population spend close to 20% of their income on energy. A more efficient stove will free some of their cash for other uses and would constitute a substantial benefit for the urban poor. In addition, introducing a more fuel efficient cooking stove is one approach to alleviating fuel wood shortage since there will be reduction in demand for wood (Fapetu and Oke, 2003), and hence conserving the much needed trees.

For people who use traditional open-hearth wood stove indoors in unventilated or partially ventilated kitchens, the introduction of improved stoves will reduce exposure to the health-threatening pollutants found in biomass

smoke to a significant level. Studies in recent years have associated a number of health problems with smoke exposure, Douglas (1994).

It is thus the aim of this work to contribute to the growing research work on developing a more and more energy-efficient wood-burning stove by developing one that will conserve as much of the heat as possible while making it available for cooking and at the same time minimize as much as possible heat losses. The stove is designed for households, small hotels and restaurants or any areas where cooking using wood fuel is desired.

### **Theoretical Background**

Akinbode (1990), also carried out experimental analysis of combustion of samples of local wood using the British Standard 1016, gave the following contents and values for wood: volatile matter content: 80.30%; moisture content: 7.50%; ash content: 0.15%; calorific value:  $2.278 \times 10^4$  kJ/kg; carbon: 48.00%; hydrogen: 6.30%; oxygen: 44.30%; and nitrogen 0.80%.

Ignition of wood depends on the exothermic reaction temperature, (which is about 273 °C), the presence of inflammable extractives, and the shape and size of the cross-section. Thin outstanding edges ignite readily, while chamfered, heavy timbers are slow to catch fire. Long, continuous heating below the exothermic reaction temperature can cause ignition, however.

### **2.1 Rate of Heat flow through Composite Walls**

Consider the composite wall shown in Figure 1 below:

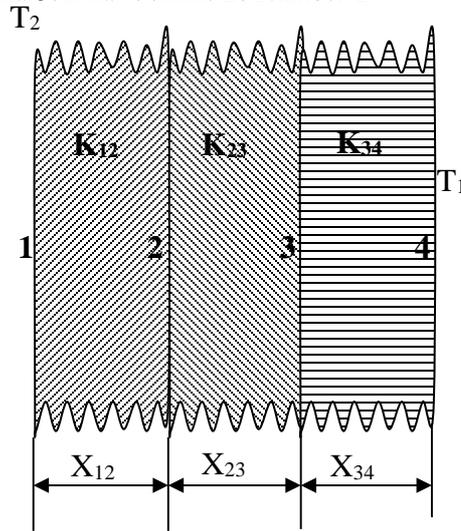


Figure 1: Composite wall.

The rate of flow of heat  $Q_r$  through a composite wall of say metal, refractory and metal is given by the Fourier law:

$$Q_r = A \frac{T_1 - T_2}{X_{12} / K_{12} + X_{23} / K_{23} + X_{34} / K_{34}} \quad (1),$$

where:

$X_{12}$ ,  $X_{23}$ ,  $X_{34}$  are the wall thicknesses of metal, refractory, and metal materials, respectively;  $K_{12}$ ,  $K_{23}$ ,  $K_{34}$  are the thermal conductivities of the stove wall materials, respectively;  $T_1$ ,  $T_2$  are temperatures of the inside stove and the ambient temperature, respectively; and  $A$  is the total surface area of the wall.

## Materials and Methods

### Design Consideration

The thermal efficiency of a cooking stove depends largely on how well the heat generated is transferred from the hot gas of the fuel line to the pot (convective heat transfer), Akinbode (1991). To be able to transfer as much of this heat as possible – while at the same time keeping heat losses due to escaping hot gases as little as possible – the fuel bed-to-pot distance should be kept as small as design limits will allow. The stove was developed with a consideration for keeping costs of both production and maintenance as low as possible to enhance affordability by low-income earners. The design of the stove was such that minimal technical skills as possessed by road-side artisans would be adequate to fabricate both the stove itself and any component parts that may

be required subsequently. The stove was designed to be relatively small in size to allow for easy movement and with only one pot seat. For a workable and good design, the following criteria have to be determined and met as much as possible:

- a) The length and diameter of the chimney in commensurate with expected quantity of flue gas,
- b) The distance between fuel bed and cooking vessels – which must be kept as small as possible,
- c) The size of the grate opening that can accommodate enough wood at a time,
- d) The minimum wall thickness of the stove,
- e) Air opening to supply secondary air for stoichiometric combustion, and
- f) The pot stand, ash collecting tray and stove stand.

