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Thermal Efficiency Study of Conventional Kerosene Pressure Stoves Equipped with Porous Radiant Inserts

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Abstract – *In this study, the thermal efficiency of a conventional kerosene pressure stove equipped with porous radiant inserts have been investigated. Four different porous materials, viz., silicon carbide (SiC), zirconia (ZrO_2), wire mesh roll filled with metal balls and alumina (Al_2O_3) have been used as porous radiant inserts. The inserts have been found to increase the efficiency of the conventional stove from 55% to 62%. SiC insert exhibited the highest efficiency (62%). Additionally, the flow rate and the vessel size have been optimized for the best thermal efficiency.*

Keywords – Kerosene, porous insert, pressure stove, radiation, thermal efficiency.

1. INTRODUCTION

When compared to the total energy consumption, in the developing countries, energy used for cooking constitutes a significant portion, while in the developed countries, its contribution is negligible [1]. In rural areas of India, the household energy consumption for cooking alone is 90%, while that for urban areas, the same is 50% [2]. This demand for cooking energy is increasing annually at the rate of 8.1% [3]. In the household sector, 75% of the energy requirements are met by fuel wood and agriculture waste. The rest are met by the petroleum products *viz.*, kerosene and liquefied petroleum gas (LPG) [4]. The use of LPG and kerosene in urban household is steadily increasing. However, in view of an increase in costs of the petroleum products and a fast depletion of fossil fuel reserves, there has been a global concern over the conservation of energy. In response to this, a focused approach has been taken by many researchers for the development of energy efficient devices based on improved combustion technology. Porous media combustion (PMC) is one such new and improved technology which results in high thermal efficiency and low emissions of pollutants [5]-[8].

The concept of the PMC is different from the conventional free flame combustion [9]. Unlike free flame combustion which takes place in a gaseous environment, in the PMC, combustion takes place within a highly conductive and emissive solid matrix wherein the sensible heat of combustion is converted to radiative energy [10], [11]. Hence, the contribution of conductive and radiative heat transfer in the PMC is significant. Further, owing to an increased surface area of the porous matrix, the convective heat transfer is also improved. This combined increased effect of the three modes of heat transfer improves the thermal performance of the burner based on the PMC. In the case of free flame combustion, convection is the dominant mode of heat transfer and contributions of conductive and radiative heat transfer are negligible because gases have low thermal conductivity and are bad radiators [12]. Peard *et al.* [13] have concluded that the use of radiative materials in the combustion zone of a burner is an effective means of augmenting thermal efficiency. It has been found by many researchers that the use of ceramic materials results in a better radiative heat transport [14]-[16]. Table 1 shows emissivity values of some commonly used ceramic materials.

Table 1. Properties of ceramic materials [15].

Material	Thermal conductivity at 1000°C (W/mK)	Total emissivity ε at 2000 K
Al_2O_3	5-6	0.28
SiC	20-50	0.90
ZrO_2	2-4	0.31

PMC is a two century old technology. However, its application in liquid fuel combustion has been introduced only in the last decade. Till date, not much study has been reported on various aspects and applications of combustion of liquid fuels in the PMC. Few researchers [8], [17], [18] have done preliminary studies on combustion of different liquid fuels in the porous media. They have used kerosene, ethanol and heptane as fuels and measured temperature distributions and emissions for combustion in different porous materials. However, as far as application of the porous materials in a kerosene stove is concerned, no work has been reported so far.

In a developing country like India, presently about 22% of the population use kerosene for cooking [19]. It is generally burnt in either wick or in pressure stoves having a wide range of efficiencies (35% to 55%). For non-Bureau of Indian Standards (BIS) certified kerosene pressure stoves, it is as low as 35%, while that for BIS certified stoves it is about 55%. This low efficiency of

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the kerosene stoves is a good reason to undertake investigation to increase the efficiency of the kerosene stoves. Looking at the huge amount of consumption, even a small increase in the thermal efficiency and reduction in pollutants will translate to considerable energy conservation and less pollution. With the objective of increasing the thermal efficiency, the present work is, therefore, aimed at exploring the suitability of porous materials in the kerosene pressure stoves.

