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Performance Analysis of Domestic LPG Cooking Stoves with Porous Media

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Abstract- *Porous media combustion is an area of current research aimed at improving the performances of combustion devices and thus its application to various systems is being widely explored. One of the potential applications of the porous media combustion is in the LPG cooking stoves. The present paper compares the efficiencies, emissions and energy cost for the conventional domestic LPG cooking stoves with and without the usage of various porous media like metal balls, pebbles and metal chips. With the usage of porous media, the maximum thermal efficiency of the stove was found to be 73% which for the conventional stoves was in the range of 67-69%. In the emission test, the % volume of CO_2 was found to increase from 0.6875 to 0.9375 and the ppm of CO was found to decrease from 225 to 118. Energy cost analysis showed a saving of about 10%. Assuming the average cooking time in an Indian family to be 8 hours per day, over a period of one month, this saving is thus 7.6% of the cost of a 14.5 kg LPG cylinder available to Indian domestic consumers. These results show a better prospect for the use of porous media in domestic LPG cooking stoves.*

Keywords - Combustion, Energy cost, Porous media, Thermal efficiency.

1. INTRODUCTION

Fossil fuels reserves are depleting day by day, and usage of the conventional fuels is increasing considerably. To meet the impending fuel crisis, therefore, an extensive research is being carried out in the area of non-conventional fuels like hydrogen and bio-fuels. At the same time, some design modifications are also explored to make the existing systems more and more efficient. The objective of these design modifications is to help conserve energy to the maximum possible extent and thereby extend the availability of the conventional fuels for some more years and at the same time, minimize the emissions of pollutants.

Liquefied petroleum gas (LPG) is one of the commonly used conventional fuels for domestic applications. Its consumption in domestic cooking is increasing every year at the rate of approximately 10% [1]. The total domestic consumption of LPG in India is almost comparable with other petroleum products used in industrial applications [1]. With some improvements in the existing LPG cooking stoves, a small saving in its consumption per family will lead to an enormous saving nation wide. Thus, there is a need for research in the LPG cooking stoves.

In any combustion system, a burner plays an important role in combusting a fuel. An improper design of a burner often leads to an inefficient combustion and excessive pollutant formation.

The combustion efficiency of a combustion device is higher than its thermal efficiency and the former may be approximately close to 100%. Experimental investigations done at IIT Guwahati on thermal efficiencies of the LPG cooking stoves available in the market showed efficiencies in the range 67-69%. This is in conformity with the maximum thermal efficiency of 70% of a LPG cooking stove reported by Central Petroleum Research Association, India [2]. In view of huge consumption of LPG in India, thus there is a need to explore ways to further improve thermal efficiency of LPG cooking stoves.

With the objective of improving the thermal efficiency of domestic LPG cooking stoves, in the present work, experiments were carried out by incorporating porous media such as metal balls, pebbles and metal chips in the mixing chamber of the conventional cooking stoves. Thermal efficiencies, emission and energy cost analyses were carried out with and without the usage of various types of porous media.

Before discussing the experimental set up and results, the paper describes the advantages of combustion in porous media burners over combustion in the conventional domestic cooking stove burners by briefly explaining the principal mechanism in both the cases.

Conventional Domestic Cooking Stove Burner

All types of burners in cooking stoves work on the principle of a Bunsen burner. The schematic of a typical burner of a conventional LPG domestic cooking stove is shown in Fig. 1. It consists of a fixed orifice for gas inlet, two ports for primary air supply, a venture-shaped mixing tube and a burner head with ports (holes) drilled in it fitted on top of the mixing chamber. The narrow zone of the mixing tube is called the throat, which diverges into the hind part called its bell. The gas flow rate is controlled by a valve in the gas line. Positions of the two primary air ports relative to gas inlet port vary according to manufacturers. In some burners, they are located slightly downstream of the gas inlet port.