In addition, the stove would be designed to accommodate a medium-sized cylindrical aluminium pot with external diameter of 0.235 m, a thickness of about 1.4 mm, and a height of 0.11m.

**Design Calculations/Specifications**

**1. Chimney**

An efficient wood stove requires a chimney whose function include conveying undesirable by-products like smoke and other gases, and as an opening for feeding secondary fuels.

The height and diameter of the chimney is informed by the size and specifications of the stove and its function. The height is determined from the need to terminate the chimney height and control the effect of wind on the spent gases. Usually, a minimum chimney height of 3 m for large stoves and a height of 0.3 m for small ones (Obi et al, 1991) is employed. This stove is considered small and therefore a minimum chimney height would be at least 0.3 m; a height of 0.35 m was adopted.

The chimney diameter is a more decisive variable compared to the height. The following equation is usually used to determine chimney diameter (Obi et al, 1991):

$$A \leq 10a \quad (2)$$

where, A is the area of the side air opening, and a is the cross-sectional area of the chimney.

At this point, A is unknown. Nevertheless, following the principle adopted by Obi et al (1991), we let A be equal to the external cross-sectional area of the pot. This is reasonable considering the fact that an air opening equal to or greater than the cross-sectional area of the bottom of the pot would be expected to supply air for combustion of fuel – and

hence heating of pot – all around the bottom of the pot.

Hence,

$$A = \frac{\pi D^2}{4} \quad \text{_____}$$

(3)

Equation (2) was then used to determine a least value of a.

The least diameter of the chimney would then be given by:

$$d = \sqrt{\frac{4a}{\pi}} \quad \text{_____}$$

(4)

**2. Combustion Chamber**

The grate is the bed provided upon which the fuel (wood) is placed and burnt; hence, in practice, the height of the combustion chamber is the distance between the bed and the cooking utensil and is kept as small as possible as this engenders efficiency (Obi et al, 1991) since the hot gasses generated for combustion would have little chance to escape before they come into contact with the cooking utensil. In the light of this, the stove is designed so that the cooking pot is either made to rest on the rim of the stove or in such a way that it is completely or partially enclosed in the combustion chamber.

Ndirika (1995) gave an estimate of this height h, as:

$$h = 0.4D \quad (5)$$

where, D is the external diameter of pot. Using the specified pot diameter in the design criteria (i.e. D = 0.235 m), h = 0.094 m ≈ 0.1 m or 10 cm for this design. This height should, of course, be large enough to accommodate the fuel.

**3. The Size of the Combustion Chamber**

This was made to be 0.015 m<sup>3</sup> of mild steel enclosure – large enough to accommodate a minimum of three pieces of wood, each of average length of 0.4 m and average diameter of about 0.025 m – with fibre glass refractive lining.

#### 4. The Minimum Stove wall thickness

From equation (1):

$$X_{23} = K_{23} \left\{ \frac{A\Delta T}{Q_r} - \frac{X_{12}}{K_{12}} + \frac{X_{34}}{K_{34}} \right\} \quad (6),$$

where,  $\Delta T = T_1 - T_2$ .

At this stage, the  $Q_r$  is unknown. However, consider the quantity of heat  $Q$ , released when 1 kg of wood is burnt given by:

$$Q = mC_v \quad (7),$$

where,  $m$  is the mass of wood consumed in kg, and  $C_v (=2.278 \times 10^4 \text{ kJ/kg})$  is the calorific value of wood.

