

EXPERIMENTAL STUDY OF DOMESTIC CHARCOAL STOVES

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Abstract

The demand of fuelwood for domestic cooking especially the charcoal fuel is increasing in the urban settlements due to the increase in population of low income class earners who are the main consumers of this type of fuel.

This paper is presenting the results of experiments conducted on the popularly used domestic charcoal stoves in Tanzania. The results revealed some significant differences on stoves performances. The type of insulation materials and some design features incorporated into the combustion chambers of the stoves had positive impacts in relative charcoal fuel saving. About two tons of charcoal fuel could be saved by a family per annum when using an improved ceramic lined charcoal stove (CLS) instead of the traditional all metal charcoal stove (TAMCS).

Introduction

The natural forests in Tanzania are aggressively been depleted as a result of the cutting down of trees at a high rate . These forests are used as the main source of commercial timber for the local construction industry and exports. In addition, they are serving as the supply source of wood and charcoal fuels used for domestic cooking.

Surprisingly, the increasing number of consumers of charcoal fuel in the urban settlements has recently stimulated a fast growing market for charcoal in the country. The high cost of energy experienced by the middle and low class income earners have, in a way, contributed in making such groups seek the cheaper alternative source of cooking energy which is the charcoal fuel.

While the demand for charcoal fuel is increasing there is also a parallel increase in the demand for timber both of which are endangering the future sustainability of the natural forests in the country. The proper control of the quantities or rates

of charcoal and timber production from such forests is apparently difficult to establish due to the nature in which those activities are conducted. In view of the existing situation there is a problem that can be split into two components. One, is the high demand of charcoal fuel to the society because it is a relative cheaper alternative source of cooking energy for domestic purposes. The second problem is the national and international outcry to preserve and protect the natural forests because deforestation can severely affect the future environment in such as aspects as the ecology, hydrological cycles and desertification.

As a partial contribution towards tackling the problem of the rate of deforestation, some research work were directed towards the examining at the charcoal consumption side by conducting an experimental study on the amount of charcoal fuel consumed at a family level with the use of the domestic cooking stoves. In this assessment, four types of popularly used domestic charcoal stoves were tested with the use of a specially designed testing procedures.

By using a standard water boiling test, four different types of domestic charcoal stoves were subjected to the same testing conditions and their performances were measured mainly in terms of the amount of heat released into the water and the corresponding fuel consumed.

The experiments had an objective of determining the influences of stoves insulation, design features and other parameters to the overall stove's performances. The results of the conducted experiments indicated that less charcoal fuel can be used to cater for family cooking purposes if the improved and efficient stoves were used instead of the traditional stoves. An improved ceramic lined stove could assist in saving about two tons of charcoal per family in a year when compared to the use of a traditional stove. The experiments had also indicated that design improvement of the combustion chamber and the type of insulation incorporated in a stove were among the important factors responsible for a stoves efficiency.

Theory

A conceptual model of a typical domestic cooking stove is depicted in figure 1 whereby the various heat input and output components are indicated by arrows. The main source of heat energy for a charcoal stove comes from the combustion process whereby charcoal is ignited in the presence of air as given by the equation:

