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Research paper

Performance characterization of a medium-scale liquefied petroleum gas cooking stove with a two-layer porous radiant burner

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HIGHLIGHTS

- Performance characterization of LPG cooking stove is done.
- Burner of the stove is composed of a two layer porous matrix.
- Input power of the stove ranges from 5 to 15 kW.
- Measured temperature distributions, thermal efficiency and CO and NO_x emissions are reported.
- Thermal efficiency is more and emissions of CO and NO_x are less than conventional LPG stove.

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ABSTRACT

Performance in terms of axial and radial temperature distributions, thermal efficiency, and CO and NO_x emissions of a medium-scale liquefied petroleum gas cooking stove with a two-layer porous radiant burner is reported. In the two-layer burner, SiC porous matrix acts as the combustion zone, and the preheating zone consists of an alumna matrix. With burner power in the range 5–10 kW, effects of equivalence ratio on radial and axial temperature distributions, thermal efficiency and emissions are investigated. For comparison, axial temperature distributions, thermal efficiency and emissions of CO and NO_x for conventional burner working in the free-flame mode are also reported. With the porous radiant burner, radial temperature distributions are almost uniform, the maximum thermal efficiency is 28% higher, and CO and NO_x emissions are significantly low.

1. Introduction

Combustion in a conventional burner (CB) is characterized by a free-flame. In this, the combustion takes place in the gaseous environment, and heat transfer is primarily by convection. As the gases have a very low thermal conductivity and low emissivity, the contributions of conduction and radiation modes of heat transfer from the post flame to pre flame zone are negligible. Thus, due to poor heat transport, devices based on CB are less efficient, and are characterized by low flammability limits, low thermal efficiency, high level of pollutant emissions, etc. [1–7]. Conventional liquefied petroleum gas (LPG) cooking stoves fall under this category.

Thermal efficiencies of the medium-scale LPG stoves (5–10 kW thermal load) available in the Indian market are in the range of 32–45%, and their CO and NO_x emissions are in the range 350–1145 ppm and 40–109 ppm, respectively. These emissions are much above the World Health Organization standards [8]. Thus, not only a significant portion of energy go waste, emissions of CO and NO_x from these stoves also pollute the environment.

The concern for energy wastage and environmental pollution from the conventional LPG cooking stoves to a great extent can be addressed by changing the way combustion takes place in these burners. In these burners, a premixed air-fuel mixture combust in the gaseous (air) environment, and the flame stabilizes over the perforated metallic burner head. The free-flame (FF) combustion in these burners is similar to that of the Bunsen burner. In these, the reaction zone is thin, and consequently, a sharp temperature gradient across the flame manifests. This combined with incomplete combustion of the fuel rich ($\Phi > 1$) mixture leads to lower thermal efficiency and higher emissions of CO and NO_x. Thus, research is needed to improve the efficiency and reduce the emissions of LPG cooking stoves.

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Nomenclature

C_p	specific heat capacity of aluminum (0.8959 kJ/kg K)
C_w	specific heat capacity of water (4.1826 kJ/kg K)
CV	calorific value of the fuel (45,780 kJ/kg)
m_f	fuel consumed to raise the water temperature from T_1 to T_2 (kg)
m_p	mass of pan along with lid and stirrer (kg)
m_w	mass of water (kg)
r	radius of PRB (cm)
T	temperature (°C)
η_{th}	thermal efficiency
Φ	equivalence ratio

Instead of combustion in the gaseous environment, i.e., in the FF mode, if a fuel is made to combust in a conducting and radiating porous matrix, owing to enhanced heat transfer, thermal efficiency goes up and emissions of CO and NO_x come down [1–7]. This combustion in the porous matrix utilizes the principle of excess enthalpy combustion proposed by Weinberg [9]. By preheating the premixed fuel–air mixture, even the lean mixture and low calorific value fuel can be combust in the porous matrix. This preheating in combustion in the porous matrix is realized due to the manifestation of the volumetric thermal radiation. Apart from preheating of the incoming premixed fuel–air mixture, volumetric radiation, conduction and increased convection owing to higher surface area per unit volume of the porous matrix, homogenization of temperature, and hence the volume of the reaction zone get elongated. These all lead to higher thermal efficiency and reduced emissions.

During the last three decades, a good amount of work on various aspects and applications of porous media combustion has been reported. Exhaustive reviews [1–7] on this subject outline these developments.

