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Porous radiant burner for domestic cooking purpose (A Review)

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Abstract

For cooking, liquefied petroleum gas (LPG) is one of the most commonly used fuels in India and many other countries. LPG being a clean fuel burns with no soot and has high calorific value than kerosene and wood. In India, as the living standard of the people is improving the number of LPG consumers is also increasing. The total domestic consumption of LPG in India is almost comparable with other petroleum products used in industrial applications. The thermal efficiency of the current LPG cooking stoves available in the Indian market are in the range of (60-65) % and at the same time the CO and NO_X emissions levels are above the world health organization standards. Considering the energy conservation, environment issues and increase in demand of LPG in the near future. The present review paper summarizes the recent modification in the design of free flame conventional LPG burner by using porous materials and highlights its potential.

1. Introduction

Porous media combustion has some unique characteristics. It is totally different from conventional combustion devices; it gives rise to high radiant output, low NO_X and CO emissions, high power density and modulation. The difference between combustion in porous medium (PM) and a conventional system arises because of better and more efficient heat transfer from burned gases to unburned mixture. In a conventional combustion system, convection is the dominating mode of heat transfer (since gases have very low thermal conductivity and are less participating in radiation) from the burned to the unburned. On other hand, in porous media combustion, the conduction and radiation mode of heat transfer are also significant. In addition, the convection heat transfer is also improved, because ofincreased surface area within the porous matrix. There is better homogenization of temperature across the porous matrix and a presence of a significant amount of radiation help to preheat the incoming air-fuel mixture upstream, thereby improving the combustion efficiency. Fig. 1 is the schematic of a two-layered porous burner. In order to have better control over flame stabilization, PM burners are constructed with two different materials, forming two zones. The first is the preheating zone, made of low porosity and less conducting materials and the second is the combustion zone, made of highly radiating and conducting materials. The pore size is also large in combustion zone. The reason for choosing a material of low thermal conductivity and small porosity in preheating zone is to avoid combustion and the resultingflashback. Proper selection of porous material (both for preheat and combustion zone) allows thecombustion start at the interface of two zoneand spread over the entire volume of the combustion zone.

1.2. Combustion in porous media

When compared to conventional free flame burners, the novel porous burners present several advantage. There principle of operation is based on the fact that combustion takes place inside a solid matrix of open cavities big enough to sustain combustion, the porous medium. It is the presence of the porous medium that offers the advantage to PMC. The most common porous burner work with a steady, premixed flames. In this case, a mixture of fuel and oxidant enters the solid porous matrix where they burn, forming the combustion products that leave the porous matrix on the other side. The thermal energy released during the combustion process heat by convection the solid matrix that subsequently radiates and conducts heat up stream. As a consequence, the incoming fuel and oxidant are preheated.

1.3. Governing parameters

When dealing with this topic, knowledge of some parameters that influence the performance of liquid fuel combustion in porous media is desirable. A brief account of some basic parameters is presented as follows.

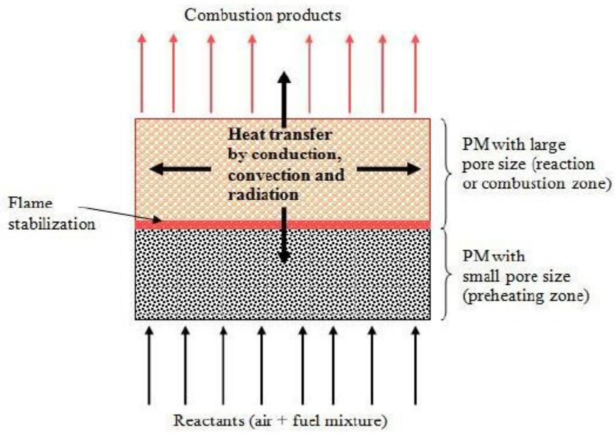

Fig. 1. Schematic diagram of two layer porous burner.

1.3.1. Peclet number

The modified Peclet number Pe is the deciding factor to specify the combustion region. If the Peclet number less than 65, the flame is unable to propagate and quenching occurs. Alternatively, for Peclet number greater than or equal to 65 flame propagates. The modified Peclet number is defined as,

$$Pe = \frac{S_l\, d\, \rho\, C_p}{k} \qquad (1)$$

Where S_l is the laminar flame speed, d is the equivalent diameter of the average hollow space of the porous material, C_p is the specific heat of the gas mixture, k is the thermal conductivity coefficient of the gas mixture.