The high velocity gas jet creates a low static pressure in the burner bell and this causes suction of primary air through the two primary air ports. Air and gas mixes in the mixing tube and through mixing chamber it comes out in the form of jets through the ports of the burner head. Combustion takes place on top of the burner head. The ports are closely located circumferentially and thus the jet flames from the individual ports merge to form a single

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flame (Fig. 2). The secondary air is entrained to the combustion zone from the bottom of the mixing chamber and air also diffuses to the combustion zone from the circumferential area surrounding the flame. Thus combustion in the burner of a domestic LPG cooking stove is a partially premixed one.

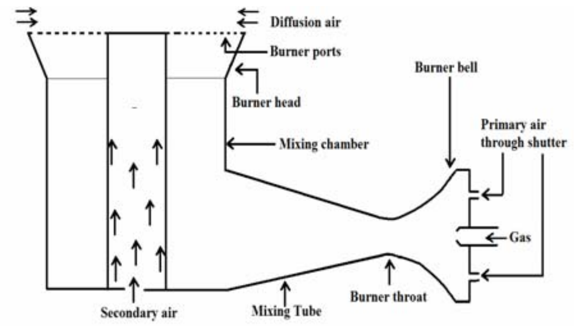

Fig. 1. Schematic diagram of a typical conventional LPG cooking stove burner.

Fig. 2. A flame in a conventional domestic LPG cooking stove.

The combustion in the burner of a domestic LPG cooking stove takes place in a gaseous environment and the flame stabilizes over the surface of the burner (Fig. 2). This combustion is known as free flame combustion. In free flame combustion, the reaction zone is very thin and because of which the temperature gradient across the flame is very high. A thin reaction zone and a sharp temperature gradient are responsible for inefficient combustion and relatively a higher amount of pollutant formation in such combustion devices. Further, because of a thin reaction zone and an elongated flame size, power density is less and size of the combustion chamber becomes larger than the required [3].

Burners based on free flame combustion have in general low power modulation. The burner of a domestic LPG cooking stove operate in the range of $P_{max}/P_{min} = 2-3$. For cooking varieties of food items, it is desirable to have an extended power range. In terms of ease, LPG cooking stoves are better compared to other types of cooking devices such as kerosene and wood stoves which are still widely prevalent in India. However, NOx emissions from such stoves are more than the kerosene stoves [5]. Also, CO emissions are also more than the prescribed regulations in the developed countries [3, 4]. Thus in view of a more stringent regulation on pollutant emissions in the near future in the developing countries, market requests for an environment friendly and economical cooking stoves are inevitable. Thus, there is a need to look for improvements in the conventional LPG cooking stoves. Incorporation of a burner based on porous media combustion in a LPG cooking stove is one such possible solution.

Porous Burner Technology

Combustion in porous media takes place in 3-D cavities of the inert porous matrix. These cavities, unlike the ports in the burner head of a conventional LPG cooking stove, are interconnected. Material of the porous matrix is chosen so as to have higher value of thermal conductivity and emissivity. Further, their extinction coefficients are also large so that they are radiatively highly participating.

In porous media combustion, flame can be stabilized over the surface or it can remain fully confined within the porous matrix. Combustion in the latter one is known as matrix stabilized and is known as flameless combustion and it has found wide applications. The porous burner proposed for the LPG stoves in the present work works on the principle of matrix stabilized combustion.

Gases have a very low value of thermal conductivity and radiatively also they are less participating. Therefore, convection is the only dominant mode of heat transfer in the conventional LPG cooking stoves as they work on the principle of free flame combustion. On the other hand, porous material being highly conducting and radiating, apart from enhanced convective heat transfer because of increased surface area in the porous matrix, conduction and radiation modes of heat transfer also become significant. Further because the pores are inter-connected and porous material is highly conducting and radiating, there is a better homogenization of temperature across the porous matrix. Presence of significant amount of radiation, preheats the incoming air-fuel mixture upstream and this helps in improving the combustion behavior. As a result of which devices based on porous media combustion have high radiant output, low levels of NO_x and CO emissions, high flame speeds, extended lean flammability limits, elongated reaction zones, high power modulation range and high power densities [3, 4].

