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Potential of Porous Media Combustion Technology for Household Applications

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ABSTRACT: Households are major energy consumers and have a significant contribute to the World's final energy consumption and CO2 emissions. Among the energy end-use in buildings lies cooking. The energy saving potential of cooking appliances is large and an investment on the development of more efficient and less polluting stoves and ovens is necessary. Porous medium combustion, already commercially available for several other applications, is a promising technology that can be applied also to household cooking. This paper reviews the research works done in the field. The number of papers dedicated to this specific application is relatively low, and most of them concentrate on experimentally proving the advantages of porous burners when compared to conventional solutions. The influence of burner characteristics and operating conditions are analysed in a few studies. However, there is still a considerable scope for the development of enhanced porous burners for household applications.

Keywords: Porous media; Combustion; Porous burners; Household heat; Cooking

Nomenclature

cp	specific heat of the reactants mixture (J kg-1 K-1)
dm	equivalent diameter of the porous medium (m)
k	thermal conductivity of the reactants mixture (W m-1 K-1)
Pe	modified Péclet number (-)
SL	laminar flame speed (m s-1)
ρ	density of the reactants mixture (kg m-3)

1. Introduction

Energy efficiency measures, along with renewable energy production, are a way to tackle climate change, reduce the environmental impacts of energy consumption and improve energy security. Several countries are developing policies towards a reduction of their energy consumption. For example, China, the biggest World energy producer, set the target of reducing its national carbon intensity by 40% to 45% between 2005 and 2020 (Wang et al., 2014). In the United States of America, another major energy-consuming country, federal energy legislation (e.g., Energy Policy Acts of 2005 or the Energy Independence and Security Act of 2007) aims at promoting energy efficiency (Azevedo et al., 2013). Also, the European Union has adopted energy efficiency legislation. The 2012/27/EU Directive establishes a common framework of measures for the promotion of energy efficiency within the European Union in order to ensure the achievement of the Union's 2020 target: saving 20% of the primary energy consumption by 2020 compared to projections (European Union, 2012). This target is currently not on track, unlike the renewable energy target set by the European Union (European Environmental Agency, 2013).

There is a large potential for energy and greenhouse gas savings in the residential sector. In its World Energy Outlook of 2012, the International Energy Agency estimates that four fifths of the economic potential of energy efficiency in the buildings sector remains untapped (International Energy Agency, 2012). Households and services are major energy consumers. For example, in Europe, they represent around 40% of the total final energy consumption (European Union, 2013) and are responsible for 40% of the European Union's total greenhouse gas emissions (European Environmental Agency, 2011). Households alone account for 25% of the total final energy consumption and CO_2 emissions in Europe. Therefore, looking specifically at the residential sector from the energy efficiency perspective is mandatory if one speaks about energy efficiency.

Porous media combustion (PMC), which is already commercially available for other applications, is among the several possibilities to increase energy efficiency in buildings. It can be used to generate heat for space or water heating or to cook. From these, the former is the dominant energy end-use in buildings. Several studies have demonstrated the applicability of PMC in household heating. To name just a few of these works, Durst, Trimis and co-workers (Trimis and Durst, 1996a, 1996b; Durst and Trimis, 1997) of the LSTM-Erlangen developed several gas porous burners with integrated heat exchangers for household application. Some of the LSTM-Erlangen's prototypes have been successfully modelled by Pereira and co-workers (Malico and Pereira, 1999, 2001; Malico et. al., 2000) and Brenner et al. (2000). Delalic et al. (2004) presented an experimental study on a porous burner with a built-in heat exchanger that can be used for central heating systems for apartment or office buildings. In this work, the authors demonstrated the advantages of the developed system. Later on, Trimis was one of the researchers involved in the development of a system based on cool flame vaporization and porous medium combustion of liquid biofuels for domestic appliances (Brehmer et al., 2003). This burner was numerically simulated by Hayashi et al. (2004, 2007, 2010). In just another example, Avdic et al. (2010) developed and tested experimentally a compact and highly efficient heating system that combines an 8 kW gas porous media burner coupled with a novel heat exchanger that transfers heat to a 50 l tank equipped with a 1.9 kW electrical heater. The system is intended for space and domestic water heating in one-family houses and has a dynamic range of around 1:8 and low emissions of CO and NO_X. All of the burners mentioned above are stationary porous burners, which refers to the fact that the flame is stabilized in a specific region in the porous matrix. Following a different approach, Contarin et al. (2003) developed a burner with embedded heat exchangers based on the reciprocating flow mechanism. If this approach is followed, the direction of the flow is periodically reversed and combustion is a transient phenomenon.

