SAFE AND ENVIRONMENT FRIENDLY WOOD FUELLED COOKING STOVE IN HAJJ CAMPS

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ABSTRACT

Prototype firewood stoves were built and tested at King Abdul-Aziz University (KAAU) for a single standard 90 cm diameter cooking pot. The stove walls were built as U shaped boxes, with internal baffles to create passages for airflow. This air was generated by means of a blower to cool the inner surfaces of these metal boxes and supply preheated combustion air. For comparison with traditional bricks or clay stoves a firebrick stove was built with the same dimensions (combustion room volume of 0.61 m^3) as one of the steel stoves. Testing of the stoves according to the standards showed that the stove with 0.46 m^3 combustion chamber and 104x112x56 cm overall dimensions had a thermal efficiency of 19.2% and temperature elevation ratio of 1.4^{o}C/min. These values are comparable to those reported for coal fired cooking stoves in developing countries.

Keywords: *Hajj, FAO, Kerosene, Firewood Stoves, Metal, Cooking Stove And Thermal Efficiency.*

الملخص

تم في قسم الهندسة الحرارية بجامعة الملك عبد العزيز بجدة صنع واختبار نموذج لموقدين معدنيين تشعل فيهما الأخشاب للطهي في إناء من الألمنيوم قطره ٩٠ سم . جدران الموقد عبارة عن صناديق مفرغة صنت على شكل حرف U تحتوي على فواصل داخلية لتشكيل مسارات لهواء تبريد السطح الداخلي لهذه الصناديق والمواجه للنار . ويتم سريان الهواء عبر المسارات بواسطة نافخ للهواء الذي سيسخن قبل خروجه إلى غرفة الاحتراق . ولعمل مقارنة بين هذا الموقد وغيره من المواقد التقليدية المصنوعة من الطوب والطين ، تم صنع موقد بالطوب الحراري مماثل في الحجم لأحد الموقدين المعدنيين الأكبر حجما . تم اختبار هذا الموقد على غرار الموقدين وبنفس الطريقة وتم رصد النتائج وتحليلها فيما بعد . أظهرت النتائج أن الموقد المعدني ذو الحجم الصغير(٤٦, م٣) كان ذو كفاءة حرارية ١٩،٢% وهى تضاهي المواقد التي تستخدم الفحم أو الخشب في بعض الدول النامية والتي تمت دراسة كفاءتها من قبل باحثين آخرين .

1. INTRODUCTION

During pilgrimage about 2 million people gather in the area of Mina and Arafat. They stay for 4 days performing Hajj and practice the ordinary life activities (eating, shopping, drinking…etc.). Many of the people live in large camps supplied by fresh water and connected to the electric and sewage networks. Preparation of hot meals for this large number of people at scheduled times present a concern for the different Hajj authorities. Compressed Butane gas in steel cylinders, before five years, was the main source of fuel for food preparation. During the past fire of 1996, the gas cylinders were the main factor, which spread out the fire on large scale through a series of deadly explosions. Since then the authorities have banned the use of such type of fuels for food preparation within the region of Mina and Arafat.

At that time kerosene stoves were an immediate alternative but because of the short notice these stoves were not well developed to provide sufficient energy for massive food cooking. Most of these stoves were manufactured locally and provided by either manual or electric air blowers. Being the only available stoves in 1999 they were used in spite of the safety regulations violation. The main drawbacks were the starting ignition and the control of the flame intensity.

Cooking food outside the camps area in Makkah and transporting the cooked food to the different camps was a solution, which suffered practical difficulties and large delays when passing through the crowded streets. To solve these problems three wheels motorcycles were used. A special caravan for large food pans was built and towed to these motorcycles, which can to some extent avoid blocked roads. The trials of the Hajj Institute to get the permission of the Civil Defense Organization (CDO) to use kerosene stoves is still in progress and is subject to debatable arguments.

Members of the research team have been working on the problem since 1999 and were able to design, manufacture and test a kerosene stove of high heat capacity (25 kW per single torch) [Zaki, 2001]. The flame intensity (heat flux) control was electricity actuated. Authentication of the stove by the CDO and the Saudi Hajj Institute has not been completed yet as it requires first an approval of the Saudi Standards Organization. The use of kerosene stoves is facing oppositions, as the fuel is flammable. It is actually less hazardous than gas but still it has to be stored in special tanks (already built at Mina). Leakage possibility exists even if it is a minor one. Electricity as an energy supply for cooking has not been yet considered seriously as the demand required will escalate and will be penalty on the supplies for Air-conditioning and lighting. Electric pots for cooking the traditional meat-rice food (Kabsa) at large quantities do not exist. Though, a special electric rice cooker has been designed and tested in Jeddah for steaming rice for Malaysian camps, (the cooking process is entirely different than the traditional food) [Abdelkarim, 2001].