In the present work, usages of different porous materials are explored to enhance the thermal efficiency of the kerosene pressure stoves. Unlike the PMC used in other applications [16], [22], herein, the concept of the PMC has been employed in a modified way. In this work, kerosene was allowed to burn in a gaseous environment as in the conventional stoves. However, some radiative materials, in the form of a porous matrix, were introduced in the flame zone so that they were convectively heated up by the combustion of kerosene. This was done to enhance the radiative heat transfer in the downstream. This arrangement was planned on the basis of the findings given in reference [23].

Kakati *et al.* used a kind of porous materials made of low cost, non combustible materials as inserts (Figure 1) in the combustion zone of a conventional kerosene pressure stove [23] and measured the thermal efficiency. They reported an improvement of about 10%. However, in their work, the reason for improvement was not clearly found out. The use of clay materials as porous inserts left some questions on justifying the same as a truly porous material. The pores of the inserts were about 8-10 mm diameter and they were not interconnected. The emissivity of the materials was low which rules out the possibility of augmenting heat transfer by radiation. The conductivity and strength of the materials were also poor. Thus, this work leaves a scope to undertake a detailed investigation with superior porous ceramic materials which have been used in other PMC applications [14]-[18].

In this study, different kinds of ceramics were used and the performance of a conventional BIS specified kerosene pressure stove was studied. The intension was to use radiant ceramic inserts in kerosene pressure stove and investigate the improvement in thermal efficiency. The following section describes construction details of a kerosene pressure stove.

Fig. 1. Porous inserts used in reference [23].

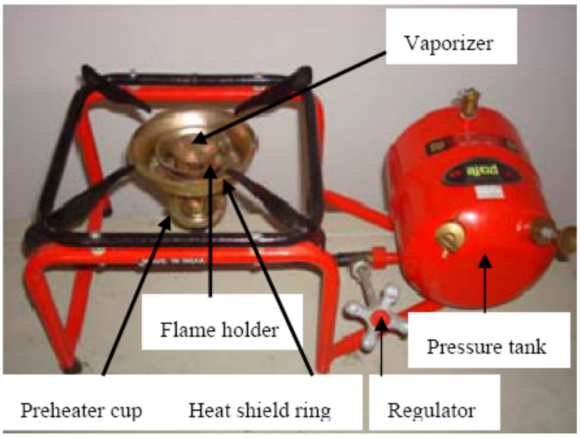


Fig. 2. Different components of kerosene pressure stove (BIS).

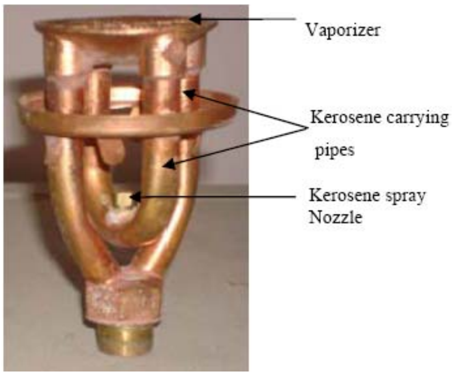


Fig. 3. Roarer stove burner.

2. KEROSENE PRESSURE STOVE

BIS specified kerosene pressure stoves are divided into two categories, *viz.*, roarer and silencer. This division is made on the basis of the type of burner. If the gas burns with a characteristic sound, the stove is known as 'roarer', and if sound is not prominent, then it is called ‘silencer’. In this study, all the measurements were done on a roarer type pressure stove.