Although cooking is globally not the dominant energy end-use in households, it is still the most universal residential energy service and pursuing energy efficiency in this segment is important. In developing countries, mostly solid fuels are used for cooking in low-income household, while in developed countries and higher-income households in developing countries, electricity or processed fuels such as liquefied petroleum gas and natural gas are used (Anenberg et al., 2013). Anenberg et al. (2013) characterized the current World situation as far as cooking fuels and technologies are concerned and discuss the policies, challenges, research priorities and opportunities in this sector. It is recognised that, among others, it is necessary to design high-performing and affordable stoves that meet user's broader energy needs.

PMC is a possible, efficient technology that can be used for household cooking. Several very valuable review articles on PMC are available in the literature (Howell et al., 1996; Mohamad, 2005; Kamal and Mohamad, 2006; Wood and Harris, 2008; Mujeebu et al., 2009a, 2009b, 2009c, 2009d, 2010; Mujeebu and Malico, 2014). They give a comprehensive overview of PMC from its initial stage until now. Yet, over the recent years, several studies were dedicated to the application of PMC in cooking appliances. The present paper summarizes the recent advantages in this field and highlights its potential. It is organized as follows: First, a general and brief overview of combustion in porous media is given in order to introduce the reader to the subject. After, the works on PMC applied to cooking are presented and discussed. At the end of the paper a critical review is made and future working directions proposed.

2. Combustion in Porous Media

When compared to conventional free flame burners, the novel porous burners present several advantages. Their 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 advantages to PMC. The most common porous burners work with 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 upstream. As a consequence, the incoming fuel and oxidant are preheated (See figure 1). This internal recirculation of heat from the combustion and products zones to the reactants region results in high power densities, low pollutant emissions, high turn down ratios and the capabilities of using low-calorific fuels or lean mixtures.

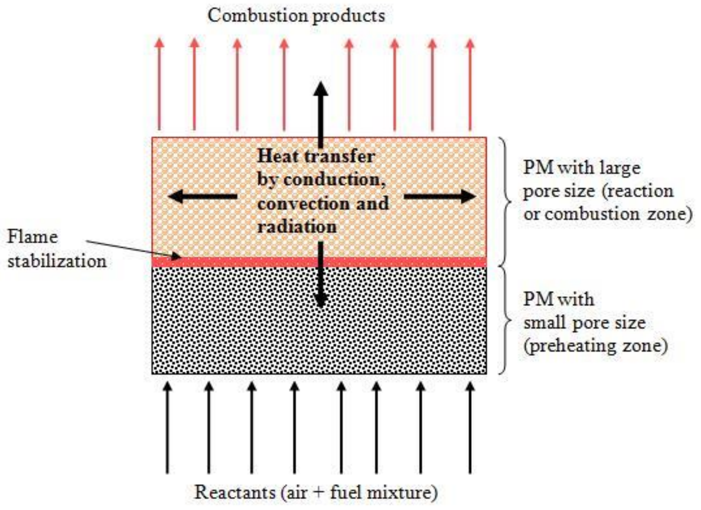

Figure 1. Schematic of a two-layer porous burner (Mujeebu et al., 2010).

There are several types of porous burners and applications, some of which already commercially available. It is not the objective of this article to give a thorough review on the subject. For that, the reader is redirected, for example, to the recent review by Mujeebu and Malico (2014). In the next section, the authors centre their attention in the development of porous burners for cooking applications.

Before entering in this review, it should be said that the development of appliances for cooking applications is characterized by certain specificities. For example, when developing household stoves, the power ranges are small (typically between 1 to 2 kW). Most of the studies in porous burners focus on porous burner with higher powers and it is not common to see research work on PMC with such low powers. Additionally, stoves which use gaseous fuels are very convenient, and are widely used in modern houses.