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With this introduction it is clear that the problem has not been solved in a satisfactory way. During the 2000 Hajj season several of the camps used wood (tree trunks and branches) for cooking. The wood stoves were built in a primitive simple way that hardly meets any safety or pollution regulations. Assessment of wood as fuel depends on its value as combustible material. Actually there are several wood fuels with charcoal on top followed by dry softwood, as received logwood and barks. The heat content for these types varies from 28000 kJ/kg for charcoal to 7000 kJ/kg for wet bank [Hiser, 1978]. It is to be mentioned here that wood burning is not so easy as expected but there are special problems in affinity with wood burning. Practice showed that to burn 1 kg of wood (dry wood) per hour an air supply of nearly 2.8 m^3/h is required as primary air [Chisholm, 1998]. The secondary air is important for wood burning. Insufficient secondary air leads to excessive soot formation. In contrast excess secondary air results in a cold combustion or what is known as premature combustion. Another particular difficulty is the operation of the stove at different power levels. This is a unique problem, which depends on the size of wood and the rate of feeding i.e. the interval between charges. Laboratory experiments showed that controlling the power by either changing the size of the feed or control the wood residence time is practically difficult [Prasad, 1998].

1.1. Wood stoves

In many developing countries wood represents a basic energy source for cooking. Food and Agriculture Organization (FAO) of the United Nations (UN) along with the Regional Wood Energy Development Program in ASIA have started programs in China, India and Indonesia for the development of the traditional energy sources for the domestic sectors. This program focused on the development of the firewood cooking stoves that were considered thermally and environmentally inefficient [FAO, 1993]

Universities and research centers had supervised the development of firewood stoves in both India [FAO, 1993] and China [FAO, 1993]. This extensive program led to a number of models and designs that were improved over 10 years period. The features of development between the Indian and Chinese models are different, and it is not within the scope of this paper to discuss these differences and the basic lines of development.

In this work firewood stove has been designed, manufactured, assembled and tested at KAAU. The stove has a unique feature where it is made up of separate modules that can be easily transported and assembled in place.

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2. FIREWOOD STOVE DIMENSIONS

Three stoves were built, one of which was a firebricks stove (FBS) with solid brick walls. The other two were all metal stoves (MS-1 and MS-2). This study considers only single pot stoves. There are different sizes of pots; the most common of which is the 90 cm diameter Aluminum pot. This size determines the length and width of the stoves' hot top plate with a central circular opening of 80 cm diameter. The top plate for the MS–1was 105 x 105 cm made of 6 mm thick carbon steel. For large size pots 140 or 180 cm diameters the dimensions can be proportionally increased. In this work the stove was developed for the standard size pot (90 cm diameter).

For a furnace chamber height of 65 cm, the furnace volume is 0.6 m^3. To allow for ash removal a grate of 15 cm, height, is made of steel sections. This leaves a volume of 0.46 m^3 for housing the combustible wood. In reference to the Indian practice [Chisholm, 1998] recommending the use of ¾ of the height for full charge fuel. The wood fuel is usually stacked in a honeycomb fashion up to the height of 37 cm (¾ of the fireplace volume), as measured from the upper surface of the grate. The furnace height determines the dimensions of the sidewalls. The MS–1 and MS–2 stoves were manufactured with air–cooled walls, while the FBS walls were made of firebricks. The bricks were locally manufactured with dimensions of 22x11x6 cm. The air–cooled metal walls were made of two parallel sheets, with 7–8 cm distance in between for airflow, as seen in Fig. 1.