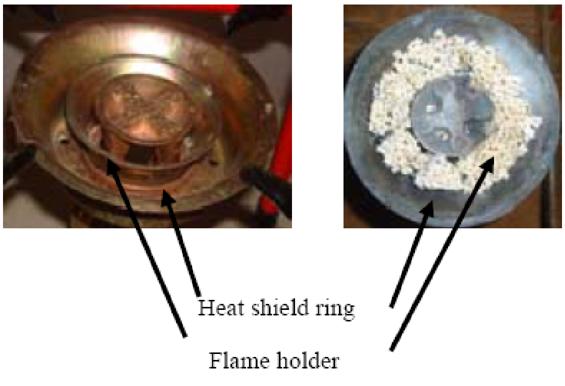
The construction of a conventional roarer type pressure stove is shown in Figure 2. It basically consists of a pressure tank with an integrated hand pump and a burner (Figure 3). The function of the hand pump is to pressurize kerosene up to ~1.8 bar. The burner is an assembly of four metal pipes and a flat circular chamber called vaporizer. When pressure is applied to the tank, kerosene moves up the through the two metal pipes and passes to the vaporizer and finally gets vaporized. It is then forced down through two other metal pipes and ejected through a central nozzle. A pre-heater cup is provided just below the burner where a small amount of kerosene is burnt initially and the heat liberated is transferred to the vaporizer and thus the vaporization process initiated. A fuel regulator is provided to regulate the flow rate of kerosene. Apart from these components, the burners are provided with two accessories, namely: a heat shield ring and a flame holder. The heat shield ring reduces the heat loss to the surroundings and the flame holder helps in stabilizing the flame. The flame holder is fitted across the burner and the heat shield ring is arranged surrounding the flame holder.

3. EXPERIMENTATION

The investigations were done on a BIS specified roarer stove manufactured by M/S Mira Udyog, Rajkot, Gujrat, India. Four different porous materials, *viz.*, silicon carbide (SiC), zirconia (ZrO_2), wire mesh roll filled with metal balls and alumina (Al_2O_3) were used as radiant inserts. Table 2 provides the detail specifications of the stove, the burner and the radiant inserts used in the experiment.

Table 2. Specifications of stove, burner and inserts.

Fuel used	Kerosene
Fuel tank pressure	1.6–1.8 bars
Fuel tank capacity	3 litre
Nozzle	Spray nozzle
Burner	Commercially available burner
Insert	SiC, ZrO_2, wire mesh roll filled with metal balls and Al_2O_3
Size of inserts	SiC, ZrO_2 and Al_2O_3: 10ppi, wire mesh: 20 mesh size



(a) Metal flame holder (b) ZrO_2 inserts

Fig. 4. Arrangement of metallic and ceramic flame holder in kerosene pressure stove.

In the present study, no major modifications were done in the stove and its burner. All the parts remained intact as in commercially available stoves. Only the metallic flame holder was replaced by radiant inserts. The radiant materials were arranged in the periphery of the heat shield ring. During the experimental trials, the heat shield ring was insulated with glass wool. Figure 4(a) shows the conventional metallic flame holder with its heat shield ring and Figure 4(b) shows ceramic flame holder with heat shield ring (ZrO_2 in the picture). In the conventional stove, kerosene is burnt in the space between flame holder and the vaporizer.

The operation of the burner in the new arrangement is quite similar to the normal stove where vaporized kerosene is mixed with air and burnt near the vaporizer. However, in the present case, highly emissive nature of the flame holder promotes radiative heat transfer in all possible directions, which is not significant in the conventional stoves. By heat of combustion of kerosene burnt in an open environment, the ceramic materials are heated up. The flame is partly trapped by ceramic materials. A clear visible flame near the vaporizer is not seen, rather the ceramics becomes red hot and illuminated. The burner is then said to be operated in partly convective and partly radiative mode.

The thermal efficiency of the burner, defined as the ratio of heat absorbed by water to the heat supplied by the fuel was evaluated by standard water boiling test recommended by the BIS [21]. In this test, a known quantity of water was taken and heated up to 90^{o}C by thermal power of the stove. The time required to bring the water from room temperature to 90^{0}C was noted and also the mass of fuel consumed during this period was recorded.

The heat absorbed by water has two components: the sensible heat gained by the initial amount of water to raise its temperature from the room temperature to that of the boiling point and the latent heat gained by the evaporated water. Since the condition after boiling is difficult to measure, in the present case, the latent heat was not considered. The fuel consumed by the stove was measured in the following manner: the stove with kerosene was weighed before and after the experiment. The temperature of water was measured by an ordinary mercury thermometer (-10 - 100^{o}C) and that of the fuel consumption by a strain gauge based weighing balance (30 kg range and 1 g least count).

