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Experimental investigation on flame characteristics in a porous-free flame burner

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Abstract

Present work studies experimentally the flame characteristics of a premixed natural gas/air mixture in a porous-free flame (PFF) burner compares it with a conventional porous (metal foam) burner with a porosity of 87%, height of 22 mm and diameter of 90 mm. For the PFF burner a hole is created at the center of the metal foam, making a combination of a free flame and a flame in the porous region. Effects of the hole diameter, $d = [6, 9 \text{ and } 12 \text{ mm}]$, foams pore density $\lambda = 10, 20 \text{ and } 30$ pores per inch (ppi) and foam materials (SiC and Al_2O_3) on the axial temperature distributions of the foams as well as on the lean and rich limits are examined. The results show that for a fixed foam pore density and foam material, the axial temperature of the foam in the PFF burner is lower than that of the porous burner. Compared to the PFF burner, the flame in the porous burner is stabilized at a lower equivalence ratio (leaner mixture), while the PFF burner extends the rich limit of the flame. Additionally, the diameter of the hole found to have insignificant influence on the lean and rich limits. Results further show that an increase in the foams pore density leads to a decrease in the axial temperature of the foam and the lean/rich limit of the flame. The axial

temperature of the SiC foam found to be higher than that of the Al₂O₃ porous foam. Furthermore, the lean and rich limits are extended by deploying the SiC porous foam.

Keyword: Experiment; Porous-free flame burner; Porous burner; Flame stabilization; Lean limit; Rich limit.

1. Introduction

Porous inert media (PIM) combustion has received more attention recently due to its considerable advantageous over the conventional free flame combustion. In PIM, the energy release during the combustion is coupled to the enhanced heat transfer (extracted or added to the flame) in the porous medium leads to a continuous chemical reactions in porous media []. Combustion in a PIM system is characterized as a heat recirculating device in which the heat recirculation between pre-flame and combustion zone enables to achieve a higher process efficiency, fuel conversion, combustion intensity, lower pollutant emissions and the possibility of operating in lean and ultra-lean combustion regime [1-3].

Diverse numerical and experimental investigations were conducted to examine the flame stabilization of premixed combustion in a porous burner [4-14]. These investigations demonstrated the effect of the material and structure of the porous medium including pore density and porosity and shape of the burner on the flame characteristics and its stabilization. It was found that porous foam properties and structure as well as the shape of the burner affects the flame characteristics including pollutant emissions, stability, temperature distribution and efficiency. Gao et al. [15] studied experimentally the effects of the porous foam materials (i.e. Al₂O₃, ZrO₂, SiC, and FeCrAl) and pore density on the stability and temperature distribution of a premixed flame. They [15] found that the flame in a FeCrAl porous burner yields the minimum temperature. By analyzing other foam materials, they further found that an increase in the porous foam thermal conductivity and a

decrease in the pore density, lead to an extension of the flame stability limits [15]. Farzaneh et al. [16] investigated numerically the behavior of methane-air combustion in a two-section porous burner. They studied the effects of thermal conductivity and absorption coefficient of the solid phase on the temperature distribution and gas velocity. Their results showed that an increase in the thermal conductivity of porous foam resulted in an increase in the flame temperature and gas velocity, as well as moving the flame toward upstream region. The effects of various fuels (methane, propane, hydrogen) on the flame stability and temperature distribution in porous burners were studied experimentally by Qu et al. [17] in a two-section porous medium burner. They found that the hydrogen-air flame has a wider stability range compared to the methane-air and propane-air flames. They also showed that the temperature of the propane flame is higher than that of methane flame for the same equivalence ratio. Wang et al. [18] studied experimentally the variation of the metal foam's axial temperature of a premixed flame in a porous media burner during startup and switch-off processes. In their study a tubular burner filled by alumina pellets was used as the porous burner by which the effects of different parameters such as diameter of the alumina pellets on the combustion temperature distribution along the burner axis and the combustion wave velocity were examined. They found that an increase in the diameter of the pellets causes the peak temperature to decrease in the reaction zone and to increase in the preheating zone. In an experimental work, Qu et al. [19] studied the flame characteristics in a premixed combustion for a two-layer catalytic alumina pileup-pellets burner. They investigated the effects of the pellet diameter and equivalence ratio on the flame stability limits and its temperature for both catalytic and inert burners. Their results demonstrated that the flame stability limits extend as the equivalence ratio or pellet diameter increases. Additionally, they found that the flame temperature distribution in catalytic burners is more uniform compared to inert burners [19].