The total surface area  $A_s$  of the stove for the shape adopted (frustum of a cone) is obtained from:

$$A_s = \pi S(r_1 + r_2) = \pi \left( \sqrt{(r_1 + r_2)^2 + h^2} \right) (r_1 + r_2) \quad (8),$$

where,  $r_1$ ,  $r_2$  and  $h$  are the upper radius, lower radius and the height of the frustum, respectively.

Substituting these, and  $X_{12} = X_{34} = 2\text{mm}$  for steel;  $K_{12} = K_{34} = 45 \text{ w/m K}$  also for steel;  $K_{23} = 0.022 \text{ W/m K}$  for the refractory (fibre glass);  $T_1 = \text{fuel wood flame temperature} = 510 \text{ }^\circ\text{C}$ ; and  $T_2 = \text{ambient temperature} = 25 \text{ }^\circ\text{C}$  into equation (6), the value of  $X_{23}$  was obtained.

#### 5. Mass of fuel required

Now, from  $Q = mc\theta$ ,

$$\Rightarrow Q = (m_w c_w + m_p c_p)(\theta_1 + \theta_2) \quad (9),$$

where,  $M_w$  is the mass of water;  $C_w$  the specific heat capacity of water (4.2 kJ/kg K);  $M_p$  the mass of pot (0.25 kg);  $C_p$  the specific heat capacity of pot material (aluminium: 0.92 kJ.kg k); and  $\theta_2$  and  $\theta_1$  are, respectively, the final (100 °C) and initial (25 °C) temperatures

Substituting a mass of water (required to fill the model pot), and mass of the model pot of 3.3 kg, 0.25 kg (obtained by measurement/calculation) respectively as well as values of  $C_w$  and  $C_p$  (aluminium) into equation (9), the value of  $Q$  was obtained.

Using the calorific value of wood  $C_v = 2.278 \times 10^4 \text{ kJ/kg}$ , the mass of wood required to produce  $Q$  was obtained from:

$$m = \frac{Q}{C_v} \quad (10)$$

#### 6 The Ash-collecting Tray

This is a light metal pan onto which the ashes are expected to drop during fuel combustion for immediate disposal even when the fire is on. A 2-mm thick mild steel material was used for its construction.

#### 7. The Stove Stand

These are three 0.1 m high angled iron stand structures located at equal distances around the circumference of the bottom of the stove. These were provided to prevent rusting and attendant heat losses through leakage occasioned by direct contact between the stove bottom

and the ground surface, in addition to providing a rigid support for the stove.

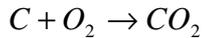
#### Stoichiometry Ratio and Combustion Analysis

Stoichiometric ratio is the chemically correct ratio of the amount of air required to sufficiently burn 1 kg of fuel.

Fuel wood has the following percentage composition: Carbon: 48.00%; Hydrogen: 6.3%; Nitrogen: 0.48%; and Oxygen: 44.30%. Each constituent is taken separately and the amount of oxygen for complete combustion is found from the relevant chemical equations.

It should be noted that volatile matter, moisture, ash and nitrogen contents are all products of combustion, and hence are not part of the combustion reactions.

i) Carbon:



i.e. 12 kg of C + 32 kg of O<sub>2</sub> → 44 kg of CO<sub>2</sub>. Hence, for 0.48 kg of C per kg of wood,

$$O_2 \text{ required} = 0.48 \frac{32}{12} = 1.28 \text{ kg and}$$

$$CO_2 \text{ produced} = 0.48 \frac{44}{12} = 1.78 \text{ kg.}$$

ii) Hydrogen:

By similar computations as above, for hydrogen, Oxygen required is 0.504 kg, and steam produced is 0.567 kg.

iii) Oxygen

Oxygen, on the other hand, does not take part in the reaction; instead, it is consumed and as such the amount 0.443 kg would be taken out of the net Oxygen requirement.