The following formula was adopted to calculate the efficiency.

$$\eta = \frac{(m_w c_{pw} + m_v c_{pv})(T_f - T_i)}{m_f C.V} \times 100 \qquad (1)$$

where m_w (kg) is the mass of water in the vessel, m_v (kg) is the mass of aluminum vessel, c_{pv} (kJ/kg/K) is the specific heat of aluminum vessel, c_{pw} (kJ/kg/K) is the specific heat of water, T_f (K) is the final temperature of water, T_i (K) is the intital temperature of water, m_f (kg) is the fuel consumtion, and $C.V$ (kJ/kg) is the lower calorific value of the fuel used. Figure 5 shows a picture of water boiling test conducted on the burner operating in partly convective and partly radiative mode.

4. RESULTS AND DISCUSSION

The thermal efficiency of the conventional roarer stove incorporated with metallic flame holder is presented in Table 3. The vessel for the experiment was selected according to the BIS standrad [21]. The flow rate of the stove was maintained between 290-310 g/hr.

The average thermal efficiency of the conventional stove without insert was found to be around 55%. Table 4 shows the results of the efficiency test conducted on a roarer stove with ceramic inserts. The test was performed for three different flow rates.

It is evident from Table 4 that the operation of the burner in the flow rate range of 300-310 g/hr is not suitable. Among the three ranges considered, the efficiency is the lowest in the above stated range. It is because, in this range, the flame was spread outside the vessel, and this caused an increased convective heat loss to the surroundings.

The best thermal efficiency was obtained for the flow rate range: 130-140 g/hr. In this range all the radiant materials exhibited higher thermal efficiencies than the conventional stove without insert. The highest efficiency was noted for SiC (60.1%). This increase in efficiency of the stove with radiant inserts may be attributed to radiation effect from the highly emissive porous materials.

Thermal efficiency is a function of ratio of flame diameter to vessel diameter [24]. For a fixed flame diameter and varying vessel diameter, efficiency varies. Table 5 shows the results of the tests conducted on vessel of different sizes (6, 9, 12 and 17 kg capacity) so as to arrive at the appropriate one for the best thermal efficiency in the selected flow rate range (130-140 g/hr). In the present case, the best thermal efficiency was obtained for the vessel size with 300 mm diameter and 165 mm height. This vessel can contain 12 kg of water. It has been found that with increase in the vessel diameter the efficiency first increases and then decreases. This can be explained as follows. If a very small quantity of water is heated by a stove of particular wattage (flow rate), the convective heat losses from the stove increases. Consequently the heat received by the vessel is reduced. Likewise, if a very large quantity is heated by a stove of particular wattage, the difference between heating rate and heat loss rate from the vessel becomes lower. As the vessel size increases, the loss of heat input into the vessel is more. This causes rise in heating time. Hence, to arrive at the best thermal efficiency for a particular flow rate, an optimum vessel size is needed.

Fig. 5. Water boiling test.

Table 3. Thermal efficiency of the commercial roarer stove.

Fuel consumption (g/hr)	Time (min)	Thermal Efficiency (%)
300	22	54.7
298	22	55.2
296	21	55.3

Table 4. Thermal efficiency of the roarer stove with porous radiant inserts at different flow rate.

Porous material	Fuel flow rate (g/hr)	Thermal efficiency (%)
Zirconia (ZrO_2)	300-310	54.6
	200-210	56.7
	130-140	58.2
Silicon carbide (SiC)	300-310	56.6
	200-210	58.3
	130-140	60.1
Wire mesh roll filled with metal balls	300-310	54.6
	200-210	56.3
	130-140	58.1
Alumina (Al_2O_3)	300-310	54.2
	200-210	55.5
	130-140	57.8

Table 5. Thermal efficiency of the roarer stove with porous radiant inserts with different vessel size.