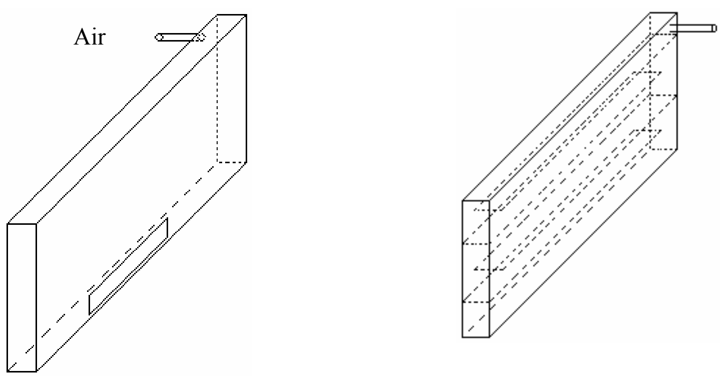

Figure 1. A sketch of the air–cooled sidewalls of the metal stove MS-1.

The air enters the wall at the ambient temperature T_a and leaves to the fireplace at T_o, which is the primary air temperature for the combustion process.

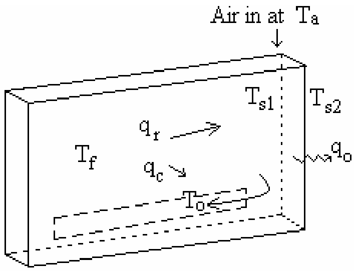

Figure 2. Heat balance of the air cooled wall

Heat is transferred from the flame to the inner side of the wall by radiation q_r and by convection from the hot gases q_c. Heat balance on the wall, Fig. 2, gives;

$$q_r + q_c = \dot{m}_a c_p (T_o - T_a) + q_o \tag{1}$$

For this equation it is assumed that the radiation and convection heat to the inner surface are transferred to the incoming air and portion of the heat is lost to the ambient, q_o. The surface temperatures T_{s1} and T_{s2} are unknowns, but for safety regulations $T_{s2} \leq 60$ °C. The radiation and convection terms in (Eq. 1) can be replaced (Stefan-Boltzmann and Newton's cooling laws) by;

$$q_r = \sigma\varepsilon h_r (T_f - T_{s1}) = \sigma\varepsilon\left(T_f^{\,4} - T_{s1}^{\,4}\right)$$

$$q_c = h_c\left(T_g - T_{s1}\right)$$

$$q_o = h_{co}\left(T_{s2} - T_a\right)$$

Substitution of the above relations in Eq. 1, gives a nonlinear relation in T_{s1} for which an iterative solution is possible for a fixed air mass flow rate.

Another approach is to set a maximum value for the inner side surface temperature, in the range of 300–500 °C and estimate the mass of air required to keep constant temperature variation between T_f and T_a. Note that for this approach the outlet air temperature T_o can be adjusted by controlling $\dot{m}_a$.

Heat balance on the inner surface only where heat across the steel plate is transferred by convection to the air flowing through the baffled wall gives:

$$q_r + q_c = U_c \,\Delta\overline{T}_m \tag{2}$$

U_c is the overall heat transfer coefficient determined from standard procedures, Incorpera [FAO, 1993], for air flowing through rectangular ducts. The dimensions of each passage are

7 cm width, 10 cm height and 95 cm long. Note that the heat transfer coefficient U_c is a function of the convection rate between the wall and the air, which in turn is a function of the flow average velocity or in other words $\dot{m}_a$. Thus iterative solution is the approach to solve Eq's. 1 and 2 assuming constant values for T_f = 1000 °C and T_a = 24 – 30 °C. The numerical results here will only give estimates of the temperature variations and will not influence the furnace dimensions, since the dimensions of the combustion space is predetermined by the size of the pot and the vertical position of the hot top plate. Therefore the experimental results, being more important at that stage, are presented in this work.

3. PROTOTYPE FIREWOOD COOK STOVES

Three prototype test-cocking stoves were built with different features, where the first stove was an ordinary firebricks stove (FBS) and natural air draft. The second one was an all metal stove (MS-1) with walls cooled by forced air supply.

