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Performance Characterization of a Cluster Porous Radiant Burner for Clean and Efficient LPG Combustion

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With increase in cost of gaseous fuels and depletion in their reserves, it has become essential to further improve the efficiency of the commercial gaseous burners which generally have low thermal efficiency and high emissions. Porous Radiant Burner (PRB) is one such emerging technology which assists lean combustion, thus yielding clean burning and improved thermal efficiency in comparison to a conventional free-flame burner i.e., CB. This paper presents an experimental investigation on LPG combustion employing a simple and yet novel technique of clustering 3 individual bi-layered PRB. Each PRB is of 70 mm diameter with a SiC foam as combustion layer and a porous alumina filter as preheat layer. Transient analysis of the surface temperature distribution was conducted to find out the range of its operational stability, that is restricted by blow-off, flashback and flame quenching. Thermal efficiency tests were carried out for a firing rate of 12.56 kW, as per BIS 14612:1999. Concentrations of CO and NO_x were measured by confining the flue gases in a hood. The new cluster PRB has a maximum thermal efficiency improvement potential of 19 % over the CB at an equivalence ratio of 0.7. Similarly, it shows improved ability to lessen the CO and NO_x emissions as highlighted by 62 ppm of CO and 13.9 ppm of NO_x, which was otherwise 264 ppm and 46.9 ppm, for its conventional counterpart. Overall performance of the cluster PRB exhibits a potential replacement to its conventional counterpart.

1. Introduction

Sustainable development is defined as the growth of the present generation without straining future generations to meet their own needs. The provision of clean and efficient energy for cooking is an indicator of one of the Sustainable Development Goals (SDG) adopted by the United Nations. Fossil fuels like coal and natural gas play an imperative role as sources of energy in the cooking sector. LPG is a modern-day fuel that is reliable and offers sustainability through clean cooking. The increasing rate of consumption and price hike of LPG in India, call for energy-efficient cook-stoves that result in effective utilization of the fuel. Common LPG cook-stoves working on free flame combustion (CB) are less efficient and more polluting, which obstructs the effective usage of the fuel. Several research works have been conducted in this regard, and lately, Porous Radiant Burners (PRBs) were developed to meet this requirement. The collective influence of the combustion and heat transfer characteristics, due to the material properties and geometric parameters of the PRBs, leads to improved thermal efficiency (η_{th}) and clean-burning. Some of the research works on LPG operated PRBs for cooking are discussed below.

Very initial developments on the performance improvement of domestic burners were carried out by Jugjai and Sanitjai (1996) by using Porous Radiant Recirculated Burner (PRRB). Subsequently, Jugjai and Rungsimuntuchart (2002) developed semi-confined mode PRRB for 5 – 30 kW power input, which yielded a maximum η_{th} of 60 %. Makmool et al. (2007) compared the η_{th} of several LPG burners available in Thailand with the help of particle image velocimetry. The η_{th} and CO emission of the PRB was found to be 47 % and 1,800 ppm. Mujeebu et al. (2011a) developed a PRB working on surface combustion mode for a fuel flow rate of 0.5 lpm. The developed PRB resulted in a fuel saving of 80 % and a reduction in NO_x emission by 75 % as compared to the tested CBs. They (Mujeebu et al., 2011b) also conducted research works on PRBs operating on surface