3. Porous Burners for Household Cooking Applications

In 1996, Jugjai and Sanitjai (1996) proposed a new burner design to improve the thermal efficiency of conventional burners used for domestic applications. They called the proposed burner, which uses porous media to transfer some of the hot gas enthalpy to the premixed mixture, a porous radiant recirculated burner (PRRB). 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. Figure 2 shows the proposed heat recirculating burner. The PRRB is composed of an inner housing and an outer housing with cylindrical shapes and co-axially assembled. Between these two housings an air jacket, which preheats the air used in the combustion process, exists. As shown in figure 2, the combustion products flow through the emitting porous medium, where some of the enthalpy of the hot products is converted to thermal radiation. Part of this thermal radiation is redirected towards the absorbing 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 wire mesh with 40 meshes per inch.

Jugjai and Sanitjai (1996) tested experimentally three types of LPG burners: a standard burner, a porous radiant burner and the newly proposed PRRB shown in figure 2. Their results show that the PRRB was the one with the best efficiency for the lower combustion loads typical of cooking stoves (1 to 2 kW). At these power loads, the performance of the PRRB is also superior in terms of CO and NOx emissions. The authors presumed that, for the case of the porous radiant burner tested, the mixing process between the secondary air and the combustion flame was not very good. This might have negatively affected the performance of the porous radiant burner and indicates that the porous radiant burner analysed can be subjected to improvements.

In a later study, Jugjai et al. (2001) proposed a swirling central flame technique to improve the thermal efficiency of a conventional LPG gas cooker. Again, the paper focuses on a free-flame burner and not on porous medium combustion. It is mentioned in this revision because in it three different types of vessel supports were considered: a conventional support, a light conventional support with a lower mass and a porous medium support. For the latter, a stainless steel wire mesh (mesh size of 16 mesh per inch) was used to recover heat from the hot combustion gases to the secondary air. The use of this simple recirculating vessel support increased the thermal efficiency of the burner in 3%.

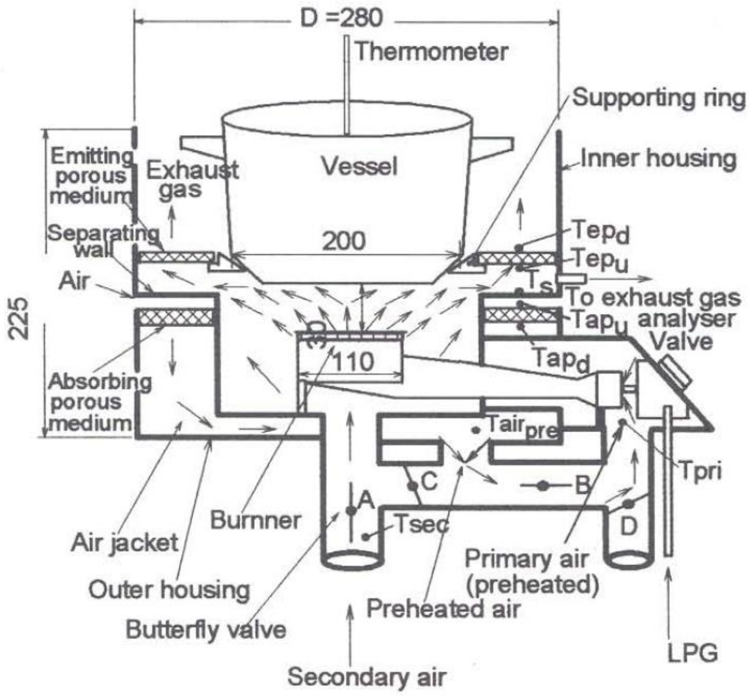

Figure 2. The porous radiant recirculating burner proposed by Jugjai and Sanitjai (1996).

The use of porous media as a heat-recirculating burner element was again explored in Jugjai and Rungsimuntuchart (2002), who presented a semi-confined PRRB. These authors scaled up the burner capacity of the burner presented by Jugjai and Sanitjai (1996) from 5 kW to 30 kW. By doing so, the burner 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 can be seen in Figure 3.

