Applied Thermal Engineering 129 (2018) 482–489

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Development and testing of energy efficient and environment friendly porous radiant burner operating on liquefied petroleum gas

Niraj Kumar Mishra [a], P. Muthukumar [b,*]

[a] Department of Mechanical Engineering, National Institute of Technology Uttarakhand, Srinagar 246174, India
[b] Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

HIGHLIGHTS

- Development and performance tests on a LPG cooking stove with PRB is presented.
- The thermal efficiency of newly developed PRB is 15.1% more than CB.
- Measured CO and NOx emissions of the LPG stove with PRB is much lower than CB.
- LPG stove with PRB can operate without any flash back or flame lift.
- LPG stove with PRB works on the natural draft without the supply of external air.

ARTICLE INFO

Article history:
Received 22 September 2017
Revised 6 October 2017
Accepted 8 October 2017
Available online 10 October 2017

Keywords:
Combustion
Porous radiant burner
LPG cooking stove
Thermal efficiency
CO and NOx emissions

ABSTRACT

In this paper, the design and development of a self-aspirating LPG cooking stove with two-layer porous radiant burner (PRB) are presented. Following the guidelines prescribed in Bureau of Indian Standards (BIS) 4246:2002, performances of the LPG stove with PRB have been tested. The maximum thermal efficiency of the PRB in the power range of 1–3 kW is 75.1%, while the respective value of the conventional burner (CB) is 65%. The measured CO and NOx emissions of the newly developed PRB stove are in the ranges 30–140 ppm and 0.2–3.5 ppm, respectively. Whereas the CO and NOx emissions from conventional domestic LPG cooking stoves (1–3 kW) are in the range of 220 ppm to 550 ppm and 5 ppm to 25 ppm, respectively. The maximum temperature difference between the center to the periphery of the PRB is limited to 115 °C. Experiments on the newly developed LPG stove with PRB have been performed over one year and no flash back or flame lift has been observed. As it is self-aspirated, the newly designed PRB works on the natural draft without any safety issues.

1. Introduction

In most of the developing nations, Liquefied Petroleum Gas (LPG) is commonly used as fuel in household cooking appliances. These appliances increase the indoor air pollution significantly which results in several breathing and heart related diseases [1]. Considering the new environmental strict norms and severe emission guidelines, the global warming and the energy crisis originated from the depletion of fossil fuels reserves, there is an urgent need to explore the ways to improve the thermal efficiency and lower the emissions of the LPG cooking appliances.

Most of the conventional burners (CB) used in LPG cooking appliances work based on the principle of a Bunsen burner. In the conventional LPG stove, combustion of premixed air-fuel mixture takes place in the open air environment over the perforated metallic burner head. As the gases have very low emissivity and thermal conductivity, the contributions of radiative and conductive heat transfer from the post flame to pre flame zone are insignificant. Consequently, due to reduced heat transportation, CB is less energy efficient and produces high emissions of CO and NOx [2–8].

The idea of utilizing energy from the premixed flame to preheat the incoming air-fuel mixture within the solid porous medium (PM) was first introduced by Weinberg [9]. Subsequent to Weinberg's idea, in the recent years, many investigators have explored the different applications of porous radiant burners (PRB), which work based on porous medium combustion (PMC) for both gaseous and liquid fuels [2–7]. The combustion of the air-fuel mixture within a PM aids in stabilizing the flame within the pore structure of the inert matrix. Post combustion products heat the PM downstream of the flame zone. Some part of this heat is then conducted

* Corresponding author.
E-mail addresses: pmkumar@iitg.ernet.in, pmkumariitg@gmail.com (P. Muthukumar).

https://doi.org/10.1016/j.applthermaleng.2017.10.068
1359-4311/

Nomenclature

Symbols	Comments (Units)
T_1 and T_2	initial and final temperatures of water (°C)
ρ	density (kg/m^3)
η_{th}	thermal efficiency (%)
k	thermal conductivity (W/m K)
C_W	specific heat of water (kJ/kg K)
C_p	specific heat of aluminum pan (kJ/kg K)
CV	calorific value (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 the lid and stirrer (kg)
m_w	mass of water (kg)
r	radius of PRB (mm)
R	entrainment ratio (–)
σ	relative density of gas (–)
D_P	burner port diameter (mm)
D_I	inlet diameter of orifice (mm)

and radiated back to upstream section, which heats up the incoming air-fuel mixture [2–7].

Jugjai and Rungsimuntuchart [10] developed a heat-recirculating domestic gas burner and reported that significant preheating effect could be achieved with porous matrix. They studied the performances of LPG stoves with PRB available in the input power range of 5–30 kW and reported ~60% efficiency against ~30% of the conventional stove without combusting the fuel inside the porous matrix. Jugjai et al. [11] also developed a kerosene combustor, and reported a stable combustion for very low equivalence ratio in the range of 0.37–0.55.