1.3.2. Equivalence ratio

The equivalence ratio is defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. Stoichiometric combustion occurs when all the oxygen is consumed in the reaction, and there is no molecular oxygen (O_2) in the products. If the equivalence ratio is equal to one, the combustion is stoichiometric. If it is <1, the combustion is lean with excess air, and if it is >1, the combustion is rich with incomplete combustion.

1.3.3. Turn-down ratio (TDR)

It is the measure of the capability of a burner to modulate through a firing range or it is the measure of flame stability of a burner and is defined as the ratio of maximum firing rate to minimum firing rate of a burner. Typical values of TDR for industrial heating operations are in the range of 3:1 to 6:1.

1.3.4. Optical thickness (OT)

Defined as the product of refractive index (n) and thickness (t), i.e.

$$OT = nt$$

Refractive index (n) of a medium is the ratio of the velocity of propagation of an electromagnetic wave in vacuum to its velocity in the medium.

2. Literature review

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Jugjai and Sanitjai (1996). By utilization of porous medium technology, new design for conventional open flame gas burner is made to increase the thermal efficiency of standard burner up to 10%. The modified design called Porous radiant recirculated burner which uses porous media to transfer some of the hot gas enthalpy to premixed mixture. Unlike the porous burners described in the previous section, the PRRB does not operate by stabilizing the flame inside the porous medium. Instead, its flame is a free-flame and the porous medium only promotes the heat recirculation from the exhaust gas to the mixture of fuel and air. Fig. 2 shows the proposed heat recirculating burner.

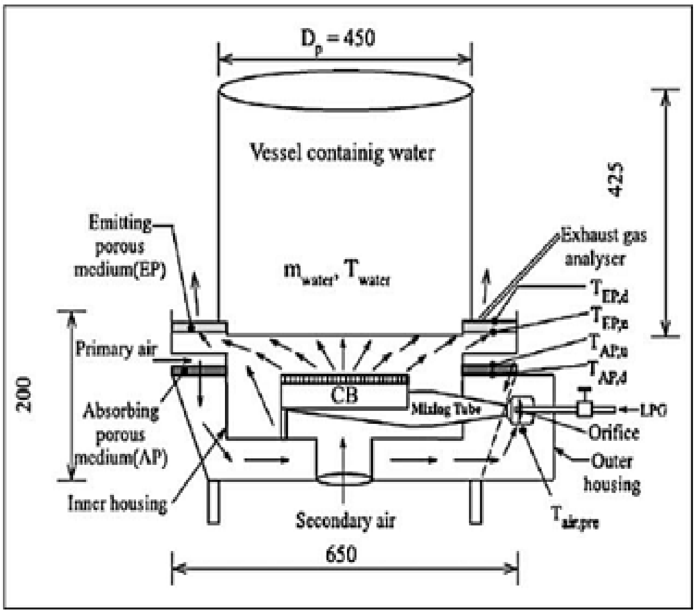

Fig. 2.PRRB Burner proposed by Jugjai and Sanitjai (1996).

Part of thermal radiation is redirected towards the absorbing porous medium through emitting porous medium, which then preheats the primary air that flows inside the air jacket. The porous media that are used in this study are made of several layers of stainless steel wires with 40 meshes per inch.

In a later study, Jugjai et al. (2001) proposed a swirling central flame technique figure 3 to improve the thermal efficiency of the conventional LPG open flame gas burner.

Fig. 3. Swirling flame burner proposed by S. Jugjai et al. (2001).

With the use of swirling central flame burner the heat transfer coefficient between hot flue gas and vessel increases thus thermal efficiency increases up to 15% compared to conventional radial flow burner.

Jugjai and Rungsimuntuchart (2002). A novel semi-confined porous radiant recirculated burner (PRRB) concept based on heat-recirculating combustion using the porous medium technology was developed for energy saving in domestic use and in a small-scale food processing industry. The proposed PRRB (SB) provide the maximum thermal efficiency of 60% with improvement in energy saving as well as environmentally compatible emissions. It can be applied in the small-scale food processing industry. The design concept is similar in the two papers and a picture of the developed burner .The use of porous media to promote the recirculation of heat from the hot combustion products to the combustion air resulted an efficiency increase of 12% further efficiency improvements are obtained when the burner presented in Fig. 3 is combined with a swirling central flame technique. In this case slightly higher CO and NO_X emission are observed.