Despite the numerous studies performed on porous burners, porous-free flame (PFF) burner is a novel technology under development which has been investigated in recent years. The primary notion of PFF burner was presented by Weakley et al. [20] and Greenberg et al. [21]. They investigated a surface-stabilized burner consist of a porous medium and a free flame combustion to improve the performance of the porous burners. The effect of inlet mixture temperature on the flame stability in a porous-free flame burner was investigated by Hashemi and Nikfar [22]. Their results showed that PFF burner had better flame stability compared to porous burner. Furtehmore, the flame stability limit found to increase with the increase of inlet mixture temperature. In another study, Hashemi et al. [23] investigated numerically the effect of thermal boundary conditions of wall burner and porous pore density on the flame stability. They found that flame stability improved by increasing the pore density. Actually the flame was stabilized at a higher inlet velocity when in their numerical model, the insulated wall condition used instead of constant wall temperature condition. Hashemi et al. [24, 25] employed the control volume method to study numerically the non-equilibrium thermal model between solid and gas phase in a porous-free flame burner. They showed the heat transfer modes (convection, conduction and radiation) through the porous-free flame burner. They further found that thermal efficiency of PFF burner was lower than that of conventional porous burner, and the thermal efficiency increases with the increase of equivalence ratio. Ghorashi et al. [26] studied experimentally the pollutant emissions of the PFF burner. They investigated the effects of the hole diameter, pore density, firing rate and porous foam material on the pollutant concentrations. The experimental data showed that the CO emission of the PFF burner is lower than that of the conventional porous burner. In addition, their results proved that pore density, firing rate and material of the porous foam had a significant effect on the CO emission.

Despite the numerical and experimental studies performed for the PFF burners, some flame characteristics in the porous-free flame burner has not yet been fully understood. Previous works studied the effects of inlet mixture properties, porous medium properties and thermal boundary condition of the chamber wall on the flame stability and pollutant emissions in the porous-free flame burner. However, in particular, the effects of the system's pertinent parameters including, hole diameter created at the center of the porous foams, pore density of the porous medium and its thermal conductivity (foam material) on the flame stabilization, lean and rich limits of flame, and burner temperature have not been identified. The present work tries to fill this gap through a comprehensive series of experimental tests for a PFF burner utilizing different porous foams (i.e. SiC and Al₂O₃). For comparison, the experiments are also conducted for conventional porous burner under the operating conditions similar to those of the PFF burner.

2. Experimental set-up

Fig. 1 illustrates the schematic of the experimental system made in the combustion laboratory at the University of Kashan, Kashan, Iran. The air was supplied by a compressor which was filtered before entering the mixer. Natural gas was supplied as the fuel with the composition presented in Table1. The initial temperature of the mixture was 298 K.

Fig. 1. Schematic of the experimental set-up for the PFF burner

Table 1. Composition of natural gas

Natural gas composition		Volume
Species	Formula	%
Methane	CH_4	89
Ethane	C_2H_6	4.1
Propane	C_3H_8	1.39
n-Butane	$\text{n-C}_4\text{H}_{10}$	0.3
Iso-Butane	$\text{i-C}_4\text{H}_{10}$	0.25
n-Pentane	$\text{n-C}_5\text{H}_{12}$	0.1
Iso-Pentane	$\text{i-C}_5\text{H}_{12}$	0.12
Hexane	C_6H_{14}	0.08
Nitrogen	N_2	4.6
Carbon dioxide	CO_2	0.05

Volumetric flow rates of air and fuel were controlled using two calibrated rotameters. Two streams were fully mixed before entering the combustion chamber. The refractory ceramic cylinder with an inner diameter of 90 mm, height of 154 mm and thickness of 30 mm was used as a combustion chamber. Five holes with an axial interval of 5 mm around were drilled on the chamber wall for positioning thermocouples inside the chamber. Tests were performed for two porous foams (SiC and Al₂O₃) each with a porosity of 87%, height of 22 mm and diameter of 90 mm. Thermophysical properties of the porous materials are presented in Table 2.

