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Performance analysis of porous radiant burners used in LPG cooking stove

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Abstract
This paper discusses the performance investigations of a porous radiant burner (PRB) used in LPG cooking stove. Performance of the burner was studied at different equivalence ratios and power intensities. Thermal efficiency was found using the water-boiling test described in IS: 4246:2002. The newly designed PRB showed a maximum thermal efficiency of about 71%, which is 6% higher than that of the conventional burners. Influence of ambient temperature on the thermal efficiency of the PRB was also investigated. Using a PRB of 80 mm diameter at the operating conditions of 0.68 equivalence ratio and 1.24 kW power intensity, the thermal efficiency was found to increase from 61% at 18.5 ^{o}C to 71% at 31 ^{o}C ambient temperature. The CO and NOx emissions of the PRB are in the range of 9 to 16 ppm and 0 to 0.2 ppm, respectively, while the respective values for the conventional burner are in the range of 50 to 225 ppm and 2 to 7 ppm.

Keywords: Porous radiant burner, LPG cooking stove, Thermal efficiency.

1. Introduction
Depleting fossil fuel sources and increasing ecological imbalance due to the combustion pollutants have necessitated the need to improve efficiency of the existing combustion devices and to reduce emissions. In recent years, combustion in porous radiant burners has been received special attention due to their higher thermal efficiencies and lower NOx and CO emissions. They are also characterized by high flame speed, wider flammability limit and high radiant output [1].
Combustion in a conventional burner is characterized by a free flame (as combustion takes place in the gaseous environment), where convection is the predominant mode of heat transfer. As the gases have poor thermal conductivity and low opacity, contributions of conduction and radiation modes of heat transfer from the burned to unburned gases is negligible. In a PRB, the heat transfer mechanism differs from a conventional burner, as the combustion takes place inside the cavities of a highly conducting and radiating porous inert medium, which is convectively heated by the flowing gas. The hot porous medium then recirculates heat, as it radiates heat in all directions and preheats the incoming air-fuel mixture. Hardesty and Weinberg [2] showed that recirculation of combustion heat extended the flammability limits beyond those of a conventional flame. These flames, referred to as 'excess enthalpy flames', could achieve peak temperatures higher than the theoretical adiabatic flame temperatures. Since, leaner mixtures could be burned, CO emissions would be low, and the resulting lower global temperatures suppress the production of NOx. Due to the existence of all three modes of heat transfer viz. conduction,

convection and radiation, the PRBs are characterized by better heat transfer and uniform temperature distribution. Heat dissipates from the porous matrix as the flame comes in contact with the highly conducting and radiating solid material. Dependence of the flame position on porosity has led to the concept of a double layered PRB with varying porosities [3].

A double layered PRB consists of a preheating zone and a combustion zone. The porosity of the pre-heating zone is low, which prevents the ignition and flame propagation. Since the ignition is prevented in the zone, the air-fuel mixture is pre-heated through the heat-recirculation from the combustion zone. The interface of the two zones acts as a flame holder. The flame stabilizes either inside the burner or just above the surface of the porous matrix, depending upon the flow velocity and thermo-physical properties of the porous material [4]. In order to stabilize the combustion process, a balance must be achieved between heat recirculation, heat release and heat losses, so that the effective flame speed is equal to the flow velocity. The flame will move downstream when the flow velocity is greater than the flame speed and vice versa. An illustration of the combustion occurring in PRB is shown in Figure 1.