Fig. 4.PRRB developed by Jugjai and Rungsimuntuchart (2002).

T Fend et al. (2003) paper will report on methodology and results of thermal conductivity, convective heat transfer coefficient and efficiency measurement of these monolithic materials. It will also present an experimental setup design to investigate how the properties of porous materials effects flow stability.

Khan (2010) showed the effect of different porous medium on thermal efficiency of LPG cooking stove. The design thermal efficiency of conventional LPG burner is 68% but its practical value war found to be 51.15%. With the use of different porous medium such as brass chip, mild steel chips and ball bearing it was observed that the thermal efficiency was different from each other and in all cases efficiency was found to be more than conventional burner.

All of the above papers explore the heat-recirculating capacity of porous media but do not consider combustion inside porous media. Later, Yoksenakul and Jugjai (2011) developed a self-aspirating porous medium burner (SPMB), where combustion take place inside the porous matrix, which formed by a packed bed of 15mm alumina sphere (Fig. 5). The burner instead to be applied in the small and medium scale enterprises (SMEs) and firing rate from 26 to 61 KW were tested.

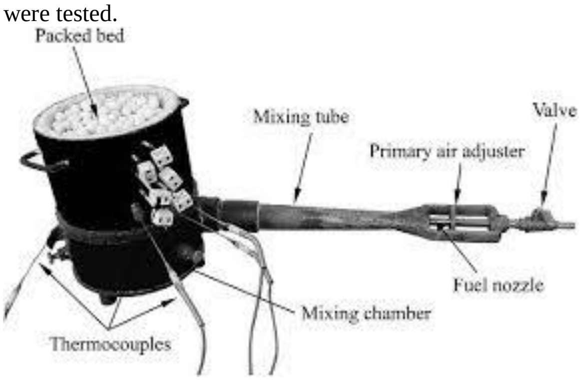

Fig. 5.SPMB developed by Yoksenakul and Jugjai (2011).

Patangi et al. (2011) deals with the performance test of PRB (porous radiant burner) used for LPG domestic cooking stove unlike the conventional LPG stoves for which the CO and NO_X emissions were found in the range 400-1050 mg/m^3 and 162-116 mg/m^3 respectively for the burn with PRB, the same burn in the range of 25-350 mg/m^3 and 12-25 mg/m^3. The axial temperature distribution inthe burnershow that the reaction zone was close to the interface of thetwo zone and at a higher thermal load, it shifted towards the downstream. The surface temperature of the PRB was found to be uniform.

Makmool et al. (2007) cooker-top burner performance survey and an implementation of a PIV technique to analyze the burner performance as well as advising local manufacturers were carried out. The thermal performance parameters and dynamic properties of the flow field at a flame impingement area, i.e. velocity magnitude, turbulent intensity, vorticity and strain rate were also reported as a function of burner type which are radial flow burner, swirling flow burners, vertical flow burners and porous radiant burners.

Kakati et al. (2007) incorporated porous medium inserts in a conventional high pressure kerosene stove. The burners with or without porous materials were used for the study in terms of thermal efficiency, kerosene consumption rate and emissions. The overall decrease in fuel consumption was found to be 34% with 10-11% increase in thermal efficiency.

Pantangi et al. (2007) the performance of a LPG cooking stove by removing the head of the conventional burner and filled it with different porous media thus forming the two-layer porous burner. The preheating zone consists of small pores porous burner while combustion zone consists of large pores porous medium.In some of the experiments, Pantangi et al. (2007). Insulated the bottom base and side of the mixing chamber using ceramic whool in order to minimize the heat losses and reduce the distance between the top surface of the mixing surface and the bottom surface of the pan. As an example, Fig. 6 shows one of converted LPG cooking stoves, where 3 to 4mm diameter pebbles were used in the preheating layer and mild steel chips in the combustion zone.

Fig.6. Porous burner studied by Pantangi et al. (2007).

