Proceedings of the 11th Brazilian Congress of Thermal Sciences and Engineering -- ENCIT 2006
Braz. Soc. of Mechanical Sciences and Engineering -- ABCM, Curitiba, Brazil,- Dec. 5-8, 2006

Paper CIT06-0468

EXPERIMENTAL STUDY OF A COMBINED THERMAL AND FLUIDYNAMIC MECHANISM OF FLAME STABILIZATION IN A RADIANT POROUS BURNER

Rafael de Camargo Catapan
Department of Mechanical Engineering - Federal University of Santa Catarina – Florianópolis/SC
catapan@labcet.ufsc.br

Fernando Marcelo Pereira
Department of Mechanical Engineering - Federal University of Santa Catarina – Florianópolis/SC
fernando@labcet.ufsc.br

Amir Antonio Martins de Oliveira Júnior
Department of Mechanical Engineering - Federal University of Santa Catarina – Florianópolis/SC
amirol@emc.ufsc.br

Abstract: In this paper, we present an experimental study of the flame stabilization in a radiant porous burner with combined thermal and fluidynamic mechanisms. In the application of porous radiant burners, usually the flame is stabilized when two or more layers of porous foams with different structures are used in series. This stabilization occurs solely by heat loss to the external environment and a basically plane flame is obtained. Here, a perforated plate with a single central injection hole was placed upstream of the ceramic foams. In this case, the flame develops a rounded, bell type, axisymetric shape and the flammability range is further extended by the flow acceleration as the flame approaches the premixed gas inlet hole. In order to test the limits of this approach, burners with different layers of 20 mm thick alumina (Al_2O_3) and zirconia (ZrO_2) ceramic foams, with a diameter of 70 mm, operating with premixed methane and air were tested. The perforated plate promoted a local increase of outflow speed, preventing flashback for lower flame speeds. It is shown that a properly designed perforated plate, through a combined thermal and fluidynamic stabilization mechanism, is a simple way of increasing the operation range of radiant porous burners.

Keywords: porous radiant burner, premixed flame, flammability limits, flame stabilization, natural gas.

1. Introduction

The development of radiant porous burner has been encouraged by advantages theses in relation to free flame burners. According to Hsu (1996), radiant porous burner has high radiation efficiencies, extended lean flammability limit, good flame stability characteristics and low pollutants emissions. Many of this features was analyzing by Hardesty and Weinberg (1974) in burners with high heat recirculation. They showed the advantages of excess enthalpy flame made by heat recirculation of combustion products to unburnt mixture. Was possible burn no inflammable mixture and fuel with low calorific power.

Takeno and Sato (1979) proposed a simple way to produce excess enthalpy flames inserting a porous, highly conductive solid into the flame to conduct heat from post flame zone to pre flame zone. This way was tested by Kotani e Takeno (1982), with a premixed combustion of methane and air in an alumina tubes burner with heat recirculation of combustion products. They observed the flame stabilized within a porous media in different positions resulting different heat recirculation rates. The Figure (1) shows a rendering of the gas and solid enthalpy across a flame within a porous medium, showing the increase of enthalpy in the flame zone as a result of sensible heat recirculation.

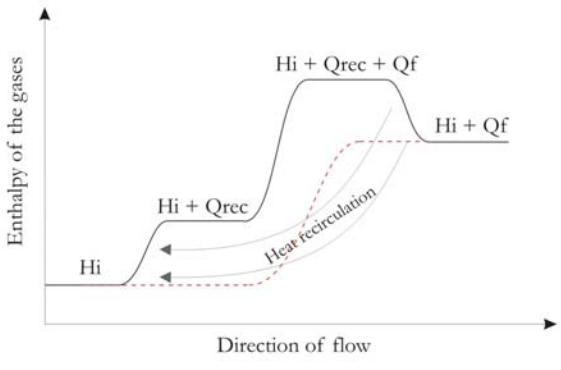


Figure 1. Rendering of the gas and solid enthalpy across a flame within a porous medium, showing the increase of enthalpy in the flame zone as a result of sensible heat recirculation, where Hi is the initial enthalpy, Qrec is the recirculated heat and Qf is the energy of the fuel (from Hardesty e Weinberg, 1974).