The matrix stabilized porous burners have two zones (Fig. 3). The preheating zone is made of low porosity and less conducting material. The combustion zone above the preheating zone is made of highly radiating and conducting material and have larger size interconnected pores. Combustion starts at the interface of the two zones and spreads over the entire volume of the combustion zone.

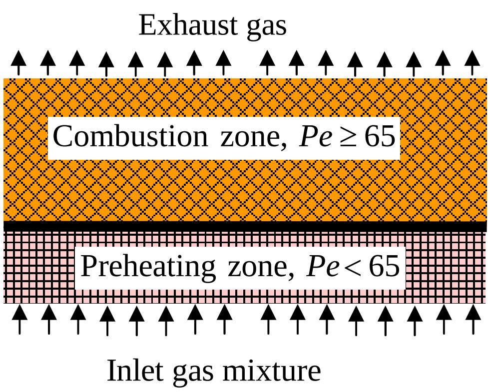

Fig. 3. Schematic diagram of a two section porous media burner.

The reason for choosing low thermal conductivity material and small size pores in preheating zone is to avoid combustion in this zone and thus avoid possibility of any flash back. This is achieved by setting the modified Peclet number $Pe < 65$ $\left(Pe = \frac{S_L d_m c_p \rho}{k} \right)$ which in turn depends on the equivalent pore diameter d_m [6]. In the definition of *Pe* given above, S_L is laminar flame speed, c_p is the specific heat capacity, ρ is the density, and k is the thermal conductivity of the gas mixture. In combustion zone, parameters are so chosen that $Pe > 65$. If $Pe < 65$, the flame is unable to propagate and quenching occurs.

The porous media combustion technology as discussed above has found successful applications in systems such as radiant tube burners, glass melting furnaces, slab reheating furnaces, boiler heat exchanger, heating system for household, auxiliary car heating and burners for steam generation, etc. [7] - [11]. With radiant porous burners, in a glass melting furnace, it has been possible to preheat the combustion air above 1000 ^{0}C by recirculating the hot exhaust gas which has resulted in fuel saving up to 50% [7]. A significant decrease in emission of pollutants was also reported. Jugjai and Natthawut [12] have used a porous insert to preheat the incoming air in a LPG cooking stove and have found an increase in thermal efficiency by about 30% over its original efficiency of about 30%. They did not however put the porous material in the combustion path and hence they could not harness the true benefit of the porous media combustion technology as discussed above in the LPG cooking stoves. It is to be noted that as discussed above, conventional domestic LPG stoves available in Indian market have efficiencies in the range of 67-69%.

As far as application of porous media in the burner of a domestic cooking LPG stove is concerned, no work has been reported so far. The present experimental investigation is, therefore, the first preliminary work in the direction of using porous media in the domestic LPG cooking stoves.

In the present work, performance evaluation of a domestic LPG cooking stove is done by using porous media like metal balls, pebbles and metal chips in the mixing chamber of the conventional LPG cooking stoves without its burner head. In the following paragraphs, we briefly discuss the experimental procedure, results and conclusions.

2. EXPERIMENTAL PROCEDURE

In India, Bureau of Indian Standards sets guidelines for testing the thermal efficiencies for all types of cooking stoves. For LPG cooking stoves, the thermal efficiencies are determined according to Indian Standards (IS) 4246:2002. Following the guidelines of IS 4246:2002, thermal efficiencies of cooking stoves in the present work were estimated by conducting the water boiling test and the procedure followed is briefly described below.