Table 1. Dimensions and features of the firewood cook stoves

Stoves → Parts Dimensions ↓	Fire Brick Stove FBS	MS – 1	MS – 2
Combustion space cm Volume m^3	100 x 100 x 61 0.61	97 x 97 x 65 0.61	96 x 95 x 51 0.46
Top plate, with 80 cm opening diameter	122 x 123 x 1.2 cm	105 x 105 x 0.6	96 x 96 x 0.5
Bottom plate cm	122 x 123 x 1.2 cm	97 x 97 x 0.3 on 12 [mm] rollers	104 x 104 x 0.3 on 4x4 square bars.
Walls	117 x 116 x 6 cm	112.5 x 55 x 8 Baffled for air flow	104 x 46 x 8 Baffled for air flow
Stove door	40 x 40 x 0.5 cm	100 x 57 x 0.3 with frame	90 x 48 x 0.5 with frame
Chimney	Duct 15 x 12 x 188 cm Height	15 Diameter x 200 cm Height	14 Diameter x 200 Height
Grate	34.5 x 60 x 13 cm	70 x 80 x 15 cm with 9 x 12.5 x No. 12	70 x 80 x 15 cm with 9 x 12.5 x No. 12
Blower	Normal air draft.	4" Blower	4"
Air passage	Natural draft, 21 holes of 3.5 cm Diameter.	Forced draft, through walls	Forced draft, through walls
Cooking Pot (Cylindrical Aluminum pot)	90 cm Rim diameter, 80 cm Inner diameter and 40 cm Height		

This second stove was built in parts to be assembled in work place. The third stove (MS-2) with all metal frames and more flexibility in assembling and disassembling. The main dimensions and features of the three stoves are given in Table 1. Both FBS and the MS-1 model have the same combustion chamber dimensions, but for the MS-2 stove the combustion volume was decreased by ≈ 20 %, to study the effect of the effect of the change in combustion volume.

4. TEST PROCEDURE, RESULTS AND DISCUSSION

4. 1 Standards for testing Firewood Stoves

In Saudi Arabia the available standards for stoves is that for gas-fired stoves (SSA 167/1980). For other fuels it is possible to accept any other recognized standard. For firewood stoves that may use crop stalks, tree leaves or dung, the present study selected the Peoples Republic of China standard (issued in 1984 by the Ministry of Agriculture)[FAO, 1993] In principle, testing all types of stoves is performed by measuring the temperature elevation (sensible heating) and mass of water evaporated for a specific mass of combusted fuel. There are some special conditions when testing firewood stoves for example for multi-pot stoves, the process should be done at the same time with all stoves at the same orientation and with minimum 1.5 m distance in between. The amount of wood during the test should be between 14 to 20% of the water mass. The water volume should be 2/3 of the pot volume. In the present work an Aluminum cylindrical pot was used with 90 cm rim diameter, 80 cm inner diameter and 40 cm height. The quantity of water for testing was 133 kg that made a level of 26 cm from the pot base. According to the standards the wood required for testing varies between 19 and 27 kg. Three parameters are usually deducted from this standard test:

a. *The thermal (Heat) efficiency* refers to the ratio of the total heat absorbed by water to the heat of firewood combusted. This definition is suitable for stoves with natural air draft. For the present stove, the energy consumed for the air blower is included thus:

$$\eta_{th} = \frac{m_w C_p (T_b - T_i) + m_e h_{fg}}{m_f CV + q_B}$$

q_B is the energy of the blower, determined by recording the voltage and current consumed by the blower during the time of experiment.

b. *The elevation rate* e_v given by

$$e_v = \frac{\partial T}{\partial t}$$

It reflects the starting performance of the stove, for a specified mass of combusted firewood.

c. *Stove temperature regain rate* measures the stove heat storing and insulation capacity during residual heat harvesting period and is defined as:

$$e_g = \frac{\partial T}{\partial t}$$

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This factor is measured after burning all the amount of firewood. The hot water in the pot is then replaced by an amount of cold water ($m_w/2$) and records the temperature change. The water temperature rise is measured for a sufficient time intervals of 20 minutes to calculate the rate of temperature rise ($\partial T/\partial t$).

4.2 Test Results

The objective of the present stove testing is not to verify a thermal analysis or to validate equation (1). It is rather a prototype test mode to examine the stove components and suggest modifications. Preliminary testing was limited to manual feed of small amounts of wood and visually observing the flame and smoke, and record the temperatures rise with time during the test. For the FBS, the starting of firing the wood was difficult and additional holes were made at the bottom plate for excess air (see table 1). The maximum outer surface temperature of the brick wall was about 55 – 60 °C. For MS–1, the air was sufficient with the front side open. A small 2-inch blower was used to cool the walls and supply the combustion air, which was insufficient, and a 4-inch blower replaced it. A metal 100 x 57 cm door was fixed to the front open side to minimize the heat loss by radiation from the open combustion chamber. The MS-2 stove was built with a front door with the dimensions presented in Table 1.