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(SSB) and matrix stabilized (MSB) modes for an input power of 0.62 kW. The SSB produced a maximum η_{th} of 71 %, whereas the same for MSB and CB was 59 % and 47 %. The MSB produced CO of 21 ppm and NO_x emissions of 7 ppm, which was found to be lower in comparison to the SSB and the CB. Yosenakul and Jugjai (2011) developed a self-aspirating PRB on a submerged flame mode for firing rates of 23 to 61 kW. The radiation efficiency was reported to decrease with an increase in firing rate. For the various firing rates, the CO and NO_x emissions were found to be less than 200 and 98 ppm, which were very less when compared to its conventional counterpart. A double-layered PRB was developed by Pantangi et al. (2011) using SiC and Al_2O_3 for an input power range of 0.8-1.8 kW. In the stable range of equivalence ratio (ϕ) 0.3-0.7, an improved η_{th} of 68 % was obtained for a PRB diameter of 80 mm. The CO and NO_x emissions were in the range of 25-350 mg/m^3 and 12-25 mg/m^3, which was found to be lower than the CB. Mishra and Muthukumar (2018) and Mishra et al. (2015) developed PRBs for domestic scale (1-3 kW) and medium scale (5-10 kW) cooking applications. The maximum η_{th} obtained from the domestic PRB was 75.1 % with CO and NO_x emissions of 140 and 3.5 ppm. The medium-scale PRB yielded an improvement in η_{th} and CO emission by 28 %, and 90 %, when compared to its conventional counterpart. The performance of PRB was found to decrease with an increase in both ϕ and power input. With alumina particles from grinding wastes and SiSiC, Herrera et al. (2015) developed a PRB. Compared to the CBs, the developed PRB operating on radiation-conduction mode yielded a maximum of 14 % improvement in η_{th}. The CO emissions were within acceptable limits for heat input rates less than 194 kW/m^2. Chaelek et al. (2019) developed an annular porous radiant burner with self-recirculation of heat (PRRB) for a firing rate of 21-44 kW. Maximum η_{th} of 51 % was attained, which resulted in a decrease in fuel consumption by ~28.6 %. Life cycle and techno-economic analyses on medium scale PRB conducted by Kaushik and Muthukumar (2018), showed huge reduction in annual operating costs when compared to CB of the same capacity.

Improved thermal and emission performances of the above-discussed LPG operated PRBs make a strong case for exploring new avenues for porous media combustion technology. The present article describes combustion characteristics of a novel Clustered Porous Radiant Burner (CPRB) of 12.6 kW wattage. The temperature mapping and performance viz., η_{th} and emission, of the developed CPRB are presented in detail. Performances of developed CPRB were also compared with a market available T-22 burner. Also, the economic saving potential of the developed CPRB has been projected to the Indian context.

2. Details of the CPRB and Conventional T-22 burner

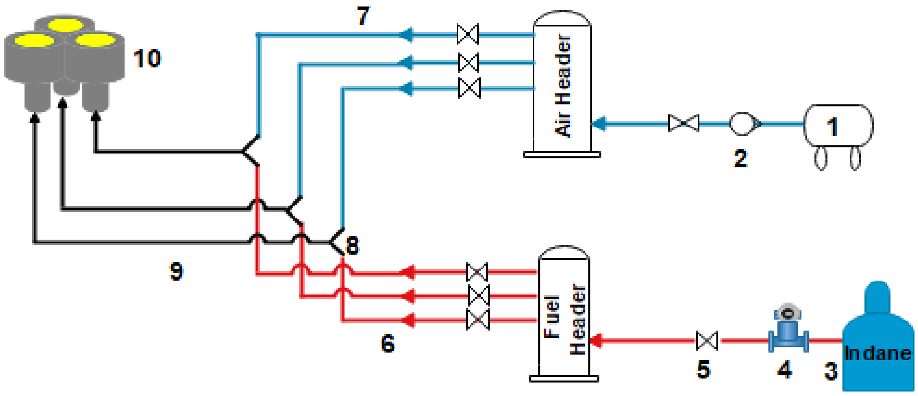
Figure 1 shows the pictorial view of the CPRB and a T-22 burner, which is a conventional burner (CB). The newly developed CPRB is a cluster of three porous radiant burners (PRBs), which consists of bi-layered porous media that act as preheater (PH) and combustion chamber (CC). The schematic diagram of an individual PRB is shown in Figure 1a, which is 70 mm in diameter. A SiC reticulated foam an Alumina press filter are used as CC and PH. CC and PH are housed inside a refractory cement casing, which restricts the heat loss to the surroundings. Mixing and homogenization of the fuel-air mixture take place in the mixing tube and mixing zone (Figure 1a). PH helps to preheat the fresh fuel-air mixture and also acts as a flame arrester due to its low porosity and lower thermal conductivity. Figure 1b shows the pictorial view of the CPRB under stable burning condition. T-22 burner is a torch-type burner and is one of the CB's available in the market for medium scale cooking. The diameter of the burner head and length of the mixing tube are 63 mm and 185 mm. The flame is attached to the mesh located at the top surface of the burner head as shown in Figure 1c.