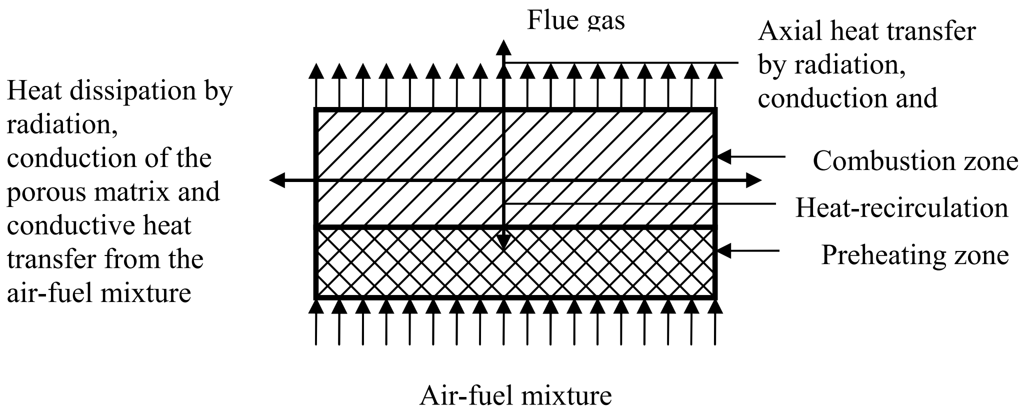

Figure 1. Illustration of combustion occuring in porous radiant burner

An extensive research in the area of PRB has led to its wide ranging commercial applications such as radiant tube burners, glass melting furnaces and slab reheating furnaces, etc [5-8]. Combustion based on the porous medium technology has now been considered as the emerging furnace design methodology for the next generation of high performance burner systems. While the above-mentioned development of the burners using porous medium technology has been focused on the large-scale industrial gas burners, little attention [9-11] has been paid to its domestic application.

It is evident from the literature that most of the reported works on combustion in porous medium are based on the industrial applications and there is a lack research work the applicability of PRB in domestic LPG cooking application. In a recent study, Pantangi [12] investigated the performance of the PRB in the equivalence ratio range of 0.3- 0.6 employing 2 layers of alumina balls (5 mm diameters) in the preheating zone. In this paper, the authors extended Pantangi [12] research work for investigating the performance of the PRB of 80 mm diameter in the equivalence ratio range of 0.5 - 0.8 employing a ceramic block of 10 mm thickness in the pre-heating zone. The authors also presented the influence of ambient temperature on the thermal efficiency of the burner.

2. Details of experimental setup

An experimental set-up used for testing the performance of PRB is shown in Figure 2. The fuel flow rate and air flow rates were controlled using rotameters. The combustion zone was made of silicon carbide (SiC) porous matrix of 20 mm thickness, 80 mm diameter, and 90% porosity. The preheating zone was filled with a ceramic block of 10 mm thickness, 80 mm diameter and 40% porosity. The schematic of the burner is illustrated in Figure 3. The burner casing was fabricated at IIT Guwahati using alumina powder and sodium silicate binder. Thermal efficiency of the cooking stove was estimated by conducting the water boiling test as described in IS 4246:2002. A 5 kg LPG cylinder was connected to the burner through a regulator and a pressure gauge.