Others researchers studied combustion in porous media, especially in radiant porous burners. Know of operational conditions, pointedly flammability limits, limits of blow off and flashback and radiation efficiencies, is very important for your study. In this context, the experimental study had been a great importance in validation of numerical model and prevision of operational range.

Following Barra *et al*. (2003) the porous burner can have different designs. It is usual, porous burner made with two layers with different properties. Trimis and Durst (1996) showed that the rate of heat loss from the reaction zone increases as the pore size decreases, resulting in flame quenching as the pore size is decreased below a critical value. Therefore, when the combustion takes place within a double layer of ceramic foams, in which the layer located upstream has pore size below the critical value, there is a tendency of stabilization of the combustion front at the interface between the two layers. Hsu (1996) calls the layer with small pores as the preheating region (PR) and the layer with the larger pores as the stable-burning region (SBR).

Hsu *et al*. (1993) researched numerically and experimentally the premixed combustion of methane and air within a porous burner made from ceramic foam. The PR was made with 65 ppi and SBR with 10, 30 and 45 ppi. They obtained a range of flame speed for each equivalence ratio. In all studied equivalence ratios, the flame speed within a porous medium was higher than the laminar free flame speed for the same conditions. In numerical study, they founded two different regions of flame stabilization. The first region, near to the interface between layers with different properties was experimentally confirmed. The second region, near to the exit surface of the burner for environment temperature close to the burner surface temperature, was not confirmed.

In a similar study, Khanna *et al*. (1994) measured the CO and NOx emissions and radiation efficiencies of the porous burner. They looked that NOx/No increase with the increase of flame speed for all studied equivalence ratios. In general, CO emissions increase with flame speed. However, for a fixed equivalence ratio, the CO is minimum at intermediate values of the flame speed. The radiant thermal efficiency of the burner decrease with increasing the flame speed. Hsu (1996) compared the results obtained by Khanna *et al*. (1994) with a porous burner with a thermal radiation barrier. He not found differences between results. In this experiment, he used a third layer of ceramic foam upstream of SBR, called radiation reflection region (RRR). A second stabilization region was got in the interface between SBR and RRR.

This mechanism for flame stabilization and has been explored by Pereira (2002) in the design of surface and volumetric porous burners. In this study, he used three thermocouples axial lines for flame structure measurements. He observed the flame stabilization in the interface between ceramic foams with different properties. Beyond this, he found a minimum temperature variation in the three lines. This information shows the plane shape of the flame.

Barra *et al*. (2003) and Barra and Ellzey (2004) studied a porous burner made from two layers of ceramic foams with different properties. The numerical studies show that the properties of porous matrix influences the limits of stability and that a good design of porous burner can be find by correct selection of this properties.

Chaffin *et al* (1991) shows an alternative way of flame stabilization and enlargement of yours stability limits. In this study, the flame stabilization was controlling by the combined of the interface of different properties of ceramic foams and a ring shape heat exchanger near of interface. The results show a minimum variation of temperature peak position and consequently of flame position with flame speed and equivalence ratio variations.

Hayashi *et al*. (2004) studied a radiant porous burner with large superficial area composed by two layers. The first layer was made from an insulation perforated plate and avoided the flash back. The combustion reaction occurs in the second layer made from SiC ceramic foam. The results show that the flame position is constant and near to the interface. This behavior is due the blockage of heat transferred in the solid in the counter-flow direction at the interface combined with high flow speed on the interface. However, for low power and low excess air ratio conditions, the flame stabilizes inside the holes of the perforated plate.

Recently, we proposed a simple way of flame control within a porous radiant burner with large superficial area (Catapan, 2005). Differently of Hayashi *et al*. (2004), we used a perforated plate with few holes that decreased the passage area of the unburnt gases in relation to ceramic foam. The advantage of this design in flame stabilization is that above each hole the flow expands and decelerates, originating a flame stretch, and the flame position stabilizes where the local flame velocity equilibrates the flow speed in a mode essentially like a Bunsen burner flame. This fluidynamic stabilization of flame makes difficult the flash back and expands the flame stability limits range.

