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Investigation of Premixed Flame Stabilization and Burning Rates in a Three-Section Porous Ceramic Burner

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Abstract
An experimental investigation of premixed methane/air combustion within a novel porous ceramic burner is described in this paper. The burner is composed of three rectangular porous ceramic layers stacked on each other and insulated around the circumference. The upstream layer is assumed to be the preheat zone, while the others are served as the combustion zones. The operating parameters include fuel/air mixture flow rate and equivalence ratio. The main objectives of this study are documenting the flame stabilization within the burner and determination of operating range. The burner is tested over the range of lean limit ($\Phi \leq 0.65$). The experimental data demonstrates the advantages of burning a combustible gas inside the porous ceramic burner. The burner shows a great ability to extend the blow off limit at each equivalence ratio.

Keywords: porous burner-flame stabilization-burning rate-blow off

1. Introduction
Porous media combustion offers superior advantages compared with a free-burning flame, namely higher burning rates, increased flame stability, extension of the lean flammability limit, ability to burn fuels with low energy content and low emissions of pollutants such as NO_X and CO. In addition, porous burners show a very high turndown ratio and are of relatively smaller size than conventional burners. These advantages are mainly the results of the high heat capacity of the porous medium, the large inner surface of the porous medium, high heat conductivity and high emissivity of the solid matrix in comparison to a gas. The high temperature post-flame zone serves to heat the porous solid in the pre-flame zone through radiation and conduction via solid matrix. The hot porous solid in the pre-flame zone, in turn, preheats the incoming reactants through convection [1, 4].

Although a burner may be constructed from a single section of porous media, burners consisting of two sections with different characteristics have attained significant attention in the last years. Through proper selection of the properties of the two sections, the interface between the two sections serves as a flame holder preventing flashback for a range of conditions [2].

Various aspects of combustion within porous inert media have been investigated experimentally and theoretically. Hsu et al. [3] studied a burner consisting of two porous ceramic cylinders of different pore sizes stacked together: a small pore section (preheat region) followed by a large pore section (stable burning region). The flame was stabilized at the interface of two blocks over a range of mixture flow rates for a given equivalence ratio. They introduced a new definition of lean limit to account for the effect of porous ceramics.

Brenner et al. [4] reported a numerical and experimental investigation of matrix stabilized methane/air combustion in porous inert media. Their model enabled a numerically parametric study to be made for a porous medium burner with a rectangular cross-section geometry. Mathis and Ellzey [5] used various porous ceramics and reported measurements of flame stabilization, operating range and emissions for several porous burners.

A critical component of porous media combustion is the porous material. Important characteristics of the porous structure are the maximum operating temperature and thermophysical properties [6]. Various porous materials have been used in the experimental studies. Using reticulated ceramic foam as the porous medium has several advantages over other forms of porous materials; It has a higher operating temperature than most of metallic porous media, the typical porosity in the range of 85-90% which results in less pressure drop and much larger volumetric surface area than other porous mediums which assures more convective heat transfer between the gas and the solid [7]. Barra et al. [8] presented a parametric study of the effects of material properties on

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flame stabilization in a porous burner. Their results indicated that matrix properties significantly affect the stable operating range.

Whereas the solid matrix itself acts as an efficient radiator, many researchers focused on the development of low emissions radiant burner, consequently, optimizing radiation output is a primary consideration [5]. Flame stability and operating range are important performance considerations for any burner operating on premixed fuel/air. Both these characteristics are affected by the material properties of porous matrix [2].

In this study a novel design for the porous burner composed of three different porous ceramic layers has been introduced. The third layer (outer section) with small pores causes the flame to be more concentrated in the inner core and consequently can extend the blow off limit of the burner. Moreover, it leads to more effective heat recirculation due to the enhanced control of heat loss from the burner. The operating parameters include fuel/air mixture flow rate and equivalence ratio. The main objectives of this study are documenting the flame stabilization within the burner and determination of operating range. The location of the flame, flashback and blow off limits are determined from the temperature measurements.

2. Experimental setup

In the current study a three section porous ceramic burner is fabricated. The experimental apparatus consists of an insulated porous medium burner, a flow measurement and control system, a mixing chamber and a temperature measurement system. The burner is composed of three rectangular porous ceramic layers stacked on each other and insulated around the circumference. A schematic diagram of the experimental setup used in this work is shown in Figure 1.