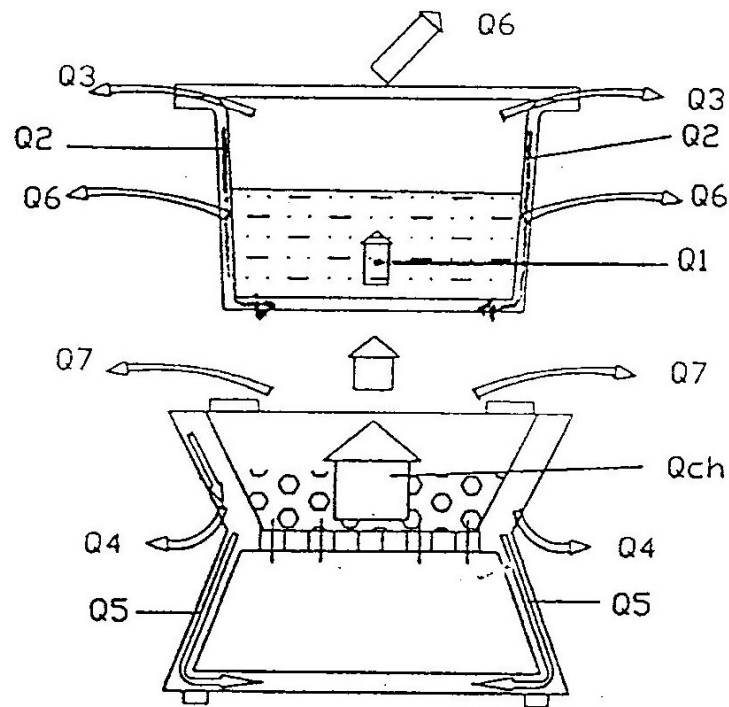
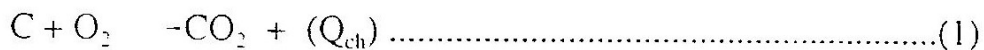


Fig. 1:Heat balance of a charcoal stove system



In this combustion process, the carbon bonded element in the charcoal is burnt in the presence of oxygen (O₂) from air, to release carbon dioxide (CO₂) and heat energy (Q_{ch}) together with some ashes as the by products. The gross calorific value of charcoal fuel is in the range of 28 to 33 Mjoules / kg^[1].

After combustion, Q_{ch} is conceptually released to the surrounding environment through seven major ways and these are quantified as Q₁ through to Q₇, as in fig. 1. The following analysis expresses the basic equations required to determine the seven various heat components:

The heat stored in pan contents: Q_1 , can be expressed as:

$$Q_1 = m_w \cdot c_w \cdot (T_b - T_o) \dots\dots\dots (2)$$

Where, $c_w = 4.2 \text{ kJ / kg}$ and the heat stored in the pan and its lid, Q_2 is determined as:

$$Q_2 = m_p \cdot c_p \cdot \Delta T_p \dots\dots\dots (3)$$

$$\Delta T_p = T_p - T_o \text{ and } C_p = 0.896 \text{ kJ / kg K for aluminium pan}^{[2]}$$

Heat loss through steam, Q_3 is determined by the equation,

$$Q_3 = m_s \cdot c_{pw} \cdot \Delta T_s + m_s \cdot h_s \dots\dots\dots (4)$$

whereby the change in enthalpy through evaporation, $h_s = 2256.7 \text{ kJ / kg K}$ for steam^[2].

$$\Delta T_s = T_s - T_a$$

The heat loss from stove walls, Q_4 , is mainly distributed through the radiation and convection processes. Thus the total heat loss is a summation of the convection and radiation components.

$$Q_4 = Q_c + Q_r$$

$$Q_c = h_{av} \cdot A \cdot (T_w - T_a) \text{ and } Q_r = \epsilon \sigma A (T_w^4 - T_a^4)$$

The average heat transfer coefficient, h_{av} , is derived from Nusselt number^[10] by using the following equation

$$Nu_{av} = h_{av} \cdot L / k \text{ where } Nu_{av} = c(G_r \cdot P_r)^n$$

To determine the values of Nu_{av} , c and n , the type of flow must be selected and the selection can be made from the standard table 1.

In the experiments laminar flow was assumed and the following values were selected $Gr \cdot Pr^* = 10^5$, $c = 0.59$ and $n = 0.25$. Hence the average heat transfer

Table 1: Heat transfer coefficients and the type of flow, source ^[3]

Type of Flow	Range of Gr.Pr	c	n
Laminar flow	10^4-10^9	0.59	1/4
Turbulent flow	$10^9 - 10^{13}$	0.10	1/3

coefficient, h_{av} , was expressed as:

$h_{av} = 0.59(10^5)^{0.25}.k/L$ or $h_{av} = 105 k / L$ where $L = D/4$, and D is the average stove/grate diameter. The value of k is chosen from table 2 . With h_{av} value determined the heat loss by convection $Q_c = 10.5 k A(T_w - T_a) / L$.