In this study, we use a combine thermal and fluidynamic mechanism of flame stabilization. The first stabilization mechanism present in this radiant porous burner is the thermal stabilization imposed by the presence of a solid matrix, i.e., heat recirculation and heat loss to the surroundings. A second stabilization mechanism is present when two or more layers of different porous structures are used together. These two mechanisms are well known from the literature and are briefly discussed in the previous paragraphs. A third stabilization mechanism is fluidynamic and is related to the reactants injection in the burner. All these mechanisms are explored in this work to achieve stable and uniform combustion.

Now, we present an experimental study of a combined mechanism of flame stabilization in a porous radiant burner based in the porous burner made by Pereira (2002). Here, a perforated plate with a single central injection hole was placed upstream of the ceramic foams. The flame position and shape were showed by thermocouple measurements within a porous burner in different flame speeds and equivalence ratios. We show the stability limits and the radiation efficiencies with the variation of the diameter of the injection hole.

In the following, the experimental set-up and burner design is described.

2. Experimental set-up

2.1. Experimental apparatus

The Figure (2) presents a schematic view of the apparatus for testing of radiant porous burners. Basically, it is composed of a burner section, air and fuel supply systems and measurement systems, including temperature measurement and data acquisition.

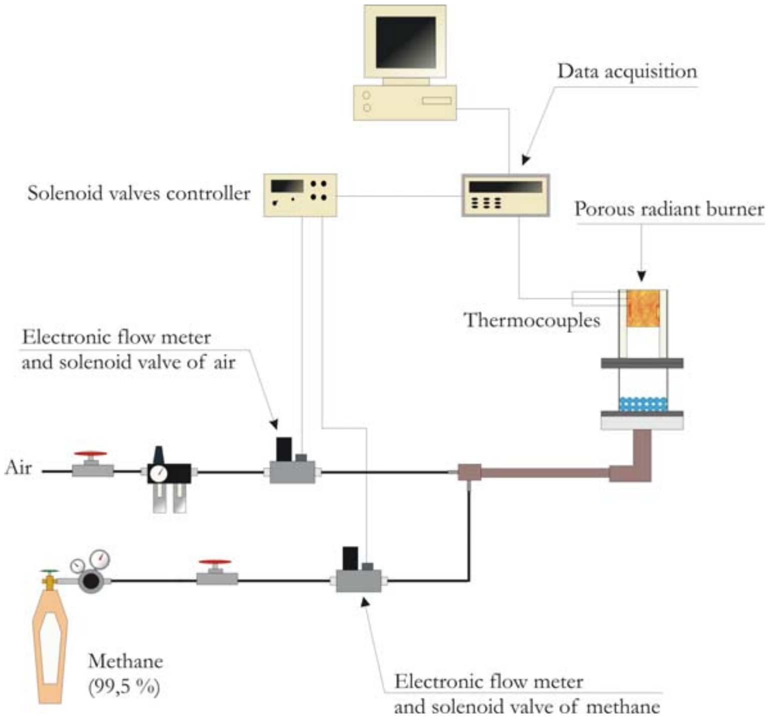


Figure 2. Schematic view the apparatus for testing of radiant porous burners.

The air supply system is composed of a check valve, air flow control valve and an electronic flow meter (from Omega Engineering Inc.), with measurement range between 0 and 500 liters per minute (lpm) and measurement uncertainty of ± 0.75 lpm. The fuel supply system is composed by a check valve, solenoid control valve and an electronic flow meter (from Omega Engineering Inc.) with the measurement range between 0 and 50 lpm and measurement uncertainty of ± 0.05 lpm. Air and methane is premixed in a steel tube with 1000 mm length. Type R (platinum and platinum + 13% rhodium) thermocouples insulated inside alumina beads are used to measure the temperature within the porous burner. These have measurement range between 50ºC and 1768ºC and measurement uncertainty of ± 4ºC. Values of temperature are recorded by an Agilent 34970. A data acquisition system was interfaced to a personal computer.