Figures 3 through 5 show the temperature variations during the comparative standard test where 26 kg of wood were completely burned in each stove and the starting amount of water was 131 kg. After the boiling of the water and completely burning of all wood the hot water was replaced by new fresh water at room temperature up to half of the original amount. The heat regain was then measured through the records of the temperature rise. Fluke – Hydra data logger was used for temperature recording sensed by the T type OMEGA thermocouples. The outer surface temperatures, for both MS–1 and MS–2 stoves, were continuously monitored.

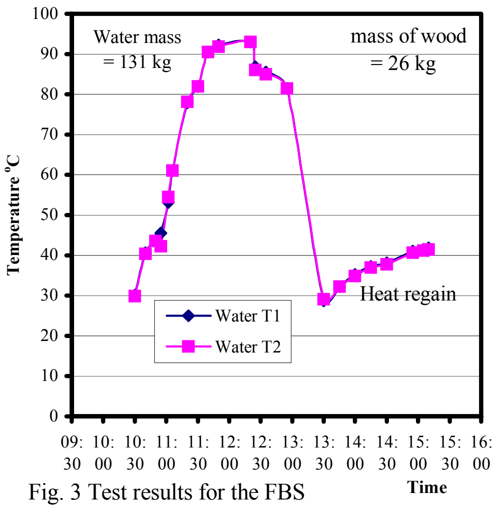

Fig. 3 Test results for the FBS

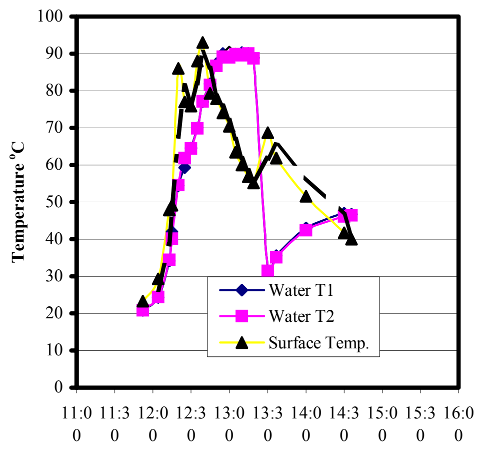

Fig. 4 Test results for MS-1 stove.

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For the FBS it is seen that the gradient of the temperature elevation is;

Elevation: $$\frac{\partial T}{\partial t} = \frac{90-30}{1:10} = 51.2\left({}^{\circ}C/hr\right) = 0.86\ \left({}^{\circ}C/\min\right)$$

The regain ratio from Fig. 6 is;

Regain: $$\frac{\partial T}{\partial t} = \frac{41.0-28.7}{1:40} = 7.86\left({}^{\circ}C/hr\right) = 0.13\ \left({}^{\circ}C/\min\right)$$

The evaporation quantity during the test was determined from the decrease in water level at the end of the boiling period. For the FBS,

$$\Delta H = 26 - 24.4 = 1.6\ cm$$

$$\therefore \quad \Delta m = \rho\,(\pi/4)D^2\,\Delta H = 8\ [kg]$$

$$\text{The heat gain} = \Delta m\ h_{fg} + m_{water}\ c_p\ \Delta T$$

$$= 8 \times 2660 + 131 \times 4.18\ (94 - 25)$$

$$= 59063\ kJ$$

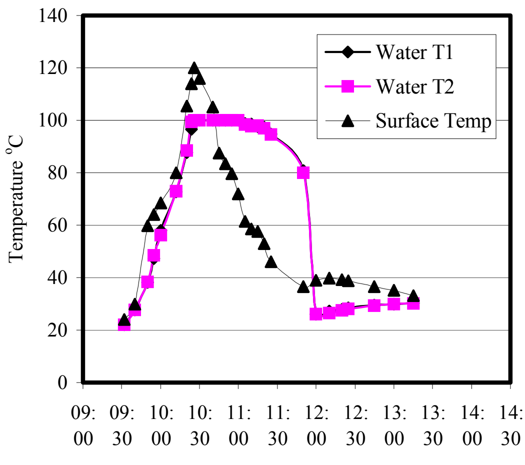

Fig. 5 Test Results for MS-2 Stove

The combusted wood was 26 kg, for Q_{HV} of 15500 [kJ/kg] for wood.

The efficiency of the stove is: $\eta_{FBS} = \dfrac{59063}{26x15500} = 15\%$

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Following the same procedure for the other stoves, the test results for the three stoves are tabulated in Table 2.