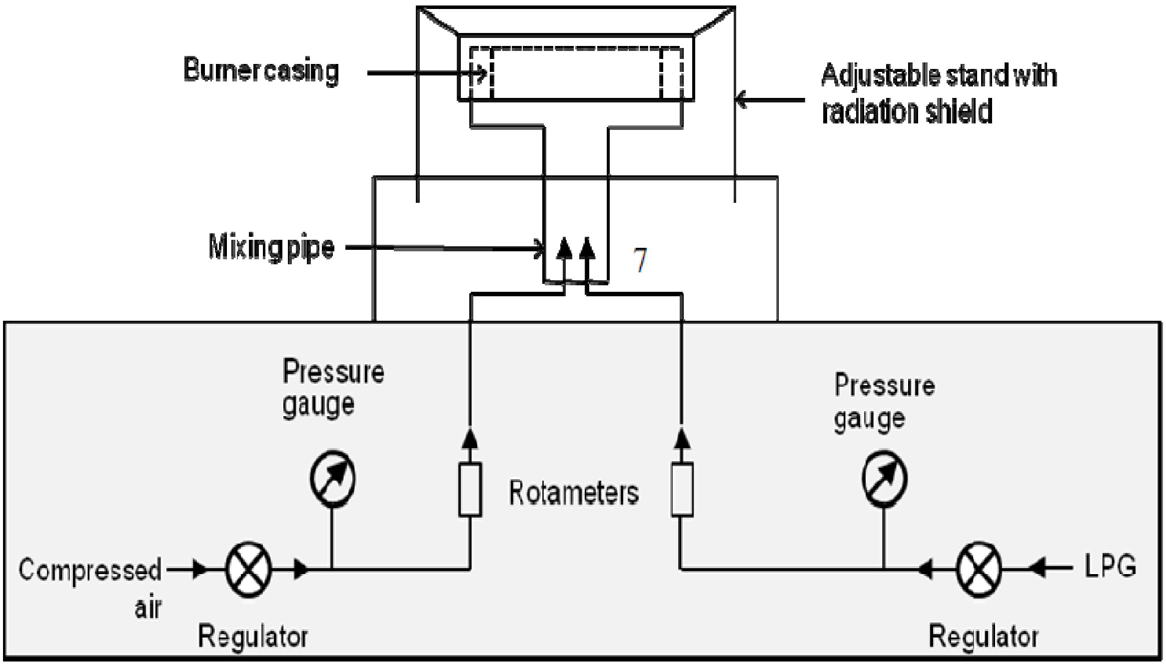

Figure 2. Layout of the experimental setup [12]

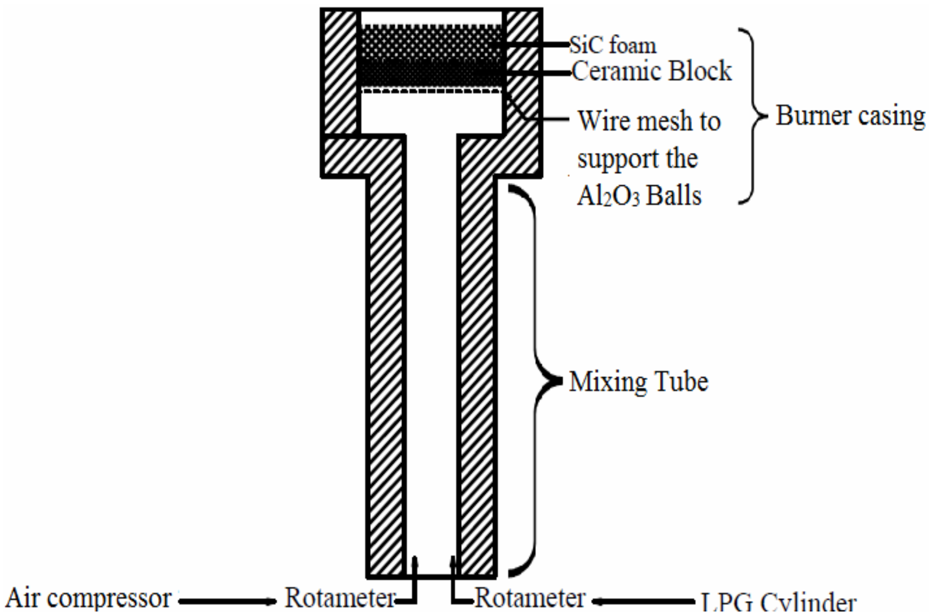

Figure 3. Schematic illustration of the PRB [12]

The aluminum vessel used for water boiling test had dimensions of 270 mm diameter and 140 mm height. The mass of the vessel with its lid and the mass of water used in the pan were noted. Initial temperature (T_1) of water and ambient temperature of the surroundings (T_a) were noted. Then, the LPG cylinder was kept on the weighing balance and the burner was turned on. After stabilizing the flame, the vessel was kept on the burner. The weight of the cylinder (W_1) was noted. Water was heated up to 80 °C and for maintaining uniform temperature; water was stirred slowly until the end of the test when the temperature (T_2) of water reached 90 °C ± 0.5 °C. Then, the burner was turned off. The final weight of the cylinder (W_2) was noted. The difference in the weight ($W_2 - W_1$) yielded the mass (m_f) of LPG consumed during the experiment. The percentage of thermal efficiency (η_{th}) of the stove was estimated based on the following formula:

$$\eta_{th} = \frac{(m_w \times C_w + m_a \times C_a)(T_2 - T_1)}{m_f \times CV} \times 100 \tag{1}$$

where, m_w and m_a are the masses of water and aluminum vessel along with the lid and stirrer, respectively; C_w and C_a are specific heats of water and aluminium vessel, respectively; m_f is the mass of the fuel consumed during the test and CV is the calorific value of the LPG (45, 636 kJ/kg). The temperatures at different locations on the surface of the porous matrix was recorded using the calibrated K- type thermocouples (accuracy ± 1 °C). The output of the thermocouples was acquired directly in the computer through a data acquisition unit. The positions of the thermocouples are shown in Figure 4.
The CO and NOX emissions were measured using the TESTO 350 XL portable flue gas analyzer. The sampling was done as suggested in the Bureau of Indian standard, IS: 4246:2002. A maximum uncertainty in the calculation of thermal efficiency was found to be ± 2.3 %.