Porous material	Vessel diameter (mm)	Vessel height (mm)	Fuel flow rate (g/hr)	Thermal efficiency (%)
Zirconia (ZrO_2)	370	175	130-140	56.2
Silicon carbide (SiC)	370	175	130-140	57.3
Wire mesh roll filled with metal balls	370	175	130-140	56.5
Alumina (Al_2O_3)	370	175	130-140	56.1
Zirconia (ZrO_2)	300	165	130-140	60.4
Silicon carbide (SiC)	300	165	130-140	62.4
Wire mesh roll filled with metal balls	300	165	130-140	60.3
Alumina (Al_2O_3)	300	165	130-140	60.1
Zirconia (ZrO_2)	285	155	130-140	58.9
Silicon carbide (SiC)	285	155	130-140	60.8
Wire mesh roll filled with metal balls	285	155	130-140	59.2
Alumina (Al_2O_3)	285	155	130-140	58.5
Zirconia (ZrO_2)	260	120	130-140	58.2

Silicon carbide (SiC)	260	120	130-140	60.1
Wire mesh roll filled with metal balls	260	120	130-140	58.1
Alumina (Al_2O_3)	260	120	130-140	57.8

Table 6. Thermal efficiency of the roarer stove with porous radiant inserts and without heat shield ring insulation.

Porous material	Thermal efficiency (%)
Zirconia (ZrO_2)	55.1
Silicon carbide SiC	56.2
Wire mesh roll filled with metal balls	55.4
Alumina (Al_2O_3)	54.8

Rahima and Ijaz [1] have shown that with increase in flow rate, the heat transfer process is enhanced. However, beyond certain point, the surface area available for heat transfer at the vessel bottom for a given mass of water and a fixed temperature becomes the controlling factor. The rate of heat loss with the flue gases to the environment grows faster than the heat absorption rate of the vessel.

The next trial was done for the same porous materials, flow rate, vessel size as the previous one but without insulating the heat shield ring. This was done with a motive to investigate the role of insulation in improvement in efficiency. The results are presented in Table 6.

It is evident that the insulation of the heat shield ring was helpful in enhancing the efficiency of the system. Without insulation, the average thermal efficiency of the stove with ZrO_2 insert dropped from 59% to 55% and for the SiC insert, it dropped from 61% to 56%. With metal balls filled wire mesh roll, the drop was from 59% to 55% and with Al_2O_3 insert, the same dropped from 59% to 55%. This drop is attributed to increase in heat loss to the surroundings. Thus, the minimization of heat loss from the heat shield ring to the surroundings necessitates the need for thermal insulation. Our next effort is to design and fabricate a heat shield ring made of low thermal conductive and less emissive material. Work in this direction is underway.

The uncertainty associated with the thermal efficiency has been calculated considering accuracies in the measurements of mass of the vessel, mass of water, temperature of water and fuel flow rate. The uncertainty was estimated using sequential perturbation technique [25] and the uncertainty in the thermal efficiency was found to be ± 4.5%.

5. CONCLUSION

The incorporation of porous radiant inserts in the combustion zone increases the thermal efficiency of the roarer type conventional kerosene pressure stove. This trend was observed with all four types of porous media considered in the present study. This increase in efficiency is attributed to the radiation effect from the highly emissive porous materials. SiC insert exhibited the highest efficiency (62%). Further, the thermal efficiency was observed to be a function of flow rate and vessel size. The best thermal efficiency was found for the flow rate: 130-140g/hr and the vessel size: 300 mm diameter and 165 mm height. Further, the experiments with and without insulation of the heat shield ring showed that with insulation the thermal efficiency of the stove can be increased by 4-5%.

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NOMENCLATURE

m_w	mass of water (kg)
m_v	mass of aluminum vessel (kg)
c_{pv}	specific heat of aluminum vessel (kJ/kg/K)
c_{pw}	specific heat of water (kJ/kg/K)
T_f	final temperature of water (k)
T_i	intital temperature of water (k)
m_f	mass of fuel consumed (kg)
$L.C.V$	lower calorific value of fuel (kJ/kg)
ε	emissivity (dimensionless quantity)

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