(a) (b) (c)

Figure 1: Pictorial view of Clustered Porous Radiant Burner and Conventional Burner (a) individual burner of Clustered Porous Radiant Burner (b) Clustered Porous Radiant Burner (c) T-22 burner

3. Description of the experimental set-up

The experimental set-up comprises of an arrangement to supply the required quantities of fuel and air to the individual burners of the CPRB as shown in Figure 2. In the present case, experiments were conducted for an input power of 12.5 kW, which corresponds to an LPG fuel flow rate of 1 kg/h. Compressed air at 1.5 bar is supplied from a compressor and is collected in an air-header. The flow rate of air is measured by a rotameter (accuracy 50 lpm) and is controlled by a control valve. It is then distributed equally to three air-lines, which are located at equal distances on the periphery of the header. Similarly, the fuel (LPG), is obtained from a 19 kg LPG cylinder and is collected in a fuel-header which divides it equally amongst three fuel lines. A Coriolis mass flow meter is used to measure the mass flow-rate of fuel and the flow is controlled by a control valve. The air and fuel from each air-line and fuel-line are mixed and the air-fuel mixture is supplied to the individual burners of the CPRB. The influence of the ϕ on the η_{th} and emissions was found. The ϕ is varied by varying the air-flow rate while keeping the fuel flow rate constant.



1. Compressor 2. Rotameter 3. LPG cylinder 4. Mass flow meter 5. Control valve 6. Fuel-Line 7. Air-Line 8. Air-fuel mixer 9. Air and fuel mixture line 10. Clustered Porous Radiant Burner

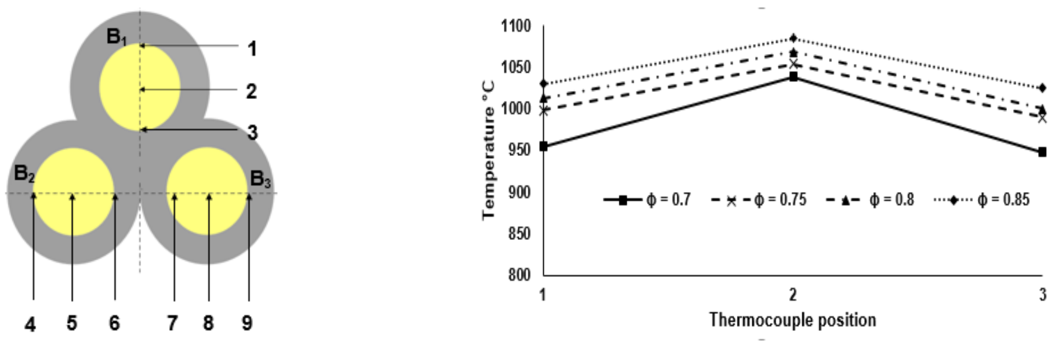
Figure 2: Schematic diagram of Clustered Porous Burner set-up

4. Performance parameters and their evaluation procedure

The performance parameters of a device are indicative of their operational features and productivity. The stability, thermal efficiency (η_{th}) and emissions are the most common parameters for the performance evaluation of a burner applicable for cook-stoves. Figure 4 shows the arrangements to measure η_{th} and emissions.