Therefore, total mass of oxygen required per kg of wood is

$$1.28 + 1.76 - 0.443 = 2.597 \text{ kg}$$

By gravimetric analysis, 23.3% of air is oxygen, therefore, total amount of air required to supply this 2.597 kg of oxygen for 1 kg of wood is:

$$M_{a1} = \text{Mass of air/kg of wood} = \frac{100 \times 2.597}{23.3} = 11.1459 \text{ kg}$$

The total amount of air M<sub>a</sub> needed for the 0.046 kg of wood estimated in section above is thus:

$$\text{Mass of air} = \text{Mass of wood} \times 11.15 = 0.046 \times 11.15 = 0.513 \text{ kg}$$

The volume of air V<sub>a1</sub> required to burn 1 kg of fuel wood will be:

$$V_{a1} = M_{a1} / \rho_a = 11.1459 / 1.23 = 9.06171 \text{ m}^3$$

The volume of air V<sub>a</sub> required will thus be:

$$V_a = M_a / \rho_a = 0.513 / 1.23 = 0.4171 \text{ m}^3,$$

where ρ<sub>a</sub> is the density of air = 1.23 kg/m<sup>3</sup>.

## TESTING AND PERFORMANCE EVALUATION

### Test Parameters and Measured Data

#### 1. Operating Procedure

The pot carrier was removed and the ash-collecting box was positioned. The pieces of fire wood were next placed on the grate inside the combustion chamber and the woods were then ignited by sprinkling some kerosene on them and lighting up with a flame. The pot carrier was repositioned and the loaded pot placed over it. After cooking for a measured period of time, all unburnt wood and

charcoal were quenched and removed from the grate. All the spent ashes were removed from the ash collector tray.

#### 2. Tests

The following tests were conducted on the stove: water-boiling, food-cooking, and efficiency tests.

Time T<sub>w</sub>, taken to boil a quantity of water was calculated from:

$$T_w = \frac{t}{M_{w1}} \text{ (11)}$$

where, t is the time taken to boil the water, and M<sub>w1</sub> is the initial mass of water.

Time taken  $T_f$  to cook food was calculated from

$$T_f = \frac{t'}{M_{pf} - M_p - M_{evw}} \quad (12)$$

where,  $t'$  is the time taken to cook the food (rice in this case);  $M_{pf}$  is the combined mass of pot, water and the food;  $M_p$  is the mass of empty pot; and  $M_{evw}$  is the amount of evaporated water during cooking.

The efficiency or percentage heat utilization PHU (as given by Akinbode, 1991) is:

$$PHU = \frac{4.18(M_{wb} - M_p)(100 - \theta_1) + 2260(M_{w1} - M_{wb})}{M_f \times C_v} \quad (13),$$

where,  $M_{wb}$  is mass of water remaining after boiling;  $M_f$  is the mass of fuel wood used; and  $C_v$  is the Calorific value of fuel wood.

The specific consumption of fuel wood per kg of cooked food, SFC is given by:

$$SFC = \frac{M_f}{M_{pf} - M_p - M_{evw}} \quad (14).$$

## Results and Discussion

Table 1: Results of Design Analysis.

Quantity	Description	Value
A	Total area of side air openings.	0.0434 m <sup>2</sup>
A	Cross-sectional area of Chimney	≥ 0.00434 m
D	Smallest possible diameter of Chimney	0.07434 m
Q <sub>r</sub>	Rate of heat flow through the composite walls of the stove	6327.788 W
A <sub>s</sub>	Total surface area of the Stove	0.33 m <sup>2</sup>
X <sub>23</sub>	Thickness of refractory required for the composite walls of the Stove.	0.6 mm
M	Mass of fuel wood required to boil 1 kg of water.	0.014 kg
M <sub>ai</sub>	Mass of air required to burn 1 kg of fuel wood.	11.146 kg
V <sub>ai</sub>	Volume of air required to burn 1 kg of fuel wood.	9.0617 m <sup>3</sup>

Table 2: Results of Tests carried out on the Stove.