A 5 kg LPG cylinder was connected to a regulator and then with a pressure gauge in between to the burner. To purge air and to establish the required gas pressure, LPG at a pressure of 2.942 kN/m^2 was allowed to pass through the burner for a few minutes. Only one burner of the cooking stove was tested at a time. The aluminum pan used for water boiling test was selected according to the range of gas flow rate used in the experiment. The pan mass along with its lid and the mass of water used in the pan was noted. Temperature T_1 of water was noted and recorded as long as it remained constant. The cylinder was disconnected and its weight W_1 was noted and then again the cylinder was connected to the line. The gas supply was turned on and it was ignited. Water was warmed up to 80^{o}C and for uniformity in temperature; stirring was started and continued until the end of the test when the temperature T_2 of water reached 90^{o}C ± 1^{o}C. Then the burner was put off. The cylinder was disconnected and its new weight W_2 was noted. The difference in the weight $(W_2 - W_1)$ estimates the mass of gas used to heat water by $(T_2 - T_1)$.

The percentage thermal efficiency η_{th} of the stove was calculated based on the following formula:

$$\eta_{th} = \frac{(G \times C_w + W \times C_v)(T_2 - T_1)}{\left(W_1 - W_2\right) CV} \tag{1}$$

Where G is the quantity of water (in kg) in the vessel, CV is the calorific value of the gas, W is the weight of the vessel in kg, C_w, C_v (kJ/kg) are the specific heats of water and vessel respectively. For every burner, experiments were repeated three times and average of the three values was taken as the final efficiency. The same procedure was also followed when porous media was used.

To compare the thermal efficiencies of burners with porous media with those of the conventional LPG cooking stoves, a market survey was done to get the various types of burners used in conventional domestic cooking stoves. Seven types of burners were selected from the Indian market. Burner heads of the same are shown in Fig. 4.

While using the porous media, the burner head (Fig. 4) was removed and as shown in Fig. 5, the mixing chamber was filled with the porous media. Unlike the conventional burners, in which the combustion takes place entirely over the surface of the burner head, in case of porous media used in the present study, most of the combustion was taking place inside the porous matrix in the mixing chamber. To minimize the heat loss, the bottom base and the side of the mixing chamber was insulated using ceramic wool. Table 1 summarizes the four combinations of porous media that formed two zones of the burner as discussed in section *Porous "Burner Technology"*.

The four combinations as given in Table 1 were arrived on the basis of the desired height and color of the flame. The objective was to achieve almost flameless combustion. This was done by appropriately choosing the respective thicknesses of the two zones and sizes of metal balls and pebbles.

Thermal efficiency test in each case was followed by exhaust gas analysis. Percentage volume of CO_2 and ppm of CO were determined using Miniwarn (Make: Dräger, Combustible Gases: CO: 0-2000 ppm and CO_2: 0-5.00 % Vol., H_2S concentration > 100ppm). The energy cost analysis was done analytically for all the four sets of porous media and the same was also compared with the conventional burners considered in the present study.

a. Nikitsa Burner
b. Regular Burner
c. Side Flame Burner
d. Sunflame Burner
e. BPL Burner
f. Super Flame Burner
g. Aluminum Base Burner

Fig. 4. Conventional burners available in the market chosen for comparison (only burner heads are shown).

In the following paragraphs, we briefly describe experiments with four sets of porous media:

Case 1: *3 mm and 8 mm metal balls*

In this case, the 3 mm metal balls formed the preheating zone and 8 mm balls formed the combustion zone. The flame height was less compared to the conventional burner and a complete blue flame was also achieved. The flame in this case stabilized above the surface. In this case, insulation was not provided. The soot formation was observed in the preheat region indicating undesirable combustion in that region. The reason for undesirable combustion in the preheat zone is attributed to high thermal conductivity and emissivity of the metal balls. The thermal efficiency in this case was found to be 68%, which is very close to the efficiency of conventional burners. Since there was no improvement in the thermal efficiency, but a blue flame of less height was obtained in this case, the relative thicknesses of the two zones were retained for other combinations of porous media.

Fig. 5. Insulated mixing tube of a conventional burner filled with metal balls as porous media.