The use of porous media to promote the recirculation of heat from the hot combustion products to the combustion air resulted in an efficiency increase of 12%. Further efficiency improvements are obtained when the burner presented in figure 3 is combined with a swirling central flame technique. In this case, slightly higher CO and NOx emissions are observed.

Figure 3. The porous radiant recirculating burner developed by Jugjai and Rungsimuntuchart (2002).

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 takes place inside the porous matrix, which is formed by a packed bed of 15 mm alumina spheres (see figure 4). The burner intends to be applied in the small and medium scale enterprises (SMEs) and firing rates from 23 to 61 kW were tested.

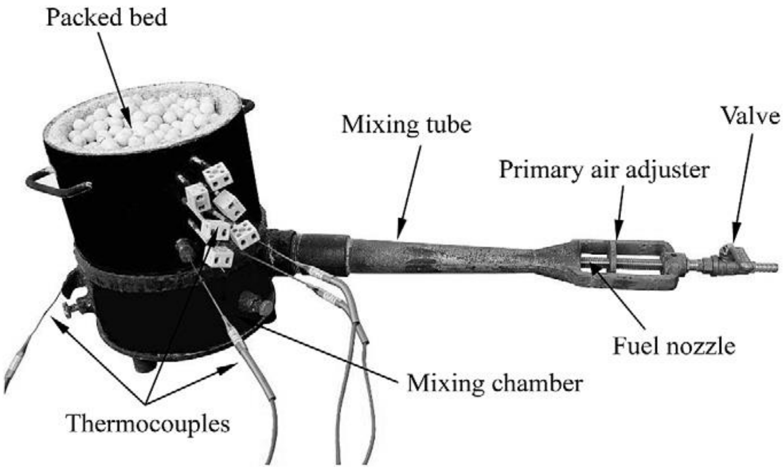

Figure 4. The self-aspirating porous medium burner developed by Yoksenakul and Jugjai (2011).

The burner may require around 1h to reach steady state, which is too long for household applications but suitable for SMEs. An output radiation efficiency of 23% and a turn-down ratio of 2.65 could be achieved. The CO emission was less than 200 ppm and NOx emission was less than 98 ppm.

In a previous study, Makmool et al. (2007) conducted an experimental investigation in order to evaluate the performance of 400 burners available in Thailand with not more than 5 kW. Among the several types of burner analysed were porous radiant burners. No burner details are given in the paper. On average, the porous radiant burners show improved thermal efficiency over the conventional burners and relatively large CO emissions of about 1800 ppm. However, the experiments done on the porous radiant show a wide variability. As one can see from the results of Yoksenakul and Jugjai (2011), the CO emissions of porous radiant burners can be relatively low.

One of the Institutions that has dedicated various research works to the application of porous media combustion for cooking is the Indian Institute of Technology Guwahati. Kakati et al. (2007) incorporated porous medium inserts in a conventional high pressure kerosene stove. The inclusion of the porous medium inserts resulted in a 34% reduction in the fuel consumption, a 10% increase in the thermal efficiency and a significant reduction of the CO, HC and NO_x emissions. In another study of the Indian Institute of Technology Guwahati, Pantangi et al. (2007) incorporated porous media (metal balls, pebbles and metal chips) in the mixing chamber of a conventional LPG cooking stove. Although kerosene and wood stoves are still prevalent in their country, India, LPG stoves are easier to utilize (Pantangi et al., 2011) and this type of fuel is subsidized. As a consequence, they are increasingly used in the country. However, the LPG stoves currently employed emit more NO_x than the kerosene and the biomass stoves and present higher CO and NOx emissions than those prescribed by the World Health Organization (Pantangi et al., 2011). This asks for improvements in the conventional LPG cooking stoves and motivated the work of Pantangi et al (2007). At this point, it should be said that the choice of fuel is always a relevant issue when developing innovative domestic appliances. People are culturally used to certain types of fuels, and local circumstances, such as local infrastructures and access to fuels, fuel prices, household income and policies like subsidies, also contribute to the fuel choice. It is therefore important that manufactures and R&D teams adapt to the local circumstances.