2.2. Burner design

The burner was made with different layers of 20 mm thick alumina (Al_2O_3) ceramic foams (manufactured by Foseco Ind. e Com. Ltda.), as shown in Figure (3). The SBR was made with 10 porous per inch (ppi) ceramic foams and the PR with 40 ppi ceramic foams. All ceramic foams had diameter of 70 mm and 80% of volumetric porosity.

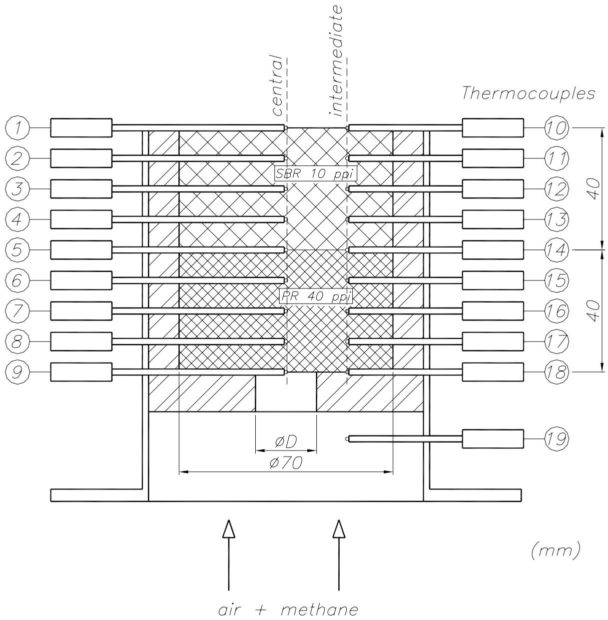


Figure 3. Schematic drawing of the radiant porous burner.

A perforated plate with a single central injection hole was placed upstream of the ceramic foams, Fig. (3). In this study, we used two perforated plate with diameter of 17 mm and 35 mm (*"D"* in Fig. 3).

Two thermocouples lines, each of which with 9 thermocouples, was placed within of ceramic foams as shown in Figure (3). The central line was placed in the centre of the porous medium and the intermediate line in the half way between central line and the external cylindrical surface. The thermocouples show where the reaction zone is located, because a great gradient of the temperature is recorded in this region. For the steady state flame, we will know the position of flame front and the flame shape. Axisymetric variations in the flame will not be identified, due the only one thermocouple line in the periphery of the ceramic foam.

Due to the hot bed measure great, it is not possible to know if we are measuring the gas phase temperature or the solid phase temperature. According to Barra e Ellzey (2004), the flame within porous media is composed by two regions. In the pre heating zone, the solid phase temperature is highest than the gas phase temperature. In this zone, the thermocouple is heating by radiation from solid phase and cooler by gas phase. The reaction zone star when the solid phase and the gas phase temperatures are equals. As from this moment, the thermocouple is heating by the gas phase and cooler by radiation to solid phase.

2.3. Experimental method

The experimental method used in this work follows Hsu *et al*. (1993). It consists of choosing a fuel equivalence ratio and a gas volumetric flow rate that allows for flame propagation within the porous burner. The flame stabilizes in the SBR in a region near the interface between the PR and the SBR. The equivalence ratio is slowly adjusted to the desired value and the volumetric flow rate is increased until the upper limit for flame propagation (the blowout limit) is reached. Then, the burner is reinitialized and the volumetric flow rate is decreased until the lower limit for flame propagation (the flashback limit) is reached. The larger possible fuel equivalence ratio is limited by the upper temperature limit for the porous matrix used. Here, the fuel equivalence ratio follows the usual definition as,

$$\phi = \frac{\left(\dot{m}_F / \dot{m}_a \right)_a}{\left(\dot{m}_F / \dot{m}_a \right)_S} \qquad (1)$$

The flame speed (S_L) is calculated dividing the gas flow rate by the burner area. The calculated flame speed by this method is a reasonable approximation for plane flame shape. However, we observe in this study that the flame shape is three-dimensional and the real flame speed is very difficult to determine. A flame is considered stable when the recorded temperatures within the porous burner vary by less than 10ºC in ten minutes. The blow off limit is identified as the flame speed beyond which the flame stabilizes outside the burner and is visually seen as a trembling blue flame at the burner surface. The flash back limit is defined as the flame speed for which the flame penetrates in the perforated plate, is identified by increase in the temperature in the thermocouple 19, Fig. (3). The radiation efficiency of the burner is defined as ratio between the energy emitted by the burner through thermal radiation and the total energy released by the combustion process. We define that the surface temperature of the burner is equal to arithmetic mean of the temperatures indicated by thermocouples 1 and 10, Fig. (3).