Table 1. Two sections of porous burner with different combinations

Porous media	Zone 1	Zone 2
Ball – Ball	Metal balls of diameter 3 mm	Metal balls of diameter 8 mm
Pebble – Ball	3-4 mm average diameter	Metal balls of diameter 8 mm
Pebble – Ball with insulation and reduced height	3-4 mm average diameter	Metal balls of diameter 8 mm
Pebble and metal chips insulation with the reduced height between the burner surface and the bottom surface of the vessel.	3-4 mm average diameter	Metal chips

Case 2: *Pebbles and 8 mm metal balls*

To avoid the undesirable combustion in the preheating zone, metal balls were substituted with pebbles of an average diameter of 3 mm. Because of low thermal conductivity and emissivity of pebbles, combustion was not observed in this zone. The thermal efficiency in this case was observed to be 69%. The temperatures of the surrounding atmosphere, the stove metal body and the floor where the stove was placed were found to be more than the previous case. This rise in temperature is attributed to the fact that in this case, combustion was mostly taking in the mixing chamber and subsequently height of the flame was very small. To minimize the heat loss, in the next set of experiments, insulation was thus provided.

Case 3: *Pebbles and metal balls with insulation on the mixing chamber*

To avoid the heat loss, ceramic wool insulation as shown in Fig. 6 was provided along the sides and the base of the mixing chamber. Further, to minimize radiation heat loss in the upstream, distance between the top surface of the mixing chamber and bottom surface of the pan was reduced. With these modifications, thermal efficiency was found to increase to 72%. However, in this case too, like the previous two cases, fully matrix stabilized combustion was not observed.

Fig. 6. Combustion in the porous medium of metal balls.

Case 4: *Pebbles and metal chips with insulation on the mixing chamber*

To achieve the flameless combustion, as shown in Fig. 7, metal balls in the combustion zone of the mixing chamber were replaced with mild steel chips. As expected, the metal chip matrix, unlike the previous cases of metal balls, was found to become red hot and no flame was observed outside the chip matrix. The thermal efficiency in this case was found to be 73%. In this, the heat generation was so high that the side wall of the mixing chamber became red hot. Temperature of mixing tube was also found to be higher than the previous three cases.

Fig. 7. Combustion in porous medium of metal chips.

3. RESULTS

In the following pages, we compare thermal efficiencies, emissions and energy cost for the conventional domestic LPG cooking stoves with and without porous media. These results are the summary of the experiments and observations made in Section 2.

Thermal Efficiency

The thermal efficiency of the seven types of conventional burners selected from the Indian market was in the range 67-69%. The same for the burners with its mixing chamber filled with porous media as described in cases 1-3 in Section 2 was found in the range 69% - 72%. By replacing the metal balls in the combustion zone by mild steel chips (Case 4 in Section 2), the thermal efficiency was found to be 73%. These results are summarized in Table 2. It is observed that with the use of metal chips in the combustion zone and providing insulation over the mixing chamber, thermal efficiency can be improved by 4% of the maximum value achievable with conventional stoves.

Table 2: Thermal efficiencies of different burners

Sr. No.	Burner model	Thermal efficiency (%)
1.	Conventional Burners	67 - 69
2.	Metal balls and gravel (Cases 1-3 of Section 2)	68 - 72
3.	Metal chips (Case 4 of Section 2)	73

Exhaust gas analysis

Emissions resulting from combustion are an important environmental factor. In case of incomplete combustion, the quantity of CO in the exhaust gas will be more than that for the stoichiometric air-fuel ratio. In porous media combustion, CO levels have been reported less than the free flame combustion. In Table 3, for the three cases considered in Table 2 of Section 3.1, %volume of CO_2 and ppm of CO in the exhaust are summarized. Thermal efficiencies of the three cases are also included in Table 3 to correlate the %volume of CO_2 and ppm of CO in the exhaust.

Table 3: Comparison of exhaust gases for different configurations of porous media with conventional burner

Sr. No.	Burner model	Thermal efficiency (%)	% Volume of CO2	ppm of CO
1.	Conventional Burners	67 – 69	0.6 – 0.7	225
2.	Metal balls and gravel (Cases 1-3 of Section 2)	68 – 72	0.7 – 0.8	188
3.	Metal chips (Case 4 of Section 2)	73	0.93	117

It is seen from Table 3 that when thermal efficiency increases, % volume of CO_2 in the exhaust increases and the ppm of CO decreases. In case of metal chips, thermal efficiency is the maximum and hence ppm of CO is the minimum.