In their work, Pantangi et al. (2007) evaluated the performance of a conventional domestic LPG cooking stove converted to work with porous media combustion. The authors removed the heads of conventional burners and filled the mixing chamber with different combinations of porous media, forming a two-layer porous burner. In this type of porous burners, the premixed oxidant and fuel first pass through a small pores porous medium, the preheating zone, and then through a larger pores porous medium, the combustion zone, where the reaction takes place (see figure 1). In the preheating region, the pore sizes usually result in a modified Péclet number below 65. The modified Péclet number (Pe) is defined as:

$$\mathrm{Pe} = \frac{S_\mathrm{L} d_\mathrm{m} c_\mathrm{p} \rho}{k}, \tag{1}$$

where S_L is the laminar flame speed, d_m the equivalent diameter of the porous medium, c_p the specific heat of the gas mixture, ρ its density and k its thermal conductivity. On the contrary, the combustion zone should be characterized by a modified Péclet number higher than 65, in order that a flame can be sustained inside the medium.

In some of the experiments, Pantangi et al. (2007) insulated the bottom base and side of the mixing chambers using ceramic wool, in order to minimize the heat losses and reduced the distance between the top surface of the mixing surface and the bottom surface of the pan. As an example, figure 5 shows one of the converted LPG cooking stoves, where 3 to 4 mm diameter pebbles were used in the preheating layer and mild steel chips in the combustion zone.

Figure 5. One of the porous burners studied by Pantangi et al. (2007).

Pantangi et al. (2007) concluded that, in general, when porous media combustion was used the performances of the burners were better than the ones of the conventional burners analysed. 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%.

On another study, Sharma et al. (2011) studied experimentally a 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 these modifications resulted in a 15% efficiency increase.

In the works described above, only preliminary investigations were performed and retrofitting of conventional stoves was undertaken. In a subsequent study, Pantangi et al. (2011) developed and proposed a porous radiant burner. They built a two-layer porous burner, where the preheating zone is formed by 5 mm diameter alumina balls and the combustion zone by SiC foam having 90% porosity. They analysed the influence of the burner diameter, burner casing wall thickness and length of the porous matrices. For the best burner configuration and operating conditions analysed, a 68% thermal efficiency was obtained. This value was 5% lower than the one obtained for the burner depicted in figure 5 and previously studied (although a direct comparison is not possible since all testing conditions are not detailed in the papers). The CO and NOx emissions obtained with the newly developed porous burner were lower than that reported for conventional burners and improvements were achieved in relation to the retrofitted burner studied in Pantangri et al. (2007).

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 a better efficiency in Pantangi et al.'s study (2011). The combustion zone has the same characteristics; however, the preheating zone is now composed of a ceramic block of 10 mm thickness and 40% porosity. Also the operating conditions tested were different, since the equivalent ratios tested were significantly higher and the ambient temperatures different. A 71% maximum thermal efficiency of the porous radiant burner was obtained, above the efficiency for conventional LPG burners. This efficiency was obtained for an equivalence ratio of 0.68, 1.24 kW power intensity and 31ºC ambient temperature. The reported CO and NOx emissions were always below 16 ppm and 0.2 ppm, respectively. From a comparison of Pantangi et al.'s (2011) results with those of Muthukumar et al. (2011), one can conclude that it is better to use a ceramic block of 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 it was noteworthy. For the same operating conditions, an efficiency improvement of 10% was achieved from varying the ambient temperature from 18.5ºC to 31ºC. Therefore, when comparing the thermal efficiency of burners, the ambient temperature is a parameter that has to be taken into account.