Each layer has a 50*50 mm cross section and 22 mm height. Pore densities of 12, 4 and 8 pores per centimeter (ppcm) as specified by the manufacture are used for the upstream section, the intermediate section and the downstream section, respectively. The upstream layer is assumed to be the preheat zone, while the others are served as the combustion zones. The porous ceramic for the preheat zone is composed of Al_2O_3 and SiO_2. Porous ceramics composed of SiC, Al_2O_3 and SiO_2 are used for the combustion zones. In order to detect the flame location, six K type thermocouples are placed at approximately 1.5 cm axial intervals along the burner. The thermocouples are inserted in small holes inside the insulation such that the probes measure the temperature at the outside perimeter of the porous ceramics.

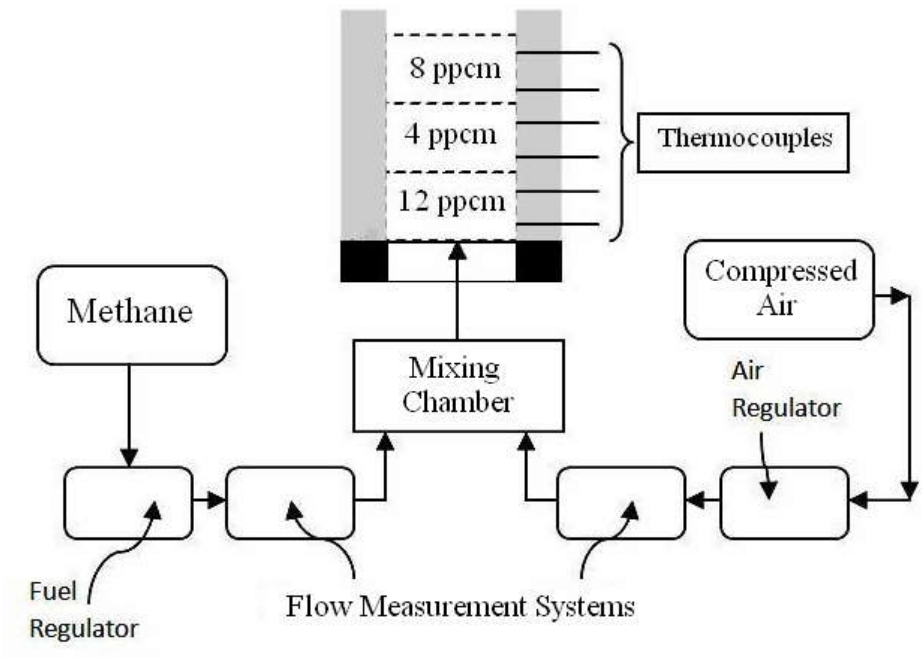

Figure 1. Experimental setup of the present porous burner

3. Test procedure

To account for the effect of porous ceramic, the concept of lean limit introduced by Hsu et al. [3] is applied in this study. This concept involves defining a region of the burner as the stable burning region (SBR) which consists of 4 and 8 (ppcm) porous ceramics in this burner. At each equivalence ratio the maximum and minimum flow rates at which the entire flame is stabilized within the SBR are measured. If the flow rate exceeds $\dot{V}_{max}$ then the flame will blow off the burner. If there is any flame lift, the flame is considered unstable. The lowest value of equivalence ratio at which the flame will be stabilized in the SBR, even at a narrow range of flow rates, is regarded as the lean limit of combustion in the porous burner. The range of flame speeds at which a flame can be stabilized within the SBR is calculated by dividing total flow rate $(\dot{V})$ by the cross sectional area of the burner.

To start up the burner the air/fuel mixture is ignited at the burner exit, then the value of equivalence ratio and total volumetric flow rate are adjusted until the flame propagates to the SBR/PR interface. Later on, the equivalence ratio and flow rate are set to the desired test value and the flame is allowed to be stabilized.