Energy Cost Analysis

Apart from increasing the thermal efficiency of the LPG cooking stoves by using porous media, one other objective of the present study has also been to see if the proposed technology is perfected, how much fuel saving in terms of money is feasible. To check this aspect, energy cost analysis was done.

The energy cost (in Rs.) which is paid by the user for consumption of LPG for one hour was calculated for all the cases. Energy cost was calculated from the following formula [13, 14]:

$$\text{Energy cost} = \text{Heat released by the fuel} \times \text{Cost of 1 MJ of fuel}$$

The energy costs for different cases considered in the present study are summarized in Table 4.

Energy cost calculation is based on the following parameters.

Calorific value of LPG (CV) = 45.56 MJ/kg

Heat released by the fuel $= \text{fuel consumed} \times \text{calorific value}$

$$= (W_2 - W_1) \times 45.56 \text{ MJ}$$

Cost of 14.5 kg LPG cylinder = Rs. 315

Cost of 1 kg LPG = Rs. 21.72

Energy content of 1 kg LPG = 45.562 MJ

Cost of 1MJ of LPG $= \frac{21.72}{45.562}\left(\frac{\text{Rs.}}{\text{MJ}}\right) = 0.4768\left(\frac{\text{Rs.}}{\text{MJ}}\right)$

Energy cost $= (W_2 - W_1)\left(\frac{kg}{hr}\right) \times 45.56 \text{ MJ} \times 0.4768\left(\frac{\text{Rs.}}{MJ}\right)$

$$= Rs.(W_2 - W_1) \times 21.72$$

Table 4: Energy cost comparison of the porous media burners with the conventional burner

Sr. No.	Burner model	Thermal Efficiency (%)	Heat utilized in cooking (MJ)	Energy cost (Rs.)
1.	Conventional Burners	67-69	9.6-9.4	> 3
2.	Metal balls and gravel (Cases 1-3 of Section 2)	68 – 72	9.4 – 8.8	< 3
3.	Metal chips (Case 4 of Section 2)	73	8.5	2.9

From Table 4, it is observed that energy cost in case of metal chips is the lowest. Compared to conventional burners, if metal chips are used as porous media, for one hour cooking, a saving of Rs. 0.5 is achieved. Assuming a maximum of 8 hours of cooking per day in a family of 4-5 members, on a monthly basis, this saving can amounts to 7.6% for a 14.5 kg LPG cylinder.

4. CONCLUSIONS AND RECOMMENDATIONS

Use of porous media in the domestic LPG cooking stove was explored. Experiments were performed with three different combinations of porous media. To compare the improvements, experiments were also performed with seven different models of conventional LPG cooking stoves available in the market.

Thermal efficiencies of the LPG stoves using porous media without insulation were found to be comparable with the conventional stoves. The % volume of CO_2 was found to be more and ppm of CO was found to be less in the exhaust gas. These signified better combustion in case of porous media. By providing insulation on the side of the mixing chamber and by using pebbles and metal balls as porous media, thermal efficiency was found to increase to 72%. The maximum thermal efficiency of 73% was found when pebbles were used in the preheating zone and mild steel chips in the combustion zone. The % volume of CO_2 was found to be further more and ppm of CO was found to be further less in the exhaust gas. Energy cost analysis showed that for over a period of one month, the money saved is 7.6% of the total cost of 14.5 kg LPG cylinder available to Indian consumers.

The present work has been the first experimental investigation to study the feasibility of using porous media in the domestic LPG cooking stoves. This work has established that with the use of porous media in LPG cooking stoves, its thermal efficiency can be improved and cooking can also be economical. The work at Center for Energy, IIT Guwahati is underway to perfect this technology by performing extensive experiments on various aspects of using porous media in domestic LPG cooking stoves.

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