In a recent study, Muthukumar and Shyamkumar (2013) extended Pantangi et al.'s (2011) and Muthukumar et al.'s (2011) works. They tested the performance of a two-layer porous burner similar to the previously developed ones (see figure 6). In this case, the diameter of the porous matrices was chosen to be 90 mm. Like in Muthukumar et al. (2011) the preheating zone consists of a ceramic matrix with 40% porosity and a thickness of 10 mm and the combustion zone a SiC foam with a thickness of 20 mm. However, in this study the porosity of the SiC was varied from 80 to 90%. The thermal efficiency and CO and NOx emissions were experimentally obtained for equivalent ratios and powers ranging from 0.54 to 0.7 and 1.3 to 1.7 kW, respectively. The highest thermal efficiencies obtained were around 75% with the SiC foam that has the highest porosity. This efficiency is higher than the ones of the LPG conventional burners available in the Indian market. The porous burner also performed 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 stoves emit 4 to 7 mg m^{-3} of NO_x and 250 to 650 7 mg m^{-3} of CO.

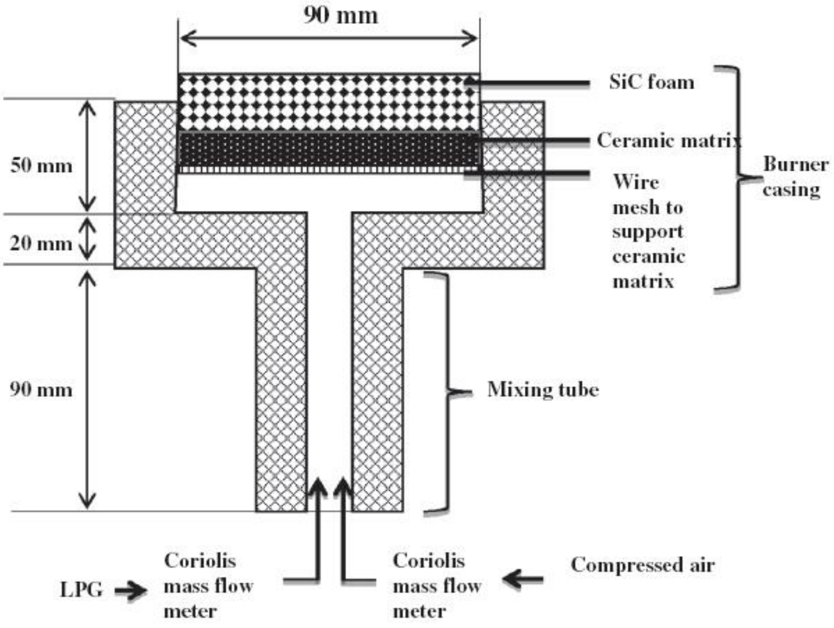

Figure 6. The two-layer porous burner developed by Muthukumar and Shyamkumar (2013).

Mishra et al. (2013) scaled up the previously two-layer porous burners developed by Muthukumar and Shyamkumar (2013) to a power range of 5-10 kW for medium-scale LPG cooking applications. For this new burner, the diameters of the porous media are 120 mm. Once again, the experimental tests proved that the porous burner is more efficient and less pollutant than the correspondent commercial LPG cooking stoves. The authors demonstrated that thermal efficiencies decreased with an increase in the thermal load.

At the the Universiti Sains Malaysia, Mujeebu et al. (2011a, 2011b, 2011c) developed two different two-layer, premixed LPG porous burners for household applications. In one of the burners (abbreviated as MSB) the flame was stabilized within 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 the preheating and reaction zones were made from alumina foams of 26 ppcm and 8 ppcm, respectively. These zones were made of porcelain foam with 18 ppcm and alumina spheres of 30 mm size for the MSB. Figure 7 shows a picture of the SSB, however, the assembly shown is suitable for both the submerged and surface combustion mode burners.

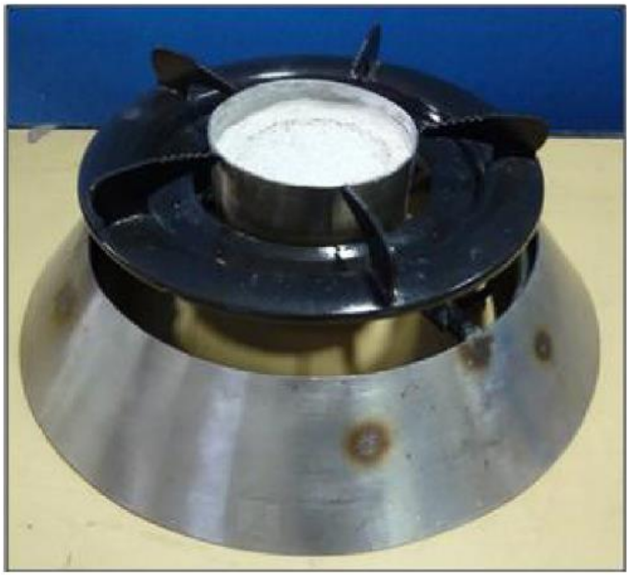

Figure 7. The surface stabilized burner developed by Mujeebu et al. (2011c).