3. Results and discussion

We tested the radiant porous burner with ϕ = 0,55 e ϕ = 0,60. According to experimental procedure, was found the upper and lower stability limits for burner configurations with perforated plated of 17 mm and 35 mm. The highest total power obtained was 3,7 kW in ϕ = 0,55 e S_L = 53 cm/s and the lower total power was 0,5 kW in ϕ = 0,55 and S_L = 7 cm/s.

Figure (4) presents a temperature profiles across the porous burner with a perforated plate of 17 mm, recorded in the central line (Fig. 4a) and in the intermediate line (Fig. 4b). The “x” axis represents the non dimensional length and is equal to x/L where “L” is burner length and “x” is the position. Figure (4a) presents the displacement of the temperature peak in the central line when the flame speed is increased. According to Pereira (2002), the flame front position is equal to the temperature peak position. In Figure (4a) we observe that flame front is close to the burner surface for S_L = 40 cm/s. For higher flame speed than this one, i.e., S_L = 50 cm/s, occurs the blow off. This occurs because the higher radiation heat exchange to the environment by porous matrix when the flame front is near to the burner surface. The flame front is cooled and your speed is decreased. Figure (4b) presents the temperature profiles across the porous burner recorded in the intermediate line. We observe that the flame front position is stable with increase the flame speed and the temperature profile is smoother than the profile in the central line.

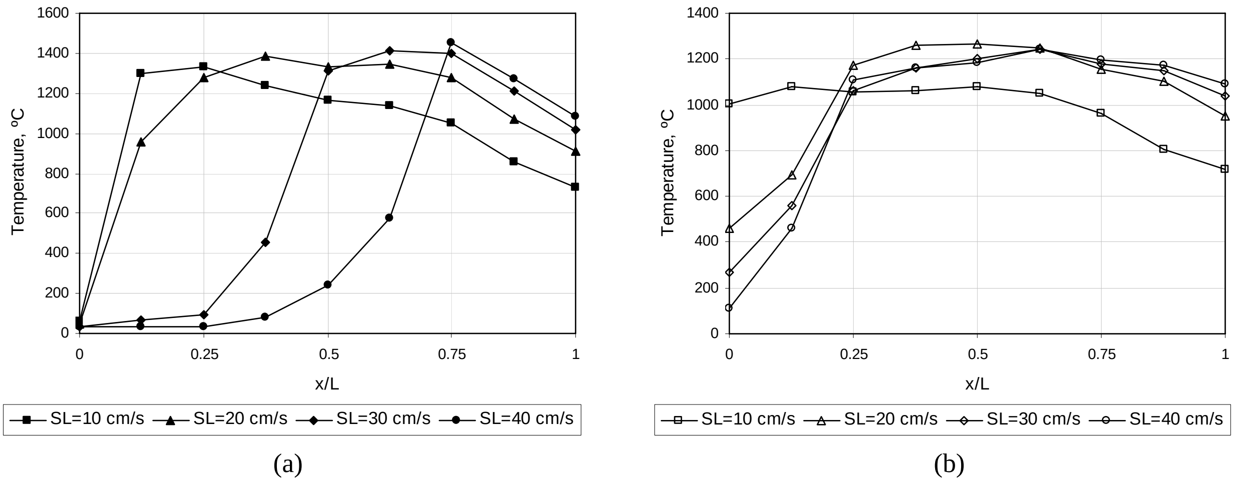
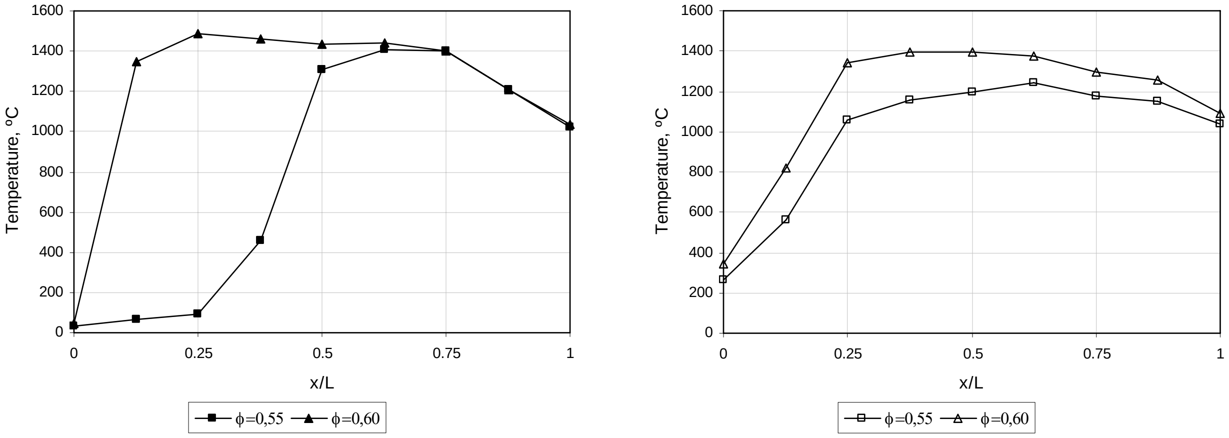