* - Gr.Pr for hot or cold surface facing up or down for a laminar flow in free convection has values ranging between 10^5 to 2×10^7 , ^[3]. The minimum value of 10^5 was taken for convenience.

Table 2: Thermal conductivity values k for various engineering materials. Source: ^[2]

Substance	Thermal conductivity k W/m K
Pure copper	386
Pure aluminium	229
Cast Iron	52
Mild steel	48.5
Concrete	0.85 - 1.4
Building brick	0.35 - 0.7
Wood (oak)	0.15 - 0.2
Rubber	0.15
Cork board	0.043

Recalling the equation for the radiated heat component Q_r ,

$$Q_r = \epsilon \sigma A(T_w^4 - T_a^4).$$

The emmissivity $\epsilon = 0.3$ for stove wall and the Stefan- Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ W/ m}^2\text{K}^4$ ^[2]. Combining the two heat component equations, the total heat loss from the stove wall, Q_4 could be expressed as:

$$Q_4 = 10.5k/L.A(T_w - T_a) + 1.7 \times 10^{-8}A(T_w^4 - T_a^4) \dots\dots\dots (5)$$

The heat stored in stove walls, Q_5 could be expressed as:

$$Q_5 = M.c_p.\Delta.T_s$$

$$\Delta T_s = \frac{1}{2} ((T_o + T_i) - (T_{os} + T_{is})) , \text{ thus}$$

$$Q_5 = 0.5m.c_p ((T_o + T_i) - (T_{os} + T_{is})) \dots\dots\dots (6)$$

The heat loss from the pan and lid is transferred to the surroundings by convection and radiation processes in a similar manner to heat loss from the stove walls. The equation expressing the lost heat is given as:

$$Q_6 = Q_{cp} + Q_{rp} \text{ where } Q_{cp} = h_{av}.A_p.(T_p - T_a)$$

and $Q_{rp} = \epsilon\sigma A_p.(T_p^4 - T_a^4)$. By substituting for $\epsilon = 0.3$ and $\sigma = 5.67 \times 10^{-8}$, and assuming similar conditions as for a stove wall then,

$$Q_6 = 10.5k/LA_p(T_p - T_a) + 1.7A_p.(T_p^4 - T_a^4) \dots\dots\dots (7)$$

The other heat loss component is the heat escaping with the flue gas or waste gases. This could be determined by taking the difference between the heat input and the sum of the six heat components as pre-determined in the equations. Therefore:

$$Q_7 = Q_{ch} - (Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6) \dots\dots\dots (8)$$

Experimental Method

The useful heat from the stoves is mainly described as the summation of the heat stored in the water Q_1 and the heat escaping with the steam Q_2 . This heat component is the one used for cooking purposes in a stove. As for the purpose of conducting a comparative heat performance experiment, the standard Water Boiling Test (WBT)^[1] was applied on the four chosen charcoal stoves. This experiment was conducted in a room with confined conditions for which the wind was shielded and the ambient temperature was constant.

In the experiment, a fresh quantity of water weighing 2000 grams or 2 litres was boiled and the testing was repeated four times for each stove. Similarly, each stove was filled with 400 grams of charcoal fuel and burnt until the boiling test was completed. The charcoal in each stove was ignited by using 30mls of kerosene

fuel and left to continue burning for 10 minutes before starting the experiment. While the experiment was going on, the boiling process was left to continue until the boiling water temperature had dropped to 98^oC. from the boiling temperature of 100^o C.

Apart from time and temperature data records, the other data records included the weight of burnt charcoal and weight of evaporated water. Four repeated testings were conducted and the average data been determined. With the given limited time and financial resources, only four different types of domestic stove designs were tested. Those tested designs were the Traditional All Metal Charcoal Stove (TAMCS), Dodoma Stove and two Ceramic Lined Stoves designated as CLS₁ and CLS₂.

Design and Insulation Features of Stoves

The TAMCS, was fabricated from scrap mild steel sheets ranging between 1.0 and 2.0 mm thickness. Its body was cylindrical with a diameter of 254 mm and a height of 176 mm. The grate for holding the fuel was at a height of 94 mm from the base of the stove. Combustion air was admitted to the stove through an opening in the ash chamber below the grate. This stove had no wall insulation.