Pataniji et al. (2007) concluded that, in general, when porous media combustion was used, the performances of the burner were better than the ones of the conventional burner analyzed. The best results were obtained when metal chips were used in the combustion chamber and the mixing chamber was insulated. In this case and when compared to the best conventional burner, the thermal efficiency of the porous media burner was improved by 4%, the CO emissions were reduced by 52% and the fuel consumption was reduced by 10%.

Keramiotis et al. (2011). An experimental investigation on two-layer porous burner with an AL_2O_3 flame trap and a 10ppi (pores per inch) SiSiC foam. The burner was operated with methane and LPG. The results revealed a homogeneous temperature distribution, low NO_X and CO emissions and wide flexibility with respect to fuels and thermal loads. The effects of fuel interchange on efficiency and emissions were also analyzed.

Patangi et al. (2011) study conventional kerosene pressure stove modified to incorporate an alumina heat shield and a porous radiant insert made of zirconia in the combustion zone. They concluded that this modification resulted in a 15% efficiency increase.

In a subsequent study, Pantanji et al. (2011) developed and proposed a porous radiant burner they built a two layer where the preheating zone is form by 5mm diameter alumina balls and the combustion zone by SiC form having 90% porosity. They analyzed the influence of the burner diameter, burner casing wall thickness and length of the porous matrices. For the best burner configuration and operating condition analyzed a 68% thermal efficiency was obtained. This value was 5% lower than the one obtained for the burner depicted in figure 4 and previously studied (although a direct comparison is not possible since all testing conditions details in the papers). The CO and NO_X obtained with the newly developed porous burner were lower than that reported for conventional burner.

In a different study Muthukumar et al. (2011) tested a similar LPG porous radiant burner. The diameter of the burner was equal to the one that presented better efficiency in pantangi et al studies (2011). The combustion zone as the same characteristics; however, the preheating zone is now composed of a ceramic block of 10 mm thickness and 40% porosity. Also the operating condition tested were different, since the equivalent ratio tested were significantly higher and the ambient temperature different. A maximumthermal efficiency of 71% was obtained which is above the efficiency of conventional LPG burners. Efficiency was obtained for an equivalence ratio of 0.68, 1.24 KW power intensity at 31^0C ambient temperature. From a comparison of pantangi et al. (2011) result with those of Muthukumar et al. (2011), one can conclude that it is better to use a ceramic block if 10 mm thickness and 40% porosity as preheating layer than 5 mm diameter alumina balls forming a porous media with 12- 15 mm thickness.

In their work, Muthukumar et al. (2011) investigated the influence of the ambient temperature on the thermal efficiency of the porous burner and concluded that for the same operating conditions, and efficiency improvement of 10% was achieved for varying the ambient temperature from 18.5 to 35^0C therefore when comparing the thermal efficiency of the burners the ambient temperature is the parameter that has to be taken into account.

In a recent study, Muthukumar and sham kumar (2013) extended pantangi et al.'s (2011) and Muthukumar et al.'s (2011) works. They tested the performance of a two layer porous burner see Fig 7. In this case, the diameter of the porous matrices was chosen to be 120 mm. like in Muthukumar et al. (2011) the preheating zone consists of ceramic matrix with 40% porosity and a thickness of 10mm and a combustion zone a Sic zone with a thickness of 20mm. however, in this steady the porosity of the SiC was vary from 80 to 90 %. The thermal efficiency and CO and NO_X emissions were experimentally obtained for equivalent ratios and power ranging from 0.542 to 0.7 and 1.3 to 1.7 KW, respectively.

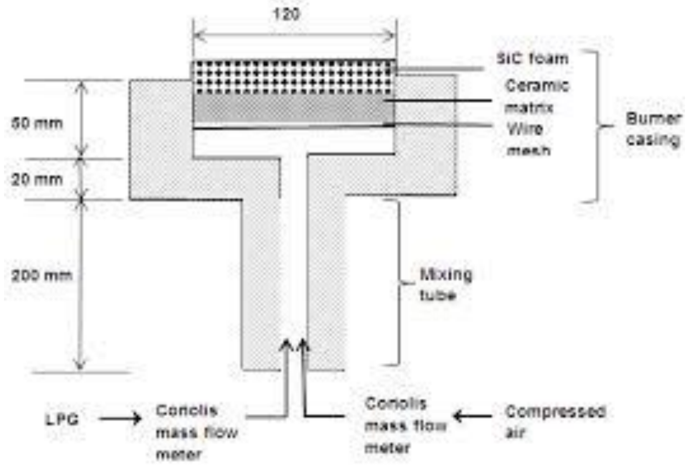

Fig. 7. The two-layer porous burner developed by Muthukumar and Shyamkumar (2013).