Figure 4. Temperature profiles across the porous burner with a perforated plate of 17 mm, for ϕ = 0,55, recorded (a) in the central line and (b) in the intermediate line.

In the Figure (4a) we observe that the flame front is close to the downstream surface of the burner for S_L = 10 cm/s. For the same conditions, the Figure (4b) doesn’t present a peak of temperature that defines the flame front position. This shows that flame front only crossed the central line of the thermocouples. When we increased the flame speed, the flame front in the central line is displacement across the porous medium until the blow off. However, the flame front position in the intermediate line is constant. The flame develops a rounded and bell shape that is lengthened when the flame speed is increased.

The variation of the flame front position in the central line was observed when we change the equivalence ratio for a same flame speed. With the increase of the fuel mass fraction, i.e., increase the total power of the burner, increase the propagation speed of chemical reaction and the flame front found a new stability position. This behavior is visualized in the Figure (5) where are presented the temperature profiles across the porous burner with a perforated plate of 17 mm, operating with S_L = 30 cm/s, ϕ = 0,55 and ϕ = 0,60, recorded (a) in the central line and (b) in the intermediate line.

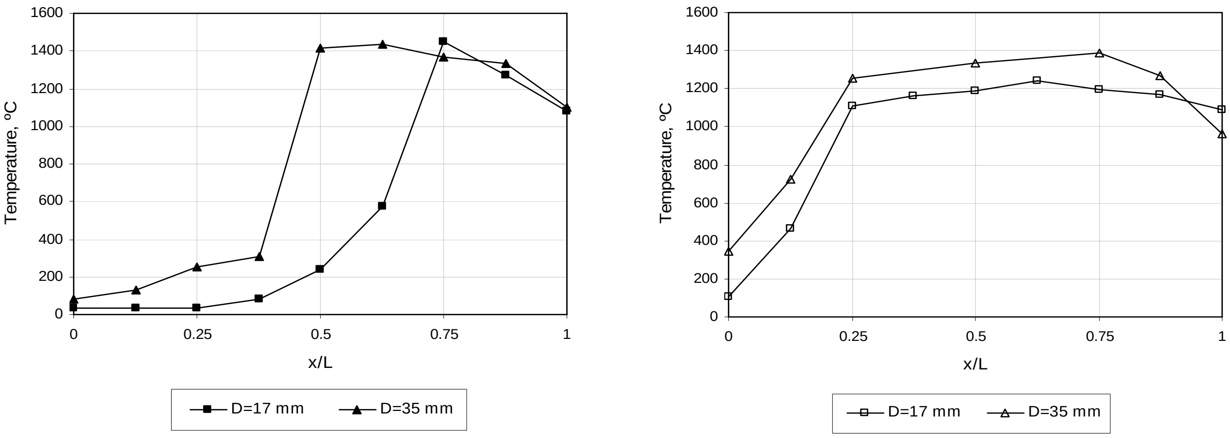


(a) (b)

Figure 5. Temperature profiles across the porous burner with a perforated plate of 17 mm, for SL = 30 cm/s, ϕ = 0,55 and ϕ = 0,60, recorded (a) in the central line and (b) in the intermediate line.