The Dodoma stove, figure 2, was designed to have similar design features as those of TAMCS but had been improved in the combustion chamber and in the stove walls. The grate had a conical shape protruding downwards. It had two metal walls separated by an annular air gap of about 25 mm. This air gap was purposely

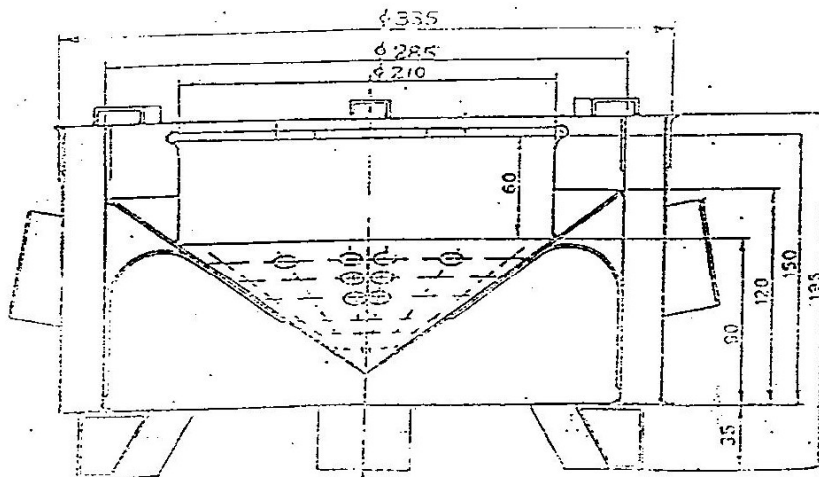


Fig. 2: Dodoma Stove (DS)

introduced in the stove to act as an insulator to heat losses between the inside and outside stove walls.

The CLS₁, figure 3, was a cylindrical and skirt like shaped stove design whose outer sides were made of thin mild steel sheets. Sometimes these stoves are made from thin mild steel sheets ranging between 0.5 and 1.5mm. thickness. Its combustion chamber was composed of a composite layer of clay and vermiculite materials. The vermiculite material layer was specifically introduced as an insulation material and was deposited on the bottom part of the air or ash chamber. With its skirt - like design, there was no metal part used in supporting the base of the combustion chamber. Instead it was supported by a thick layer of perforated clay material.