The highest thermal efficiency obtained were around 75% with the SiC for that has the highest porosity. This efficiency higher than the once of the LPG conventional burners available in the Indian market. The porous burner also perform better than conventional burners as far as emissions are concerned. For the 90% porosity SiC foam, NO_X emissions ranged from 0 to 0.75 mg/m^3 and CO emissions from 12 to 124 mg/m^3. Conventional LPG cooking stove emit 4 to 7 mg/m^3 of NO_X and 250 to 650 mg/m^3 of CO.

Mishra et al. (2013) a two layer porous burners developed by Muthukumar and Sham Kumar (2013) to a power range of 5 to 10 KW for medium scale LPG cooking applications. For this new burner the diameter of porous media are 120mm. once again, the experimental test prove that the porous burner is more efficient and less pollutant than the correspondent commercial LPG cooking stoves. The author demonstrated that thermal efficiencies decreased with an increase in thermal load.

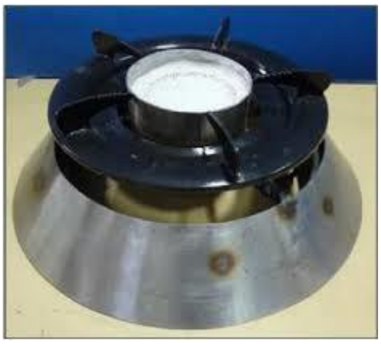

Fig. 8. The surface stabilized burner by Mujeebu et al. (2011).

In one of the burners (abbreviated as MSB) the flame was stabilized with in the porous matrix, i.e., the burner was operated in the submerged combustion mode while in the other (abbreviated as SSB) the flame was stabilized near the downstream interface of the porous medium just above the solid matrix i.e., the burner was operated in the surface combustion mode for the SSB (Fig. 8) the preheating and reaction zone were made from alumina foams.

The authors prove experimentally that the SSB is suitable for cooking applications where it is desirable that flame is extendible extended sufficiently above the surface of the porous medium, whereas the MSB work suitably as radiant heating burners(e.g., for household heating). Note that all of the porous media burners mentioned before worked in the submerged combustion mode. By comparing the performance of the burners working with premixed and no premixed flames, the authors conclude that the two layer porousburner work in a more appropriate way when the reactants enters the burner as a mixture. When compared to a conventional burner. Higher thermal efficiencies and a significant reduction in NOx and CO emissions were reported. However, the authors referred that further improvements of the burners are possible and recommended.

Mujeebu et al. (2011) also discussed the influence of the reaction layer geometry on the performance of the porous burner. Six different configurations for this region composed of alumina spheres were experimentally tested: 10, 20 and 30mm spheres combined with one or two reaction layers. Mujeebu et al. (2011) concluded that the best performance was obtained for only one reaction layer made of alumina sphere with diameter of 30mm.

Ismail et al. (2013) develop a two layer porous burner with co-generation, which, while functioning a domestic cooking stove, can generate a voltage of 9.3 V through thermoelectric cell. As seen in Fig. 9 the body of the burner was made hexagonal in order to provide six vertical faces to which the thermoelectric cells are attached. The porous media that composed the preheating and reaction layers of the burner are made of alumina porous material. The size of the burner developed by Ismail et al. (2013) was suitable to be used as an efficient outdoor cooking stove and butane was used as fuel the authors prove that it could charge smallelectrical devices such as mobile phone chargers.

Wu et al. (2014) developed a LPG flat flame burner for household cooking and water heating based on porous media combustion. Like in the SSB developed by Mujeebu et al. (2011) for cooking applications, the flame is stabilized on top of the porous matrix.

Choosing this stabilization mode allows for higher flame temperatures, which results in a higher heat transfer. Fig. 10 shows a schematic diagram of the burner studied by Wu et al. (2014). The porous matrix above which the flame stabilized, is made of bronze pellets with an average diameter of 0.5mm, has a low porosity of 0.237 and is 3mm thick.