In Figure (5) we observe the displacement of the flame front to close of downstream surface of the porous medium for increase of the equivalence ratio. In this region, the flame front become fixed, because the high flow speed near to the perforated plate is equal to the chemical reaction speed.

In other experiment, we test the radiant porous burner in the same operational conditions with a perforated plate of 35 mm. In general, the two configurations of the burners present stable flame with same shape, i.e., three dimensional and bell shape. For lower flame speed (S_L < 30 cm/s), the two configurations present the constant flame front position. However, for S_L > 30 cm/s, the configuration with perforated plate of 17 mm presents the flame front position more close to the upstream of the burner than the configuration with perforated plate of 35 mm. This behavior can be visualized in Figure (6) where are presented the temperature profiles across the porous burner, operating with ϕ = 0,55, S_L = 30 cm/s, recorded (a) in the central line and (b) in the intermediate line.



(a) (b)

Figure 6. Temperature profiles across the porous burner, for ϕ = 0,55, S_L = 30 cm/s, with perforated plate of 17 mm and 35 mm, recorded (a) in the central line and (b) in the intermediate line.

Differences between the upper stability limits were found between the two configurations. For ϕ = 0,55, the configuration with perforated plate of 17 mm presented an upper stability limits in S_L = 45 cm/s and the configurations with perforated plate of 35 mm presented in S_L = 53 cm/s. Both configurations presented blow off in the central region of the burner surface according to bell type shape. The differences between two stability limits are due the higher flow speed by perforated plate of 17 mm than the flow speed by 35 mm. For ϕ = 0,60, don't was found the upper stability limits due the high temperature of the solid matrix, near to thermal degradation limit of the ceramic foam (1550ºC).

Figure (7) presents the radiation efficiencies as a function of flame speed for everyone studied conditions. The values varied between 20 % and 33% with the highest value in intermediate flame speed. As from S_L = 20 cm/s, the radiation efficiencies decrease with increase of the flame speed. This behavior was observed by Khanna *et al.* (1994) and Pereira (2002). However, a radiation efficiencies decrease when the flame speed is decreased. This is due the lower surface temperature by radiation heat losses to environment in the lower flame speed (Fig. 4). For higher flame speed the total power is increased, however, the radiation efficiencies are decreased because the surface temperature is limited by adiabatic flame temperature.

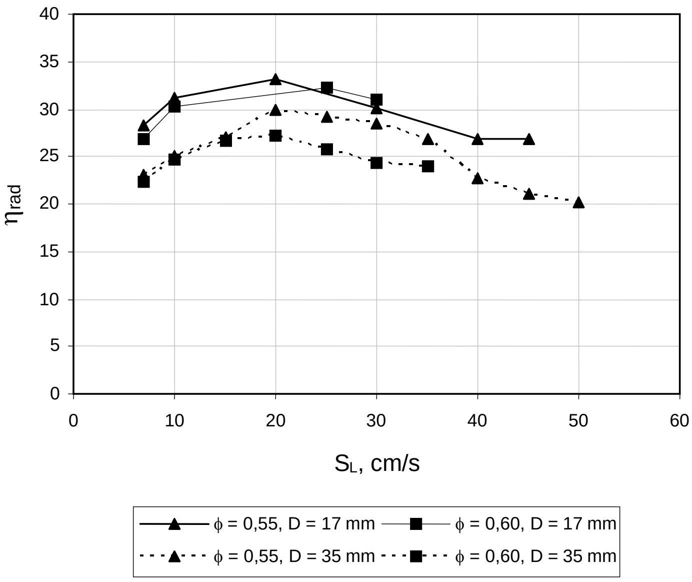


Figure 7. Radiation efficiencies as a function of flame speed for ϕ = 0,55, ϕ = 0,60 and perforated plate of 17 mm and 35 mm.