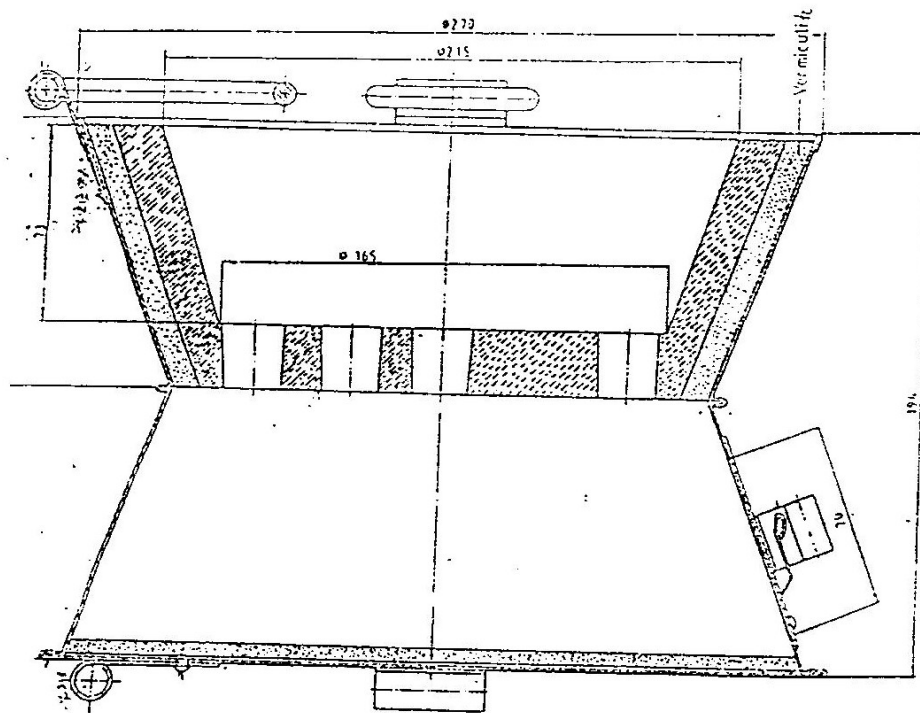


Fig. 3: Ceramic Lined Stove - skirt body (CLS₁)

The design of CLS₂, figure 4, resembles that of CLS₁ with the exception of the variation in its body shape which was cylindrical. In addition, there were also some small design modifications made in the combustion chamber whereby it was encased with a metal sheet. The composite vermiculite and clay layers were fully contained and supported within the metal encasement. The composite layers of vermiculite and clay materials were included in the stove design in order to introduce heat insulation.

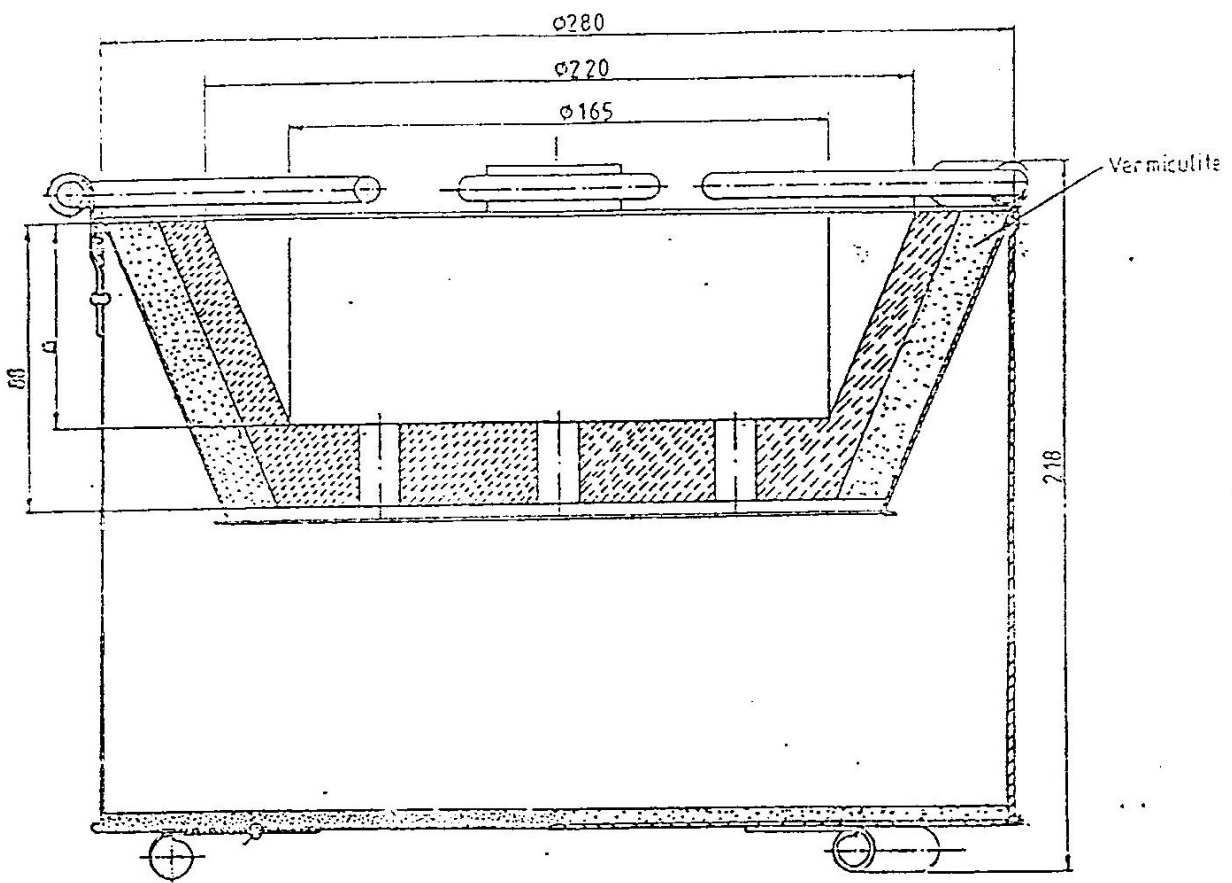


Fig. 4 : Ceramic Lined Stove - cylindrical body (CLS₂)