Fig.9. The micro cogeneration system developed by Ismail et al. (2013).

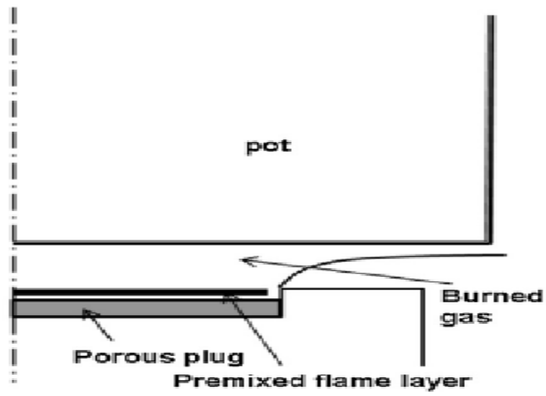

Fig. 10. The flat flame burner developed by Wu et al. (2014).

Wu et al. (2014) proved experimentally that the porous burner has a higher turn down ratio than a free flame burner and that increasing the excess air causes the operating range to become smaller. Additionally the NOX and CO emissions were generally lower in the surface stabilized porous burner developed than in a Bunsen flame burner. The author show that for the flat flame burner the efficiency and the emissions were not so effected by the distance between the burner exit and the pot/pan surface as in the case of Bunsen flame burner. This is favorable characteristic for domestic cooking applications.

All of the above papers explore the heat-recirculating capacity of porous media but do not consider combustion inside porous media. Later, Yoksenakul and Jugjai (2011) developed a self-aspirating porous medium burner (SPMB), where combustion take place inside the porous matrix, which formed by a packed bed of 15mm alumina sphere. The burner instead to be applied in the small and medium scale enterprises (SMEs) and firing rate from 26 to 61 KW were tested.

Snehasish et al. (2015) study on numerical and experimental analysis of combustion of LPG (48% n-butane, 25% isobutene 23% propane, 4% ethane by mole fraction) in a domestic stove with a two layer porous radiant burner. The combustion consists of silicon matrix with 90% porosity and the preheating zone is made of 3mm diameter alumina balls. Towards improving the thermal performance of the cooking stove effects SiC matrix thickness preheater thickness, solid phase conductivity, and scattering albedo on CO emissions and radiative flux are studied. In addition, following guidelines of the WHO, the most effective burner on the basis of minimum CO emission and maximum thermal efficiency is proposed.

L Eral et al. (2015). Performance study of an induced layer porous radiant burner with submerged combustion using natural gas was performed at high altitude to assess the feasibility of employing a porous burner operated in induced air for household applications.

B Herrera, K Cacua, L.Olmos-Villalba. (2015). A porous burner made of a bed of Al_2O_3 particles coming from grinding residues and combined with ceramic foam of SiSiC has been evaluated respect to Liquefied Petroleum Gas combustion stability and thermal efficiency for cooking in food industry. The results showed that for specific heat input rate lower than 154kW/m^2, the upper and lower equivalence ratio on the stability limit follow approximately a linear trend, as well as the wide of the range of stability remains constant.

M. Sharma et al. (2016). The concept of PMC has been employed in kerosene pressure stove to investigate the efficiency and emissions. Further the condition of optimum efficiency and emissions are find out with different burner geometry. It is found that the highest efficiency of the stove with porous media is found to be 10% higher than stove available in Indian market.

1. By use of different porous material to find out the thermal efficiency.
2. Varying the size and shape of porous material.
3. Use different fuel to compare the thermal efficiency.
4. New design of burner.

3. Conclusions

Porous burners are one of the possible available technologies for the development of energy efficient and eco-friendly household appliances. The low emissions and high efficiency that characterize porous media combustion are by now well established; however, practical studies that focus on household applications of this technology are not so common, even though large possibilities of improvement of such systems exist. This paper reviews the studies dedicated to the development of porous burners for cooking.

The literature review presented in this paper shows that there is considerable scope for the development of enhanced porous burners for household applications. The effects of fuel type, burner geometry and size, porous media materials and structures and catalytic combustion are yet to be thoroughly explored as far as porous burners for household applications are concerned.

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