4. Conclusions

We present an experimental study of the flame stabilization in a radiant porous burner with combined thermal and fluidynamic mechanisms. Burners with different layers of 20 mm thick alumina (Al_2O_3) and zirconia (ZrO_2) ceramic foams, with a diameter of 70 mm, operating with premixed methane and air were tested. A perforated plate with a single central injection hole was placed upstream of the ceramic foams.

The main findings can be summarized as:

1. For the studied operational conditions, the flame develops a rounded, bell type and axisymetric shape.
2. When we increased the flame speed for the same equivalence ratio, the flame front in the central line is displaced across the porous medium until the blow off. However, the flame front position in the intermediate line is constant.
3. The variation of the flame front position in the central line was observed when we change the equivalence ratio for a same flame speed.
4. Both configurations presented blow off in the central region of the burner surface according to bell type shape.
5. Differences between the upper stability limits were found between the configurations with perforated plate of 17 mm and 35 mm. The differences are due the higher flow speed by perforated plate of 17 mm than the flow speed by 35 mm.
6. The radiation efficiencies values varied between 20 % and 33% with the highest value in intermediate flame speed.
7. The flammability range can be extended by a properly designed perforated plate.

5. References

Barra, A. J., Diepvens, G., Ellzey, J. L., Henneke, M. R., 2003, "Numerical study of the effects of material properties on flame stabilization in a porous burner", Combustion and Flame, Vol. 134, pp. 369-379.

Barra, A. J., Ellzey, J. L., 2004, "Heat recirculation and heat transfer in porous burners", Combustion and Flame, Vol. 137, pp. 230-241.

Catapan, R. C., Pereira, F. M., Oliveira, A. A. M., 2005, "Development of a radiant porous burner with a combined thermal and fluidynamic mechanismo of flame stabilization", Proceedings of 18th International Congress of Mechanical Engineering, Ouro Preto, Brazil.

Chaffin, C., Koenig, M., Koeroghlian, M., Matthews, R. D., Hall, M. J., Nichols, S. P., Lim, I-G., 1991, "Experimental investigation of premixed combustion with higly porous media", ASME/JSME Thermal Engineering Proceedings, Vol. 4, pp. 219-224.

Hsu, P. F., 1996, "Experimental study of the premixed combustion within the nonhomogneous porous ceramic media", National Heat Transfer Conference, Vol.6, ASME.

Hsu, P. F., Evans, W. D., Howell, J. R., 1993, "Experimental and numerical study of premixed combustion within nonhomogeneous porous ceramics", Combustion Science and Technology, Vol. 90, pp. 149-172.
Hardesty, D. R., Weinberg, F. J., 1974, "Burners producing large excess enthalpies", Combustion Science and Technology, Vol. 8, pp. 201-214.
Hayashi, T. C., Malico, I., Pereira, J. C. F., 2004, "Three-dimensional modelling of a two-layer porous burner for household applications", Computers and Structures, Vol. 82, pp. 1543-1550.
Khanna, R., Goel, R., Ellzey, J. L., 1994, "Mesurements of emissions and radiation for methane combustion within a porous medium burner", Combustion Science and Technology, Vol. 99, pp. 133-142.
Kotani, Y., Takeno, T., 1982, "An experimental study on stability and combustion characteristics of an excess enthalpy flame", Proceedings of the 19th Symposium on Combustion / The Combustion Institute, pp. 1503-1509.
Pereira, F. M., 2002, "Medição de características térmicas e estudo do mecanismo de estabilização de chama em queimadores porosos radiantes", in Portuguese, M.Sc. Thesis, UFSC, 145 p.
Takeno, T., Sato, K., 1979, "An excess enthalpy flame theory", Combustion Science and Technology, Vol. 20, pp. 73-84.
Trimis, D., Turst, F., 1996, "Combustion in a porous medium – advances and applications", Combustion Science and Technology, Vol. 121, pp. 153-168.

6. Copyright Notice