In order to obtain the values of heat loss through the stove walls, another experiment apart from the WBT, was devised for which measurements of the surface temperatures both on the inside and outside stove walls were measured. The temperature data generated from equation 5 in section 2.1 was utilised to calculate the corresponding values of heat losses. The surface temperature was measured by using: nickel chromel - alumel (K-type) thermocouple wires, a digital millivoltmeter and an ice-box. The probes of the thermocouple device were placed at the hot and cold (ice at 0 °C) junctions. The function of the probes was to produce a small voltage signal from the hottest contact point. The signal was amplified and made readable with the use of a digital millivoltmeter instrument and was converted to the conventional temperature measurements in degrees Celsius with the use of the standard thermocouple tables. Moreover, four sets of data readings were taken for each stove design and an average was determined. Table 4 presents results of temperature measurements on different locations on the stove for the four stoves investigated. These temperatures were used in equation

5 to evaluate the heat losses through the stove walls. The results are presented on table 5.

EXPERIMENTAL RESULTS

Given the same weight of charcoal fuel and weight of water for boiling, the performance of the four different stoves were as indicated in table 3. However for curiosity purposes, the shielding of cooking pan was done and there were interesting results worth mentioning. The tests were conducted on the two better performing stoves CLS_1 and CLS_2 . In the test, a circular metal sheet ring of width 50 mm. was placed on top of a stove to shield the pan from getting the direct cold air currents and also to prevent the hot flue air or waste gases from escaping randomly to the surrounding air, figure 5.

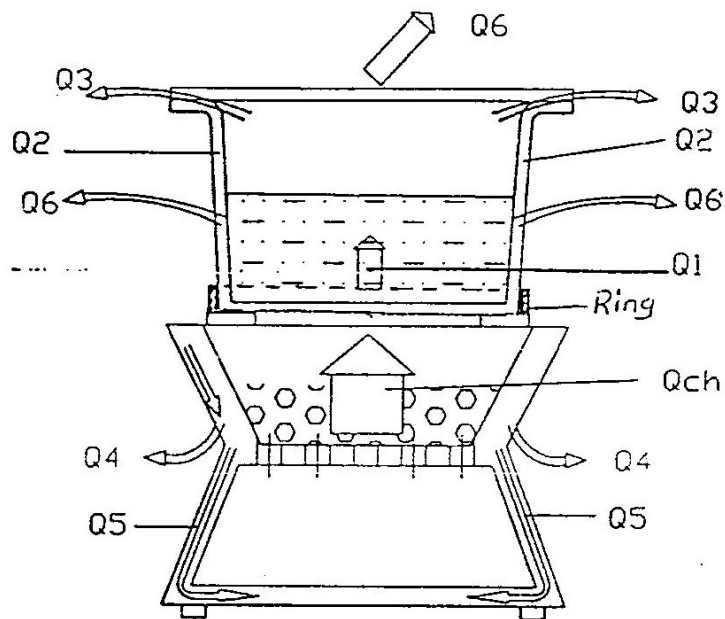


Fig. 5: Pan with a metal ring shield.

With a metal ring placed on the stoves, the WBT was then repeated as for the other previous tests. The obtained results are indicated on table 3.

The other interesting aspect was the assessment of the actual heat loss through the

Table 3 : Stoves performances in water boiling tests.