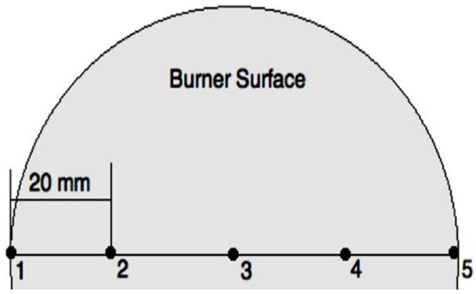

Figure 4. Position of thermocouples on the surface of the PRB

3. Results and discussions

3.1 Effect of equivalence ratio

The experiments were carried out at constant ambient temperature of 24 °C. Figure 5 shows the effect of equivalence ratio (Ø) on thermal efficiency. Equivalence ratio (Φ) is defined as the ratio of air fuel ratio (AFR) at stochiometric condition to actual AFR. Equivalence ratio (Φ) is a measure of how far the actual mixture is from the stoichiometry. Φ = 1.0 means the mixture is at stoichiometry. For rich mixtures, Φ is greater than 1 and lean mixtures, Φ is less than 1. Three sets of experiments were carried out at different wattages. Power was kept constant in each set of experiments, and the equivalence ratios were varied. Thermal efficiency was found to be inversely proportional to the equivalence ratio of the fuel-air mixture. It was observed that for a given equivalence ratio of 0.68, the thermal efficiency of the burner increased from 63% at 1.24 kW to about 65% at 1.48 kW. Also, for a given wattage of 1.24 kW, highest thermal efficiency of about 67% at Ø = 0.6 and lowest thermal efficiency of about 63% at Ø = 0.68 were observed. Lower thermal efficiency at higher equivalence ratio is due to increase in radiation output [13, 14] which in turn increases the radiation heat loss. High radiation output is not always desirable and depends on application.

3.2 Influence of ambient temperature

During the experiments, the power intensity and equivalence ratio were kept constant at 1.24 kW and Ø = 0.68, respectively. In order to study the influence of ambient temperature on the thermal efficiency of the porous radiant burner, a series of experiments were carried out at IIT Guwahati from November 2009 to April 2010 to cover a wide range of ambient temperatures from 18 ^{o}C to 31 ^{o}C. The ambient temperature was taken as the average of the values prior to and after the experiment. Figure 6 shows the influence of ambient temperature on the thermal efficiency of the porous burner. As illustrated in Fig.6, the thermal efficiency of the porous burner was found to be directly proportional to ambient temperature. At the extreme ends of the temperature range, thermal efficiencies were found to be 61.1% at 18.5 ^{o}C and 71% at 31 ^{o}C. Most of the household kitchens in India are being maintained in the temperature range of 18 ^{o}C to 32 ^{o}C. As the ambient temperature increases, the temperature gradient between the surface of vessel and the environment decreases; hence the convective heat loss from the surface of the vessel is reduced significantly, resulting in higher thermal efficiency.