The variations in the temperature profile within the time are monitored to determine whenever the flame has been stabilized. In order to reach the stable condition, it is necessary to take several readings in about 10-15 minutes. Once the flame has been stabilized at a specific location, the flow rates of air and fuel and the temperature along the burner wall are recorded. Then the total flow rate is adjusted (increased or decreased gradually) to determine the maximum and minimum burning rates, respectively. This procedure is applied repeatedly for a range of equivalence ratios below 0.65. The tests are performed for decreasing equivalence ratios until a value is reached such that the flame cannot be stabilized regardless of the flow rate.

4. Results and discussion

If the flame is stabilized inside the stable burning region (SBR) at a specific flow rate, it indicates that the burning rate in the SBR is higher than in the preheat region (PR). The preheat region assists to produce a range of burning rates at which the flame can be stabilized inside the SBR (at a constant Φ). The burner was tested over the range of lean limit (Φ≤0.65). In each equivalence ratio, flashback and blow off limits were obtained by adjusting the total flow of methane and air. The temperature profiles for the burner at equivalence ratios of 0.55, 0.60 and 0.65 are shown in Figure 2, Figure 3 and Figure 4, respectively, for a range of firing rates. Firing rate is based on the inlet velocity and the lower heating value of methane.

Occurrence of the peak flame temperatures in the downstream of the desired interface for a range of conditions indicates the ability of the interface as a flame holder in this burner and shows that the burner is effectively capable of stabilizing the flame. In general, at lower firing rates the flame tends to be stabilized closer to the interface, and with increasing firing rate, the flame stabilization occurs at far downstream until blow off is observed.