Stove type	Heat utilised (%)	Evap. water (grams)	Charcoal burnt (%)	Charcoal input (grams)
TAMCS	24.1	168.6	38.6	400.0
DODOMA	23.7	315.0	53.1	400.0
CLS1	29.6	658.0	67.2	400.0
CLS2	29.3	720.0	72.9	400.0
CLS1 & Ring	34.3	1062.0	83.0	400.0
CLS2 & Ring	33.8	742.5	66.3	400.0

stove walls. In order to obtain the values of heat losses through the stove walls, another experiment was devised with which measurements of the surface temperature both on the inside and outside stove walls were made. The obtained temperature data were fed into equation 5 of section 2.1 to calculate the corresponding values of heat losses through the stove walls. The surface temperature was measured with the use of : nickel chromel - alumel (K-type) thermocouple wires / probes, a digital millivoltmeter and an ice-box. Thermocouple probes were placed at both the hot and cold (ice at 0 °C) junctions. They sensed the heat by producing a small voltage signal from the hottest contact point. The signal sensed was amplified and made readable with the use of a digital millivoltmeter instrument. Conversion of the data to the conventional temperature measurements in degrees Celsius was made with the use of the standard thermocouple tables. Moreover, four sets of data readings were taken for each stove design and an average been determined.

Table 4 presents the results of temperature measurements on different locations on the stove for the four stoves investigated. This temperature data was applied in equation 5 to evaluate the heat loss through the stove walls and the results were presented on table 5.

Discussions

Comparatively the ceramic lined stoves CLS₁ and CLS₂ had a higher capability of burning charcoal to release more useful heat energy. This observation was derived from table 3 by comparing the relative percentage of charcoal used

Table 4: Results of temperature measurements using thermocouples.

\Stove Location	Dodom a	TAMC S	CLS1	CLS2
Center	822.0	800.0	1026.5	1013.5
Inside Wall	478.0	471.5	856.0	740.0
Outside Wall	68.0	217.0	134.5	123.0
Handle	39.0	112.5	43.5	39.5

Table 5: Stove wall heat loss

Stove design	Wall loss (Watts)	Wall loss as a percentage of rated output power (%)
DS	687	34.2
TAMCS	654	33.0
CLS ₁	413	16.1
CLS ₂	369	11.1

against the corresponding amount of water evaporated during the WBT. Another similar observation came from the experimental results on table 4 whereby the measurements of surface temperature indicated higher combustion temperatures at the grate centre for the ceramic lined stoves as compared to the all metallic stoves.

Theoretically the composite layer of clay and vermiculite material acted as a body capable of absorbing heat and also retaining it. This hot body was later radiating its heat into the grate centre even after combustion had ceased to raise its temperature to reach that level of the neighbouring hot body. This property of heat retention by the stove wall body and the backward radiation to the

combustion centre was an important design attribute in sustaining a high temperature zone and hence attaining the maximum combustion of charcoal. This condition was vital for the support of a continuous burning process even at low fuel level. This could account for the observed differences in the percentages of unburnt charcoal fuels on table 3.

Another important observation made was that when a metal ring shield was introduced on the stove, there was an increased better performance. In accounting for such an improved performance attained, it could be said that the metal ring shield assisted in preventing the random flow by directing more of the hot flue gases to reach the bottom part of the cooking pan or pot. The ring also isolated the hot flue gases from mixing with the cold air currents from the surroundings a condition which reduced the loss of useful heat to the surroundings. Hence by deliberately ensuring that as much quantity of this heat carrying media arrived at the cooking pan surface then it would be expected that more heat would be transferred into the pan and hence become available for cooking. This was in a way observed in the experiments when more water was evaporated with the same quantity of charcoal fuel.

The comparison of the relative charcoal saving among the four stove designs was of utmost importance to this research. In order to release such results the following assumptions were made:

- (1) The stove which evaporated more water was made to be a reference stove for comparison.
- (2) The obtained experimental results in every stove performance were assumed to remain the same in a similar repeated experiment.
- (3) The comparison was only based on two relevant parameters which were; the amount in grammes of the evaporated water and the quantity of charcoal fuel required for each stove to perform the same cooking (evaporating water) as the reference stove.