Bubnovich et al. [10] developed a porous media combustor formed by two beds of different sizes of alumina balls. They reported the stability range of flame propagation for different flow rates of air-fuel mixture. Avdic et al. [11] developed a porous medium burner for household heating system with maximum thermal output of 8 kW. The aim of the work was to develop a compact and an efficient combined heating system based on porous burner coupled with a heat exchanger system considering space and domestic water heating. Charoensuk and Lapirattanakun [12] developed a porous combustor burning partially premixed LPG with staged air for 3 kW thermal input. They investigated temperature distributions and flame stability for different porosities. Kanga et al. [13] experimentally and numerically studied the heat transfer performance of a ceramic honeycomb regenerator in oxy-fuel combustion. They measured pressures and temperatures in a regenerator, and compared experimental results with that of the numerical one. A fairly good agreement was observed.

Gao et al. [14] investigated the combustion phenomenon on a double-layer packed pellets of different diameters. They found that the stable operating region could be enlarged with the increased diameter of packed pellets. The flame and surface temperatures increased more with increased flame speed for the single-layer burner than for the double-layer one. Abdelaal et al. [15] investigated the combustion of LPG in porous inert media made of mullite. They showed the effect of equivalence ratio and firing rate on the radiation efficiency, surface and exhaust gas temperatures. Danon et al. [16] did the parametric study on a 300 kW furnace equipped with three pairs of regenerative flameless combustion burners. The objective of the study was to maximize the cooling tube efficiency, and minimize the CO and NO emissions. Yon and Sautet [17] developed an oxy-fuel burner with separated jets of fuel (hydrogen and natural gas) and oxidizer. They reported better thermal efficiency and a reduction of pollutant emissions. Byeonghun et al. [18] conducted an experiment to compare the emission characteristics and thermal efficiency of three porous-media burners of power in the range 15–25 kW for condensing boiler. Higher thermal efficiency and lower emissions CO and NO_x were obtained with a burner with a higher porosity.

Aimed at different applications, researchers [19–22] have also studied combustion of liquid fuels (kerosene) in porous media. Jugjai and co-authors [19–21] have developed porous radiant burner (PRB) for burning kerosene without the need of using a spray atomizer. Kerosene was supplied drop wise to the top surface of the PRB, and burnt on the lower side where the swirling combustion air was supplied and mixed with the fuel vapour. They studied evaporation mechanism and combustion characteristics inside the burner system by measuring temperature profiles and emission characteristics. Stable combustion with low emissions of pollutants was achieved in the equivalence ratio range of 0.37–0.55 and power range of 2.62–3.49 kW. Sharma et al. [22] tested the effect of porous radiant inserts in conventional kerosene pressure stove. They reported that using porous insert, the efficiency of the stove increased from 55% to 62%.

Impressed with the performance of the PRB on other applications [10–18], some researchers [23–28] have extended its usage to LPG cooking stoves. To extract heat of the burnt gases, Jugjai and Rungsimuntuchart [23] have modified the flow pattern of the air-fuel mixture in the conventional LPG stove. They did not have combustion in the PM, but they used PM to preheat the air–fuel mixture. They reported significant improvement in thermal efficiency. Dongbin et al. [24] investigated the combustion phenomenon in a porous ceramic stove doped with rare earth elements. The increased emissivity due to the addition of rare earth elements to porous ceramic was attributed to the special valence shell of rare earth elements. Mujeebu et al. [25] tested two compact premixed LPG burners based on submerged and surface combustion modes in PM. They compared combustion and emission characteristics of the two burners with the CB for thermal load of 0.62 kW. Against 47% thermal efficiency for the CB, with matrix stabilized burner, the same was 59%, and that with surface stabilized burner, they reported thermal efficiency of 71%.

With the objective of increasing the thermal efficiency and reducing the emissions of CO and NO_x in LPG cooking stoves, Pantangi et al. [26,27] developed burners in which the LPG combustion was in the PM. In their study reported in Ref. [26], they did experiments with metal balls, pebbles and metal chips. The maximum thermal efficiency increase of 4% was obtained with metal chips. The CO emission was also found about two times lower than the CBs. Towards further improving the performance of the LPG cooking stoves, in the subsequent work [27,28], researchers used a two-layer PRB. Combustion was allowed to take place in the PM, and preheating of air–fuel mixture was achieved in a preheating zone made of alumni balls in Ref. [27] and alumina matrix in Ref. [28]. Increase in thermal efficiency, and decrease in CO and NO_x emissions were both significant.

With cooking in a small size family in mind, it is observed from the literature [23–28] that all the previous studies with LPG cooking stoves with PRB have been limited to thermal load in the range of 0.5–2 kW. In hotels, hostels and community centers, normally cooking for 50–100 people are done, and for this, the burner power range is 5–10 kW. The present work, therefore, aims at the performance of an LPG cooking stove with a PRB for the aforesaid power range. To evaluate the performance in terms of