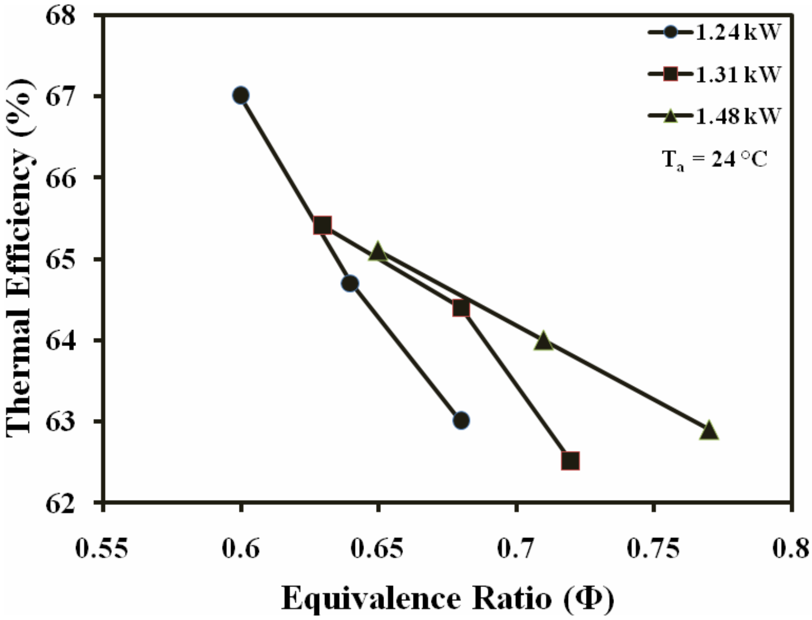

Figure 5. Effects of equivalence ratio and power intensity on thermal efficiency

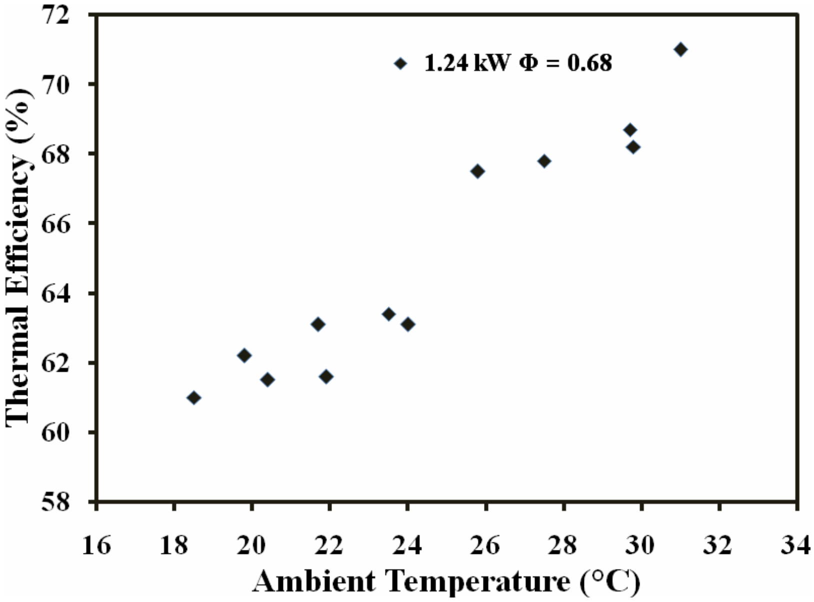

Figure 6. Effect of ambient temperature on the thermal efficiency of PRB

3.3 Emission characteristics

As illustrated in Figure 7, the measured values of CO emissions of the PRB are in the range of 9 - 16 ppm. The measured values of NOx (not shown in Fig. 7) were well below 0.2 ppm for all the cases. The values of CO and NOx of the conventional burner are in the range of 50 to 225 ppm and 2 to 7 ppm, respectively, which is very high compared to the emission characteristics of PRB. It is observed that for a given wattage, the CO emissions increase with equivalence ratio. Higher equivalence ratio means more fuel and less air, i.e. rich mixture and lower equivalence ratio means lean mixture. In the case of lean mixture, fuel gets sufficient air to combust, however, as the mixture becomes richer, the combustion byproducts increase due to lack of sufficient air, and hence increasing the CO and NOx emissions. Since the porous burner is capable of burning the lean mixtures, the CO emission is found to be low. Due to lower global temperature (surface temperature of the burner), the NOx emission is also found to be low.