Table: 2 Test results following Chinese standards, T_a = 25 °C, m_{wood} = 26 kg, m_{water} = 131 kg

Stove Type	Temperature rate °C/min		Thermal η [%]	Outer surface side–wall temperature °C
	Elevation	Regain		
FBS	0.86	0.13	15	60
MS–1	1.02	0.23	11	77.9
MS–2	1.4	0.1	19.2	116

For MS–1 and MS–2 stoves, the blower power was neglected. It was estimated by measuring the current to the blower, 0.8 Amp and the energy consumed during the test period was 1.27 MJ, which is very small compared to the combustion heat, 403 MJ (only 0.32%).

As seen the efficiency is low compared to other cooking stoves (57 % for kerosene stoves), nearly under the same testing conditions. The thermal efficiencies for other cooking stoves as compared to the present data are given in table 3.

Table 3: Estimated thermal efficiencies with type of fuel for other cooking stoves [7].

Fuel type	Thermal efficiency %
Wood (Tropical)	15
Cow dung (Hawaiian)	15
Coal (India)	20
Coconut (India)	15
Present work (wood)	11-19.2

From tables 2 and 3 it seems that the thermal efficiency of the present FBS is within the 15 % range measured for other wood stoves [FAO, 1993]. The metal design stove MS–1 show less efficiency, as the heat losses were higher than that of the FBS. The evidence appears when comparing the stoves outer surface temperatures. For MS–2 the efficiency is reasonable and approaches that obtained for coal stoves, Table 3. Figure 6 shows close-ups of the three tested stoves and some of the parts of the MS-2 stove during assembly.

Figure 6.a FBS stove during test operation

Figure 6.b MS–1 stove during test operation

Figure 6.c MS–2 stove during test operation

Figure 6.d MS–2 supporting metal frame.

Figure 6.e: Typical cover plate for both MS–1 and MS–2.

5. CONCLUSION

The MS–2 all metal stove (combustion space of 0.46 m^3 and 112x104x56 cm overall dimensions) gives a reasonable efficiency (19.2%) and a short time for heating as the temperature elevation rate is 1.4 °C/min. On the other hand the stove regain ratio is low, 0.1 °C/min, indicating poor heat retention of the oven structure. Increase the efficiency by thermal insulation of the walls or readjusting the primary air mass flow rate requires further investigation and will add to the cost. It is important to state that the present stove provides an important feature that suits the Hajj camps where it is easy to assemble and disassemble.

FUTURE WORK

As mentioned in this paper there is a need for a high capacity-cooking stove that meets the special constraints during the Hajj period. In spite of the evident effort in this work, yet developments in a number of areas exist. Some of the broad subjects that need attention are:

1. Kitchen design; It is not enough to develop a stove of reasonable efficiency and meet the special requirements. There is a need to design a kitchen (multi-stoves layout to allow efficient performance of the cooking process). Ventilation in such a kitchen is an important issue that needs in depth study. Another point that received very little attention in kitchen studies is the waste storage and disposal. There is a need to address this same issue specially when using firewood. There is a need to study the environmental effect for such kitchens, as it will be of the indoor type. Good ventilation and minimum heat loss at the limited kitchen space are of importance.

2. There are few studies on cooking stoves and specially those developed under FAO programs for use in farms in poor developing countries. Heat transfer, fluid dynamics and combustion modeling of cooking stoves is an attractive subject to improve the efficiency of these stoves. Actual application of these studies remains questionable keeping in mind the short duration of Hajj and the high pressure on Hajj guide institutes to offer a quick and satisfactory service. High efficiency at these circumstances can be sacrificed.

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NOMENCLATURE

C_p	specific heat, kJ/kg K.
C_v	lower calorific value kJ/kg
M	Mass, kg
Q	heat flux, W/m^2
Q_{HV}	Heating value, MJ/kg
q_B	blower energy $V \cdot I \cdot \Delta t$.
t	time , s
T	temperature, °C

SUBSCRIPTS

a	ambient
b	boiling
c	convection
e	evaporation
f	fuel (wood), furnace
g	gas
i	inlet
o	outlet
r	radiation
s1, s2	Inner , outer surfaces
w	water

GREEK SYMBOLS

η	efficiency

ABBREVIATIONS

FBS	Fire Brick Stove
MS	Metal Stove

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