Table 2. Thermophysical properties of SiC and Al₂O₃ porous foam [27].

Thermophysical properties	Al ₂ O ₃	SiC
Density (kg/m ³)	3987	3210
Thermal conductivity at 20°C (W/mK.)	20-30	80-150
Thermal conductivity at 1000°C (W/mK.)	5-6	20-50
Maximum working temperature in air (°C)	1900	1600

Experiments were conducted for different diameters of the central hole (i.e. 6, 9, and 12mm) which were created at the center of the porous media. Five thermocouples (1 mm K-type) were used in order to measure the temperature distribution. Through the holes on the chamber wall, the thermocouples were located inside the chamber in a way that the thermocouples beads were in contact with the lateral surface of the porous foam. The thermocouples were located at the intervals of the 2, 7, 12, 17, and 22 mm from the lower surface of the porous foam. The temperature data were recorded while the flame was stabilized in the porous medium for about 30 minutes while the temperature fluctuations were less than 5 °C.

In this study, firing rate and equivalence ratio are two major parameters through which the results are presented and discussed. The firing rate (FR) is calculated using [28]:

$$FR = \frac{LHV \times Q_f}{A}, \quad (1)$$

where LHV (kJ/m³), Q_f (m³/s) and A (m²) denotes lower heating value, volumetric fuel flow rate and exit cross section area of the burner, respectively.

For the tests conducted in this work, at first, the flow rate of natural gas was set at a specific value (i.e. specific firing rate) and the flame located at the above of porous medium. Then the air flow rate was gradually increased to a value where the flame transferred below the porous medium. The highest equivalence ratio which the flame transfers below the porous medium refers to the rich limit. With further increase in air flow rate, the flame stabilized in the porous medium. After 30 minutes that the porous medium was heated uniformly, the air flow rate was increased until the flame exited the porous medium. The lowest equivalence ratio that the flame exits from the porous medium refers to the lean limit. Flame stability is the result of a balance between the flame speed and the unburned mixture velocity [29]. The rich limit occurs if the flame speed is higher than the unburned mixture velocity and the flame forms at the below of porous medium. On the other hand, if the unburned mixture velocity is higher than the flame speed, the flame exits the porous medium and lean limit occurs.

To make sure the accuracy and repeatability of the results, the tests were performed three times for the same conditions. The uncertainty W_R of the dependent variable R is calculated using the uncertainty w_i of each independent parameter x_i as [30]:

$$W_R = \left(\sum \left(\frac{\partial R}{\partial x_i} \times w_i \right)^2 \right)^{0.5}. \quad (2)$$

The uncertainties of air and fuel volumetric flow rates were 0.1 m³/hr and 0.012 m³/hr, respectively. The uncertainty of the measured temperatures was 5°C. The uncertainty of firing rate and equivalence ratio as two dependent parameters were determined using Eq. 2. The uncertainty of the equivalence ratios is shown in figures 3, 4, 6, 7, 9 and 10, and the uncertainty of the firing rates is presented in Table 3.

Table 3. The amount of uncertainty of the firing rates

Firing rate (kW/m ²)	Uncertainty (%)
490	3.7
580	3.1
680	2.7
770	2.4

3. Results and discussion

The tests were conducted to investigate the effects of the system's pertinent parameters including, hole diameter at the center of the porous foams, pore density of the porous media and their thermal conductivity (i.e. porous foam material) on the lean and rich limits of flame and the axial temperature distribution of the porous medium in the PFF burner. Additionally, the experimental data of the PFF burner are compared against those measured for the conventional porous burner.

3.1. Effect of the central hole diameter

Fig. 2 shows the axial temperature distribution of the SiC porous medium in the PFF burner with pore density of $\lambda=10$ ppi, firing rate of $FR= 680$ kW/m³ and equivalence ratio of $\phi = 0.77$ for different diameters of the central hole for $d= [6, 9$ and 12 mm]. For comparison, the results of the

porous burner (i.e. PFF burner with $d = 0$ mm) are also plotted in this figure. It is seen that the axial temperature of the porous medium in the porous burner is higher than that of the PFF burner. For the PFF burner, the smallest hole diameter, yields the maximum axial temperature. When the diameter of the central hole increases, more cold fuel and air mixture passes through the central hole instead of flowing through the porous medium. This will enhance cooling of the porous medium and that the axial temperature of the porous medium decreases with the increase of hole diameter. It is further seen that the slopes of the axial temperatures for three PFF case are similar to the porous burner case with ($d = 0$). While one might expect that the axial temperature drops faster with sharpest gradient as the hole diameter increases. This is because

It is further seen in Fig. 2 that for all cases, the flame temperature decreases along the porous medium and the temperature is maximum at the bottom section of the porous medium ($x=0$ mm), meaning that the flame forms at the bottom of the porous medium.