Hence the relative charcoal fuel loss expression F_1 referred on tables 6 & 7 has been defined as:

$$F_1 = n D(400(x_o / x_i - 1)) / 1000 \quad [\text{Kg.}] \dots\dots\dots (9)$$

D=Number of days

x_o =Quantity of evaporated water in grams

of the reference stove

x_i =Quantity of evaporated water of a stove for comparison.

n =Number of cooking times per day.

The numerical 400 in the equation denotes the initial quantity of charcoal fuel in grams charged into a stove.

By considering the annual fuel saving of a stove and assuming that a family in Tanzania could have seven to eight people and that “cooking” was done three times per day. In this case “cooking” could simply be simulated experimentally as a WBT and for simplicity the experimental test data was used. The relative charcoal fuel losses F_1 for the tested stove designs were as summarized in tables 6 & 7.

Table 6:Relative charcoal fuel losses by various stove designs CLS₂ is a reference stove; $x_0 = 720.0$

S t o v e design/type	Evaporated water x_i (g)	Charcoal loss F_1 (Kg/year)
CLS ₁	658.0	41.4
DS	315.0	563.1
TAMCS	168.6	1432.5

Table 7:Relative charcoal fuel losses by various stove designs CLS₁ with a metal ring shield is a reference stove;

$x_0 = 1062.0$

S t o v e design/type	Evaporated water x_i (g)	Charcoal loss F_1 (Kg/year)
CLS ₁	720.0	2.8.1
DS	315.0	1038.7
TAMCS	168.6	2320.9
CLS ₁	658.0	268.9

According to this analysis and as per tables 6 and 7, it could be deduced that if a better designed charcoal stove was used as opposed to a traditional stove design TAMCS, there would be a saving of up to 2 tons of charcoal fuel per annum in a family. With the present price of charcoal in towns of about 0.1 US\$ / kg where 1US\$ is approximated to 600 Tshs, a family could save about 200.00 US\$ or Tshs. 120,000.00 per annum on charcoal fuel expenditure.

CONCLUSION

The domestic charcoal stoves whose combustion chambers were basically made of only metal parts as for case of TAMCS and DS design had problems of maintain high temperatures in the combustion chamber as the level of fuel decreases in the chamber. The ceramic lined stoves which had a layer of clay and vermiculite materials as an insulation material had better properties of storing heat and maintaining high combustion temperatures in the combustion chamber to support the combustion process as the amount of charcoal ran to depletion. The heat retention and maintenance of high temperature environment at the combustion chamber of a charcoal stove was an important property required for an improved and better performance of a stove. Among other important design features for a charcoal stove is the shield or a barrier to isolate the cold air currents from mixing with the hot flue gases coming directly from the combustion chamber. This will improve the stove's efficiency.

As a result of the potential possibilities of charcoal fuel saving revealed in the stove's comparative performance experiment, the use of improved stoves is of economic advantage first to the individual charcoal fuel consumers and secondly to the nation. An unnecessary demand of charcoal fuel could be avoided if efficient stoves were used for domestic cooking. This will in turn help to reduce the amount of charcoal fuel consumption at a national level. This could in a way play a role towards addressing the problem of reducing the rate of deforestation.

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ACRONYMS

A	Area
CO ₂	Carbon dioxide
C _p	Specific heat capacity at constant pressure
Gr	Grashof number
h _{av}	Average heat transfer coefficient
k	Thermal conductivity
m	Mass

Nu	Nusselt number
O ₂	Oxygen
PHU	Percentage heat utilised
Pr	Prandtl number
Q	Heat energy flow rate
Q _{ch}	Heat energy from charcoal fuel
Q _c	Heat energy lost by convection
Q _r	Heat energy lost by radiation
T	Temperature
T _a	Ambient temperature
T _o	Outside wall temperature
T _i	Inside wall temperature
T _{os}	Starting outside wall temperature
T _{is}	Starting inside wall temperature

Subscripts:

a	Ambient
b	Boiling
c	Convection
p	Pan
r	Radiation
s	Steam

M_c = Mass of charcoal burnt

q_{ch} = Calorific value of charcoal (q_{ch} = 28,000 kJ/kg)^[1]