The authors prove experimentally that the SSB is suitable for cooking applications, where it is desirable that the flame is 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 nonpremix flames, the authors conclude that the two-layer porous burners work in a more appropriate way when the reactants enter 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 refer that further improvements of the burners are possible and recommended.

Mujeebu et al. (2011b) 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 30 mm spheres combined with one or two reaction layers. Mujeebu et al. (2011b) concluded that the best performance was obtained for only one reaction layer made of alumina spheres with a diameter of 30 mm.

Recognizing that one of the major issues in domestic combustion is the heat loss to the environment, the work of Mujeebu et al. (2011a, 2011b, 2011c) was extended to make use of the heat that is otherwise laterally lost to the surroundings from the burner. Ismail et al. (2013) developed a two-layer porous burner with cogeneration, which, while functioning as a domestic cooking stove, can generate a voltage of 9.3 V through thermoelectric cell. As seen in figure 8, 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 compose the preheating and reaction layers of the burner are made of alumina foam, with 24 and 8 ppcm, respectively. 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 proved that it could charge small electrical devices such as mobile phone chargers.

Figure 8. The micro cogeneration system developed by Ismail et al. (2013).

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. (2011c) 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. Figure 9 shows a schematic diagram of the burner studied by Wu et al. (2014). The porous matrix, above which the flame stabilizes, is made of bronze pellets with an average diameter of 0.5 mm, has a low porosity of 0.237 and is 3 mm thick.

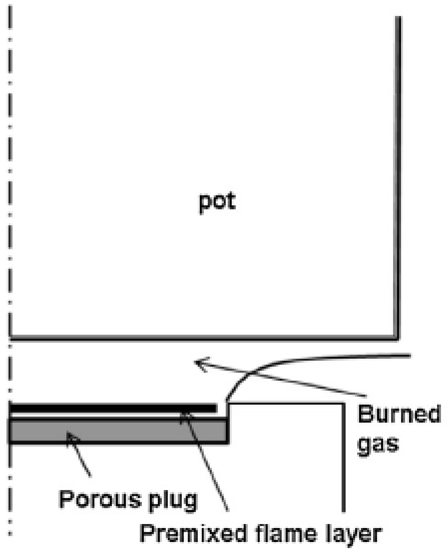

Figure 9. The flat flame burner developed by Wu et al. (2014).

Wu et al. (2014) proved experimentally that the porous burner has a higher turndown 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 authors showed that for the flat flame burner the efficiency and emissions were not so affected by the distance between the burner exit and the pot/pan surface as in the case of a Bunsen flame burner. This is a favourable characteristic for domestic cooking applications.

4. 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 first studies that developed prototypes that used porous media in cooking appliances took advantage of the capability of porous matrices to recirculate heat from the hot combustion products to the combustion air. The combustion did not occurred inside the porous matrix, but the efficiency of the burner was enhanced by this heat recirculation. Later on, retrofitting of conventional stoves was performed in order to incorporate porous media combustion and then one-layer and two-layer porous burners started to be developed for cooking. Most of the works focus on showing the advantages of porous burners when compared to conventional solutions. Some of the studies investigated the influence of certain parameters on the performance of the porous burners. In this context, they analysed the geometrical characteristics of the burners (burner diameter, wall thickness, isolation, type of porous material used, etc.) and operating conditions (ambient temperature, power, equivalence ratio, etc.) on the performance of the burners. More recent studies go in the direction of addressing a broader applicability of porous media combustion for household applications, such as the possibility of integrating then in micro cogeneration systems.

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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