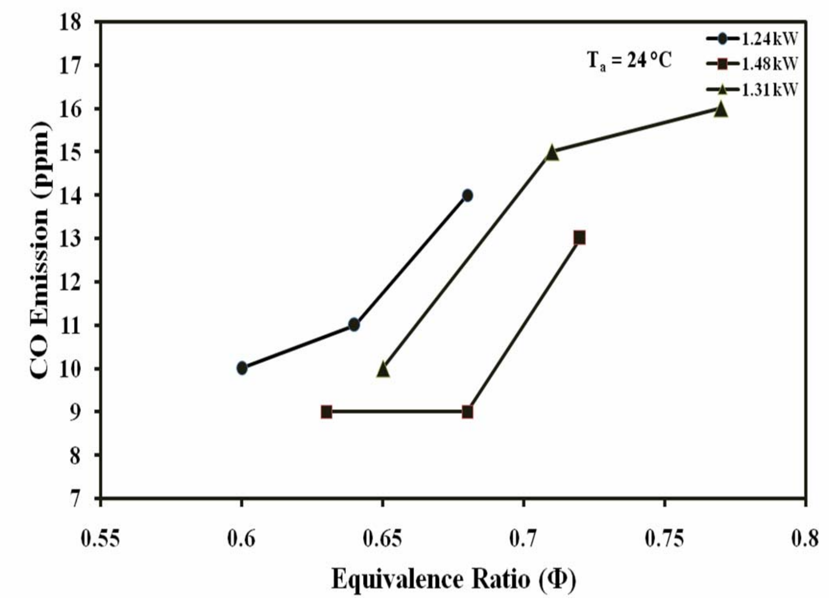

Figure 7. CO Emissions at different equivalence ratio and power intensities

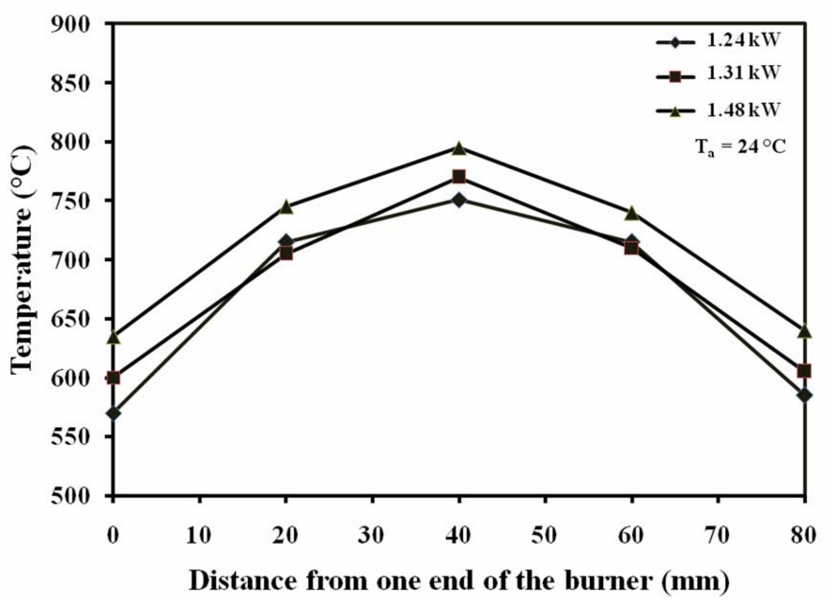

Figure 8. Temperature distribution on the burner surface of the porous matrix

3.4 Temperature distribution

The temperature distribution on the burner surface gave a depiction of the combustion behaviour and the heat distribution within the burner. To study the temperature uniformity on the surface of the porous radiant burner, temperatures were recorded (T_a = 24 °C and Ø = 0.6) at different radial positions on the surface of the porous matrix as illustrated in Figure 8. Temperatures difference at different radial positions on the burner was about 180 °C. At the lowest power input, the difference was higher due to low flow rates, which did not allow a uniform heat distribution. In the case of conventional burner, the temperature difference across the burner is in the order of 500 °C.

4. Conclusions

Performance of the LPG PRB for cooking applications have been compared against that of conventional domestic LPG stoves in terms of thermal efficiency and emission levels. Some of the important conclusions from the present studies are;

- The maximum thermal efficiency of the PRB was recorded as 71% at 1.24 kW Ø = 0.68 at an ambient temperature of 31 °C. This is about 6% more than the maximum thermal efficiency of conventional LPG burners, which is in the range of 60% – 65%.
- Thermal efficiency of PRB was found to decrease with equivalence ratio of the fuel-air mixture. At 1.24 kW highest thermal efficiency was found to be 66.8% at Ø = 0.6 and lowest was 63.1% at Ø = 0.68.
- Thermal efficiency of the PRB was found to increase with ambient temperature. The maximum thermal efficiency for 1.24 kW, Ø = 0.68 was found to be 71% at 31 °C and 61.1 % at 18.5 °C.
- Temperature at different radial positions on the burner surface of the PRB does not vary more than 180 °C.
- Within the range of power intensity investigated, the CO emissions increase with equivalence ratio. For 1.48 kW, CO emissions were observed as 10 ppm for Ø = 0.6, 15 ppm for Ø = 0.64, 16 ppm for Ø = 0.68. However, irrespective of the wattage of the burners, NOx emissions are always low (in the range of 0 – 0.2 ppm) compared to the conventional LPG burners.

Acknowledgement

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