Quantity	Description	Value
M <sub>p</sub>	Mass of empty pot	0.25 kg
M <sub>w1</sub>	Initial mass of water	3.3 kg
θ <sub>1</sub>	Initial temperature of pot and water	27 °C
θ <sub>2</sub>	Final temperature of pot and water	100 °C
T	Time taken to boil the water	20 minutes
θ <sub>1</sub> '	Initial temperature of pot, water and raw food	29 °C
θ <sub>2</sub> '	Final temperature of pot, water, and cooked food	100 °C
M <sub>f</sub>	Mass of fuel wood used	0.950 kg
t'	Time taken to cook the food (rice)	45 minutes
M <sub>evw</sub>	Amount of evaporated water in cooking	0.45 kg
M <sub>wb</sub>	Mass of water remaining after boiling	2.85 kg
M <sub>pf</sub>	Mass of pot, water and food before cooking	2.45 kg
T <sub>w</sub>	Time taken to boil a quantity of water	6.06 mins/kg
T <sub>f</sub>	Time taken to cook food	25.71 mins/kg
PHU	The efficiency or percentage heat utilization	22.08 %
SFC	The specific consumption of fuel wood per kg of cooked food	0.543 kg/kg

## **Discussion**

The basis for all works in the field of wood-burning stoves is to mitigate all the shortcomings of the traditional open-hearth stoves, where most of the heat generated is lost and the efficiency is low. In the present work, the time taken to cook 1 kg of food was 25.71 minutes with an efficiency of about 22%; these represent a significant improvement on the open-hearth stove where the time is estimated to be as high as 56.5 minutes (Maishanu, et al, 1990) and the efficiency between 5 and 10 % (Danshehu et al, 1996).

In summary, for this work, the boiling time, cooking time, specific fuel consumption, and the efficiency are 6.06 min/kg of water, 25.71 min/kg of food (rice), 0.54 kg of fuel per kg of food, and 22.08 %, respectively.

Having established this, the discussion below shows the improved nature in this work.

Akinbode (1991) gave a summary of the boiling efficiencies of four different kinds of traditional stoves used outdoors as: Metal tripod, 9.55%; Metal cylindrical shape, 19.39%; Three-stone, 12.37%; and Clay woodstove, 20.77%. It is seen that the present work with efficiency of 22.08% represents an improvement over former stoves. On the other hand, the average cooking time and the specific fuel consumption for a 3-stone stove was given by Maishanu et al (1990) as 56.5 min/kg, and 1.03 kg/kg. These are about twice higher than the corresponding figures for this work of 25.71 min/kg, and 0.54 kg/kg. These are also marked improvements.

The 1-, 2-, 3-, and 4-hole stoves developed by Maishanu et al (1990) at the Sokoto Energy Research Centre have average cooking times in minutes per kg of food of 38.5, 13.1, 5.9, 9.4 and 18.2, respectively. Hence, the present work with 25.71 min/kg is better than only the 1-hole stove. For the work by Maishanu et al

(1990), the specific fuel consumptions are, respectively, 0.38, 0.30, 0.24, 0.20, and 0.79. Therefore, except for the 4-hole stove, they all surpass the present work's specific fuel consumption of 0.54.

## **Conclusion**

The designed and constructed wood-burning stove has, boiling time, cooking time, specific fuel consumption, and efficiency of 6.06 min/kg of water, 25.71 min/kg of food (rice), 0.54 kg of fuel per kg of food, and 22.08 %, respectively. This design has thus led to significant reduction in the consumption of fuel wood, compared to the traditional open-hearth method. It has also led to reduction in cooking times. These results, not only compared favourably with similar ones elsewhere and in fact surpass others in some aspects, but also signify that a considerable amount of heat was conserved and utilized with minimal loss, in terms of percentage heat utilized in boiling and cooking, compared to the open hearth stove. This stove would thus help in mitigating the increasing relationship between availability and demand for fuel wood, coupled with the scarcity and increasing price of fossil fuels and poor thermal performances and pollutions associated with the traditional stoves.

## **Recommendations**

1. To check the initial smoke noticed during operation of this stove wood species with very low moisture content or wood dried to very low moisture content should be used.
2. Some quantity of charcoal may be added to the wood at the beginning of kindling the wood to reduce the time taken for the wood to commence burning evenly. This will also help in reducing the initial smoke.
3. A better refractive material than the fiber glass used in this work may be considered for future improvement to reduce heat loss

by conduction observed on the body of the stove.