4.1 Stability

The stability of a burner is an operational feature that determines its reliability and safety. The stability, indicated by blow-off and flame-quenching, was decided on the basis of restricting the flame within the desirable limits for each burner and was inspected visually. The CPRB was operated on submerged combustion mode. The occurrence of an extended flame in any of the individual burner was considered to be a case of blow-off while the extinguishing of the flame was considered as a flame quenching. The movement of the flame towards the upstream was considered as flashback. The second parameter for stability, i.e., each burner of the CPRB yielding similar heat output, was examined with the help of radial top-surface temperature distribution as shown in Figure 3. The radial temperature distribution on the top surface of the CPRB was measured by using K-type thermocouples (accuracy ±0.5 °C) on the positions shown in Figure 3a, and a data acquisition system (Agilent make) was used to obtain the output from the thermocouples.
The burner was found to be stable within the equivalence ratio (ϕ) range of 0.7 to 0.85, beyond which flame quenching and blow-off were observed to occur. Figure 3b shows the plot of radial temperature distribution of individual burner B1 at the positions shown in Figure 3a and is also representative of the radial temperature distribution of burners B2 and B3. The burners were considered to have a uniform radial surface temperature distribution as the maximum difference between the peripheral and the central temperature was within 50 °C. The individual burners had similar temperature profiles with a variation of ± 10 °C, indicating that each PRBs operated comparably and gave similar heat output. The highest and the lowest temperature for the CPRB was obtained at a ϕ of 0.85 and 0.7. The peak temperature was reported at the centre of each burner.



(a) *(b)*

Figure 3: Measurement of radial surface temperature (a) position of the thermocouples (b) Radial temperature distribution of burner B1

4.2 Thermal efficiency (η_{th})

The η_{th} of a burner used as a cook-stove in India is determined by the water boiling test (WBT), the procedure for which is laid down in BIS 14612:1999. The schematic diagram of the arrangement to measure the thermal efficiency is shown in Figure 4a. Water of mass 16.5 kg was taken in an aluminium pan of mass 2.99 kg, both of which were measured in a weighing balance of accuracy ± 0.1 g. The water was heated from the initial temperature to 90 °C. The amount of gas consumed was determine using the Coriolis mass flow meter. The formula for the calculation of η_{th} is given below –

$$\eta_{th} = \frac{(m_p C_p + m_w C_w) \times (90 - T_i)}{m_g \times CV} \quad (1)$$

where, m_w, m_p and m_g represent the mass of water, pan and LPG consumed (fuel), C_p and C_w denote the specific heat capacity of the pan and water and T_i and CV indicate the initial temperature and the lower calorific value of the fuel.

4.3 Emission

A hood as prescribed in BIS 4246:2002 was used to collect the flue gases and the probe of the Flue Gas Analyser (FGA) was inserted in one of the vents as shown in Figure 4b. The CPRB was tested for its CO and NO_x emissions, by Testo 340 flue gas analyser, on a dry basis and with oxygen corrected to reference value of 3 %.

(a) *(b)*

Figure 4: Schematic diagram for the measurement of thermal efficiency and emissions (a) Schematic diagram of the arrangement to measure the thermal efficiency (b) Schematic diagram of the arrangement to measure the emissions

5. Results and Discussion

5.1 Thermal efficiency (η_{th})

The effect of ϕ on the η_{th} of the CPRB and its comparison with CB are shown in Figure 5. Highest η_{th} of 55.6 % was attained for ϕ of 0.7 while the lowest η_{th} of 50 % was found at ϕ of 0.85. The increase in ϕ led to the decrement in η_{th} because of higher heat loss from the hotter flue gases to the surroundings. The CB (T-22 burner) yielded η_{th} of 47 % under similar conditions, which was up to 8.6 % lower than the CPRB.

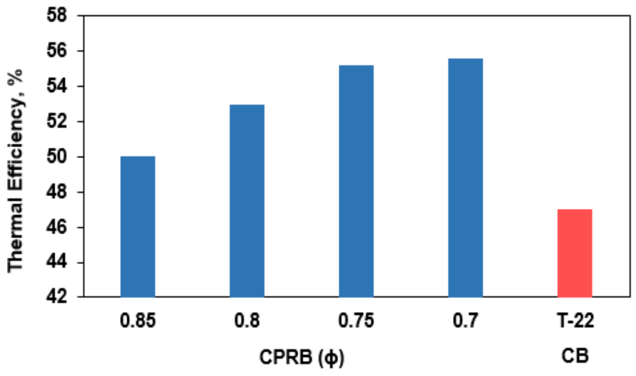


Figure 5: Variation of thermal efficiency with equivalence ratio and comparison with CB