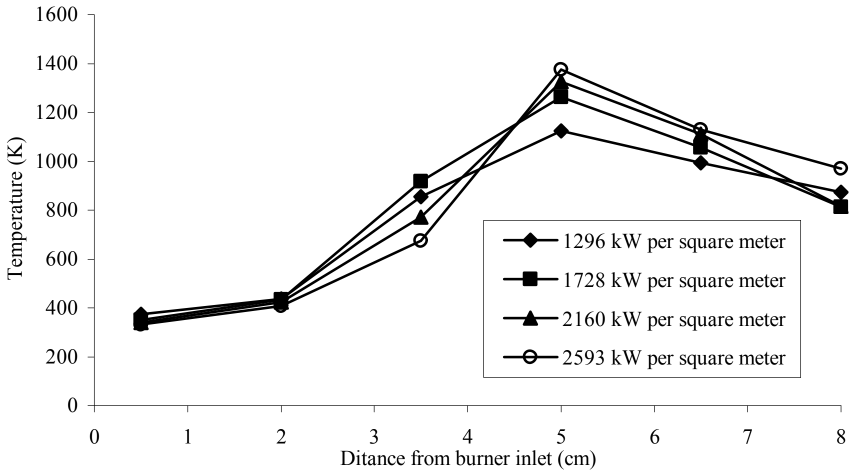

Figure 2. Temperature profiles VS. Burner length at Φ=0.55

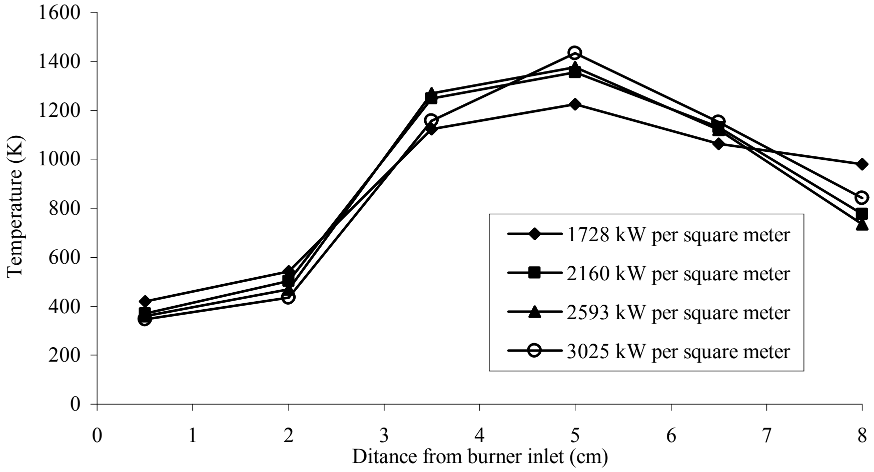

Figure 3. Temperature profiles VS. Burner length at Φ=0.60

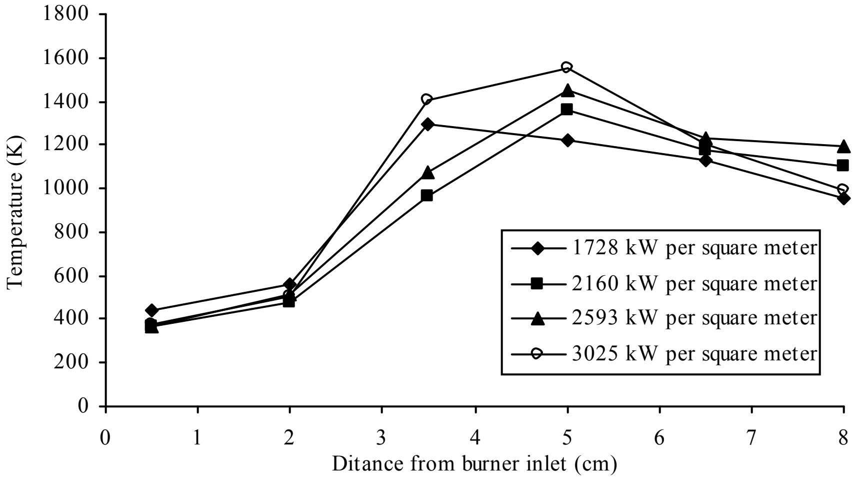

Figure 4. Temperature profiles VS. Burner length at Φ=0.65

The results show that the peak flame temperature increases with increase in equivalence ratios. Also an increasing heat load (increasing inlet velocity) causes higher temperature with an extended main reaction region due to the increased volumetric heat release. In comparison with free flame combustion, which is mostly recognized by high power-independent temperatures, combustion in a porous medium is strongly influenced by the thermal power. The maximum temperatures are greater with higher thermal powers. On the other hand, the position of the flame, where the temperature maximum is located, is displaced in the direction of the burner exit.

All of the stable conditions represent cases in which the flame speed has been enhanced due to heat recirculation. For instance, at an equivalence ratio of 0.65, firing rates of 1728 and 3025 kW/m^2 correspond to the inlet velocities of 83 and 145 cm/s, respectively. It should be noted that the laminar flame speed at this equivalence ratio is about 14 cm/s [5].

The ranges of stable burning rates at each equivalence ratio are shown in Table 1. The flame speed varies between 73 and 157 cm/s. The flash back limits are not as low as the results reported by Mathis and Ellzey [5], who used porous ceramics with lower pore diameters for the preheat region. However, the flame speed at which the flash back occurs can be reduced effectively through using a preheat region with higher pore density. Blow off limits for all cases prove the ability of the burner to sustain considerably high burning rates as well.

Table 1. Stable burning rates for the burner

Φ	Stable Burning Rate (cm/s)	
0.55	Flashback	73
	Blow off	146
0.60	Flashback	90
	Blow off	157
0.65	Flashback	83
	Blow off	145

The lean limit of combustion occurred at Φ=0.48 which is lower than the lean limit of the free flame (Φ=0.52). This reduction in the lean limit is due to the energy feedback (conductive and radiative heat transfer) through the porous matrix. There is a small range of stable burning rates at the measured lean limit.

5. Conclusions

Combustion of premixed methane-air flame inside a three section porous ceramic burner was experimentally investigated. The burner consisted of three reticulated porous ceramic layers stacked on each other and insulated around the circumference. The experimental data demonstrated the advantages of burning a combustible gas inside the porous ceramic burner. The interface between the preheat region and the combustion region stabilized the flame near the interface for a wide range of flow rates. The energy feedback in the porous ceramic matrix greatly enhanced the burner performance.

For all the domain of equivalence ratios studied ($0.48 \leq \Phi \leq 0.65$), the stable conditions occurred at burning rates greater than those of the adiabatic laminar flame. The burner showed a great ability to extend the blow off limit at each equivalence ratio. This range of stable burning rates allows greater control of the energy release rates from the burner and enhances flame stabilization. In addition, the observed lean limit is lower than the normal lean limit for a free, laminar flame.

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