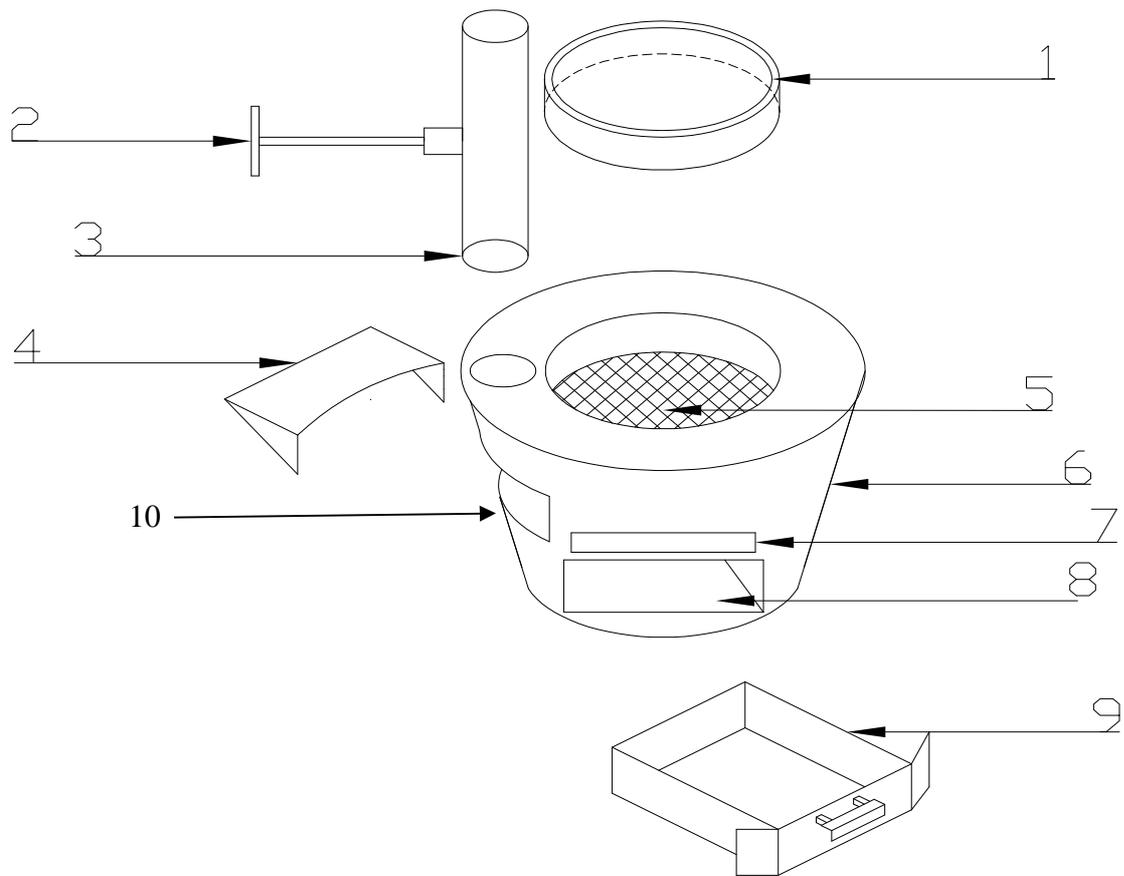
4. This stove is limited to a particular size of pot. An improvement can be made by increasing the dimensions

of the stove to accommodate various sizes of pot and/or providing more than one burning hole.

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- 11.

APPENDIX A: EXPLODED VIEW OF THE CONSTRUCTED STOVE



- |                          |                        |
|--------------------------|------------------------|
| 1. Pot rest/Pot carrier  | 6. Stove body/wall     |
| 2. Chimney damper handle | 7. Air opening         |
| 3. Chimney               | 8. Ash chamber         |
| 4. Stove handle          | 9. Ash collecting tray |
| 5. Grate                 | 10. Grate opening      |

Figure A1: Exploded View of the constructed Wood-burning Stove