Fig. 2. Axial temperature distribution of the SiC porous medium in the porous burner and PFF burner for $FR=680 \text{ kW/m}^2$ and $\lambda=10 \text{ ppi}$ for different diameters of the central hole, d. $x=0\text{mm}$ represents the bottom point of the porous medium and $x=22$ is at the top of the porous medium.

Fig. 3 demonstrates the rich limit in the PFF and the porous burners. It is seen that the PFF burner extends the rich limit by which the flame is formed at a higher equivalence ratio compared to the porous burner. The reason for this phenomenon is due to the difference in the velocity of the inlet mixture in the porous burner and the PFF burner. It should be noted that in rich mixtures, the flame speed is inversely proportional to the equivalence ratio [28]. The flame stability is the result of a balance between the flame speed and unburned mixture velocity. Because these two velocities are in opposite directions, and flame stabilizes in the porous medium when these two velocities become balance with each other. If the flame speed is higher/lower than the unburned mixture velocity, flame moves below/above the porous medium. In the PFF burner, some portion of the mixture passes through the central hole and therefore the velocity of the unburned mixture passing through the porous medium is lower compared to that in the porous burner where all the mixture flows through the porous region. Fig. 3 demonstrates that an increase in the firing rate (FR) leads to a decrease in the rich limit. By increasing the firing rate, the unburned mixture velocity increases so the flame transfers below the porous medium at a higher flame speed, which occurs at a lower equivalence ratio.

Fig. 3. Rich limit in the porous burner and PFF burner for $\lambda=10$ ppi and for different diameters of the central hole (d) and firing rates (FR).

Fig. 4 shows the lean limit in the PFF and porous burners. It is seen that compared to the PFF burner, the flame in the porous burner is stabilized at a lower equivalence ratio (leaner mixture). As it is mentioned, in the PFF burner, the temperature of the porous medium is lower than that of porous burner leading to a lower flame speed. Therefore, the flame exits the porous medium at a lower unburned mixture velocity corresponding to a higher equivalence ratio. As Fig. 4 shows, an increase in firing rate results in an increase in the lean limit. This trend is similar to that observed in the numerical work of Hashemi and Hashemi [11]. Figures 3 and 4 show that the changes of the central hole diameter in the PFF burner have no significant effect on the rich and lean limits.

Fig. 4. Lean limit in the porous burner and PFF burner for $\lambda=10$ ppi and for different diameters of the central hole (d) and firing rates (FR).

3.2. Effect of pore density

Fig. 5 demonstrates the effect of pore density on the temperature distribution in the PFF burner for $\lambda=10, 20$, and 30 ppi and for the SiC porous foam with the hole diameter of $d=9$ mm. Experiments were conducted at firing rate of $FR=680 \text{ kW/m}^2$ and equivalence ratio of $\phi=0.77$. The results show that an increase in the pore density decreases the temperature distribution, which is in agreement with the results of Gao et al [15]. A decrease in the porous medium temperature with increasing porous pore density is because of radiative heat transfer. In fact, with increasing the pore density, the foam's pore diameter decreases leading to an increase in the solid surface area. Hence, the heat transfer from the porous foam to the wall of the combustion chamber increases which results in reducing the foam temperature. Also, a decrease in the pore diameter is equivalent to an increase in the radiative extinction coefficient of porous medium [10]. An increase

in the radiative extinction coefficient resulted in a higher post-flame temperature gradient, increases heat transfer to the pre-flame zone [10], which is below the porous medium, and a reduction of temperature of porous medium. Also, as the pore density increases, the fuel mass flow rate passes through the porous medium decreases and therefore the temperature decreases.

Fig. 5. Axial temperature distribution in the PFF burner for the SiC porous medium with different pore densities, and hole diameter of $d=9$ mm and firing rate of $FR=680$ kW/m².