Owing to excellent physical and optical heat transfer properties, PMC has many prospective applications in heat exchanger [12], radiant burner [13], household heating [14], gas turbine [15], hydrogen production [16] and IC engine [17]. In the recent times, more research attention has been given to the applications based PRBs due to their extended lean flammability limit in comparison with free flame structures. Akbari et al. [18] numerically investigated the lean flammability limit of methane/air mixture in a porous medium. They observed that for a given porosity and firing rate, increasing the equivalence ratio could change the operating regime of the burner from blow-out to a stable condition and they also reported a lower limit of equivalence ratio (0.43) at which the flame stabilizes. In another study by Akbari and Riahi [19], reported the thermal performances of a PRB at different operating conditions.

Recently, some investigators have carried out research on multi-layer PRB [20–22]. Danon et al. [20] have tested three pairs of regenerative flameless combustion burners. The objective of the study was to optimize the furnace performance, i.e., to maximize the cooling tube efficiency and minimize the CO and NOx emissions. Mujeebu et al. [21] compared the thermal efficiencies of the burners operating with surface combustion and submerged combustion modes and reported that surface combustion resulted in higher efficiency up to 71%. Gao et al. [22] studied the combustion characteristic of a double-layer packed burner with alumina pellets of different diameters. They reported that the flame could be more efficiently stabilized near the interface between the two sections of double-layer burner. The flame stability limits could apparently be extended in the double-layer burner compared with the single-layer burner.

The PMC technology can effectively replace the conventional free flame combustion technology in numerous applications which not only save a huge amount of energy but also minimize the emissions to a greater extend. As LPG is most commonly used fuel in cooking stoves, keeping the efficiency improvement is the main focus, many researchers have explored the usability of PRB in domestic cooking stoves. Pantangi et al. [23] developed several lab-scale prototypes of LPG cooking stove with double-layered PRB which consists of SiC foam as combustion zone and Al_2O_3 balls as pre-heating zone. They also tested the thermal efficiency of various PRB configurations in the input power ranges of 0.8–1.8 kW and equivalence ratio of 0.3–0.7. They concluded that the thermal efficiency was strongly dependent on equivalence ratio and burner diameter. The reported maximum thermal efficiency was 68% for a burner having diameter of 80 mm. Later, Muthukumar et al. [24] have demonstrated that the efficiency of the PRB stove could be further improved to 71% by employing a ceramic block in place of Al_2O_3 balls in the preheating zone. In the above development [24], the effect of combustion matrix porosity on thermal efficiency and emissions were studied by Muthukumar and Shyamkumar [25], and they have reported that at 90% porosity, the burner could achieve the maximum thermal efficiency of 75% at an equivalence ratio of 0.54 and firing rate (thermal load) of 1.3 kW. Recently, Mishra et al. [26] developed a LPG stove with PRB for medium-scale cooking application in the power range of 5–10 kW and reported that the burner produces flameless combustion in the equivalence ratio range of 0.54–0.72. The maximum reported thermal efficiency was 28% higher than the conventional burner of same power input. All the above mentioned PRB's developed for domestic LPG cooking applications [23–26] operated only with the supply of external pressurised air around 0.2–0.5 bar gauge pressure.

In recent years, numerical modelling is becoming an essential tool for the design and development of any new device. It supports in finding the geometric and operating parameters to get the desired effect which potentially lead to the development of an optimum design. In the area of PMC, many investigators have carried out the numerical analysis for predicting the influences of various operating parameters on combustion characteristics such as temperature distribution, heat flux, and CO and NO_x emissions. Talukdar et al. [27] presented a 2-D heat transfer analysis of a rectangular PRB. They modelled combustion phenomenon in the porous medium as a spatially dependent heat generation zone and also investigated the effects of various parameters on the performance of the burner. Panigrahy et al. [28] studied the influence of combustion zone thickness (varying from 15 to 40 mm) and concluded that for a given equivalence ratio (0.5) and firing rate (3–5 kW), the burner with 15 mm thickness resulted in higher thermal efficiencies than the burner with 30 mm thickness. In an another work by Panigrahy and Mishra [29], presented the combustion modelling of LPG in a planar silicon carbide based PRB. Comparisons were made for the stability range of LPG and CH_4 in PRB as well as with the combustion of LPG in the free-flame mode. They concluded that radiative heat flux with LPG in the PRB was more than that with CH_4. The CO emission with LPG combustion in the PRB was lower than the free-flame mode.

Recently, there have been many developments concentrated on the combustion aspects and performance improvement in the PRB. Wu et al. [30] experimentally studied the effect of preheating in super-adiabatic radiant burner (SRB). They concluded that the newly developed SRB produced less CO and NO_x emissions compared to the conventional PRB. Terracciano et al. [31] developed