5.2 Emissions

The emissions of CO effect human health apart from increasing global warming and ozone depletion (Dey and Dhal, 2019). Similarly, NO_x is also a greenhouse gas and causes acid rains (Gal et al., 2017). The variation of CO and NO_x emissions with the increase of ϕ for the stable operating range is shown in Figure 6. The CO and NO_x emissions of the CPRB were found to increase with increase in ϕ. The rise of CO from 62 to 85 ppm for an increase of ϕ from 0.7 to 0.85 is due to the insufficient combustion because of lesser air-flow rate. Similarly, the increase in NO_x from 13.6 to 35 ppm is due to increase of prompt NO_x, which depends on the carbon content per unit volume of the mixture. The CO and NO_x emissions for the T-22 burner were measured as 264 ppm and 46.9 ppm.

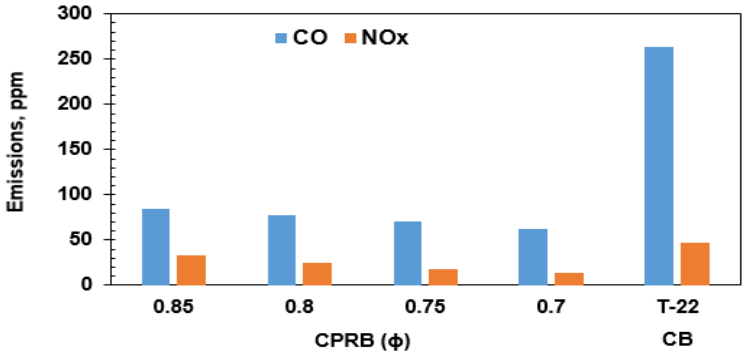


Figure 6: Variation of CO and NO_x emissions with equivalence ratio and comparison with CB

6. Cost saving potential (CSP)

Experimental studies on CPRB showed ability of improved energy utilisation compared to its conventional counterpart. To comprehend the CPRB's potential of cost saving (CSP), a rudimentary economic analysis has been performed, which is deliberated in detail in this section. The CPRB offers η_{th} from a minimum of 50 % up to a maximum of 55.6 %, whereas, for its conventional counterpart, the maximum was only 47 %. The increased η_{th} of the CPRB leads to a saving of 1.14 kg to 2.93 kg LPG for each cylinder (19 kg) consumed. The cost of 1 kg LPG is around Rs. 81, and the total number of non-domestic consumers is around 3.02 M in India. Assuming that the non-domestic customers consume one cylinder in every month, the monthly CSP of the CPRB is estimated to be Rs. 278 M to Rs. 719 M. It is observed that CPRB is a promising technology for the financial saving in commercial enterprises using non-domestic LPG cylinders.

7. Conclusion

Commonly available commercial LPG burners operating on free flame combustion are thermally less efficient and highly polluting. The increase in demand of non-domestic LPG customers in India calls for the design improvement of the medium-scale cook-stoves. Porous Radiant Burners (PRBs) designed for cooking application were reported to be highly efficient and less polluting as compared to the conventional burners (CB). A Cluster Porous Radiant Burner (CPRB) was developed to enhance the thermal efficiency, which can be a promising technology to replace the conventional free flame burners (T-22) for medium-scale cooking. Comparison between T-22 and CPRB show that the thermal efficiency of the CPRB was improved by 18 %. The emissions of CO and NO_x were reduced at most by 76.5 % and 71 %. The analysis of cost saving potential reveals that in India, using the CPRB for commercial cooking can result in a maximum saving of Rs. 740 M in every month, which is a considerable monetary saving. The study on CPRB paves ways for further improvement in the performance of its own performance by the optimisation of the geometrical parameters and clustering more PRBs.

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