Fig. 6 shows the effects of pore density on the rich limit in the PFF burner. It is seen that in the case with smaller pore density the rich limit is higher as observed by Emami et al. [31].

Fig. 6. Rich limit in the PFF burner for different firing rates and pore densities with the central hole diameter of $d=9$ mm.

Fig. 7 depicts the effects of pore density on the lean limit in the PFF burner. It is seen that by increasing the pore density, the lean limit extends and the flame is stabilized at a leaner mixture. This trend is similar to the modelling results presented in Ref. [25]. The flame speed depends on the effective thermal conductivity of the porous medium which is a function of the pore density and thermal conductivity of the foam material. Increasing the pore density, increases the effective thermal conductivity of the porous medium which leads to an increase in the flame speed [28]. In this situation, increasing the flame speed causes the flame to exit the porous medium at higher unburned mixture velocity (lower equivalence ratio).

Fig. 7. Lean limit in the PFF burner for different firing rates and pore densities with the central hole diameter of $d=9$ mm.

3.3. Effect of the porous foam material

The effect of the material of the porous foam (SiC and Al_2O_3) on the temperature distribution in the PFF burner for $\lambda=30$ ppi and for the central hole diameter of $d=9$ mm is shown in Fig. 8. The figure shows that the axial temperature of SiC porous foam is higher significantly than that of Al_2O_3 . This observation is similar to those presented by Gao et al. [15]. According to Table 1, the thermal conductivity of SiC is higher than that of Al_2O_3 . This translates to a higher heat transfer rate from hot products to the porous medium for the SiC case. Hence the axial temperature of SiC foam is higher than that of the Al_2O_3 case.

Fig. 8. Axial temperature distribution of the porous medium in the PFF burner for $FR=680 \text{ kW/m}^2$, $\lambda=30$ ppi and $d=9 \text{ mm}$ for different porous materials.

Fig. 9 illustrates the effect of porous foam material (SiC and Al_2O_3) on the rich limit in the PFF burner. It is seen in Fig. 9 that for the SiC porous foam the rich limit is extended compared to that of the Al_2O_3 case. The effective thermal conductivity of the SiC foam is higher than that of the Al_2O_3 foam. Since flame speed is a function of effective thermal conductivity and equivalence ratio $[\phi]$, the flame speed in the SiC PFF burner is higher than the Al_2O_3 burner, that leads to an extension of rich limit for the SiC burner.

Fig. 9. Rich limit in the PFF burner for different firing rates for $\lambda=30$ ppi and central hole diameter of $d=9$ mm and for different porous materials.

Fig. 10 shows the effects of porous foam material on the lean limit. As the figure shows for the SiC case, the lean limit is lower than that of the Al_2O_3 case. When SiC porous foam is used, the flame speed increases compared to the Al_2O_3 burner. Hence, the flame can be stabilized at a higher unburned mixture velocity for the SiC burner which leads to a decrease in the equivalence ratio.

Fig. 10. Lean limit in the PFF burner for different firing rates for $\lambda=30$ ppi and central hole diameter of $d = 9$ mm and for different porous materials.

4. Conclusions

In this work the flame characteristics in a porous-free flame (PFF) burner was studied experimentally. The effects of the diameter of the central hole in the porous medium, pore density and the material of the porous medium on the axial temperature distribution and lean and rich limits in the PFF burner were examined. The experiments were also conducted for the conventional porous burner and the results were compared with the PFF burner. The main conclusions from this experimental work are summarized as follows:

- Axial temperature in the porous medium for the porous burner is higher than that in the PFF burner. In the PFF burner, the flame is stabilized in a richer mixture but in the porous

burner the flame is stabilized at a leaner mixture, meaning a better performance of the porous burner at lean limit.

- Diameter of the central hole in the porous medium has no significant effect on lean and rich limits of flame.
- An increase in the pore density leads to a decrease in the axial temperature of the porous medium. An increase in the pore density causes both lean and rich limits to occur at lower equivalence ratios.
- In the case of SiC porous foam, the axial temperature of the porous medium is higher than that of Al₂O₃ foam. In comparison with Al₂O₃ foam, for the SiC porous foam, the lean and rich limits are extended.

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Compliance with Ethical Standards

Conflict of interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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