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Methane/air premixed combustion in a two-layer porous burner with different foam materials

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HIGHLIGHTS

- Flame stability limits increased with increasing thermal conductivities.
- Flame stability limits increased with decreasing pore density.
- Flame temperatures of 30 PPI SiC foams are lower than its counterparts.
- CO emission of 30 PPI foams was notably lower than its counterparts.
- HC emission increased in the order of 20, 25, 30, and 10 PPI foams.

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ABSTRACT

Selecting appropriate materials is the most important consideration in designing a porous medium burner. The choice determines the performance and service life of the burner. The premixed combustion of methane/air in a two-layer burner packed with 3 mm-diameter alumina (Al_2O_3) beads at the upstream section and cellular foam at the downstream section was studied. Cellular foam was selected as the alternative material for alumina, zirconia (ZrO_2), iron–chromium–aluminum (FeCrAl), or silicon carbide (SiC). The flame stability, flame temperature profile, flame temperature, pressure drop, and pollutant emission of these four materials were investigated. The effect of pore density on SiC foam was also discussed. Results indicated that flame stability limits expanded with increased foam conductivities but shrank with increased pore density. Carbon monoxide (CO) emission was not sensitive to the materials ($S > 30$ cm/s). The CO emission of 30 pores per inch (PPI) foams was notably lower than that of foams with other pore densities because of the higher flame temperature. Hydrocarbon (HC) concentration was almost constant for ZrO_2, Al_2O_3, and FeCrAl foams. However, the HC concentration of SiC foams decreased with increased flame speed. HC emission increased in the order of 20, 25, 30, and 10 PPI foams. Nitrogen oxide (NO_x) emission was relatively low (below 3 ppm) because of low flame temperature.

1. Introduction

Combustion in inert porous materials has attracted attention over the past decades because of their advantages such as extended lean flammability limit, low pollutant emission, high radiant output, high power density, and flame speed. The properties of applied porous materials have a significant effect on combustion performance and longevity of a burner. Alumina, zirconia, and silicon carbide-based materials are the most commonly used materials in porous burners, generally because of their large surface area, thermal resistance, and chemical stability.

Alumina is used as a porous burner material because of its durability, high temperature rating, chemical stability, and economic cost. Previous theoretical and experimental studies have investigated materials including 10 and 66 pores per inch (PPI) Al_2O_3 [1], 45 PPI ZrO_2 that is partially stabilized with magnesia (PSZ) and 10 or 20 PPI Al_2O_3 foam burner [2], and a combination of 10 and 40 PPI Al_2O_3 [3,4]. Flame can easily be stabilized at the interface between two ceramic blocks with different porosities because of radiative heat feedback. Flame stability decreased with increased pore density of Al_2O_3 sponges.

As compared with Al_2O_3-based materials, ZrO_2-based materials have excellent high-temperature resistance but poor thermal shock resistance which has been the focus in the investigation of porous burners. Hsu et al. [5,6] selected a PSZ-reticulated foam burner with the combination of 65 PPI for the upstream section and 10, 30, or 45 PPI for the downstream section of heat reflux. Several foam burners have been based on the porous burner created by Hsu et al. [5,6], such as the 10 and 65 PPI combination PSZ foam burners by Khanna et al. [7], Ellzey et al. [8], Barra

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et al. [9,10], Li and Hsu [11], Liu et al. [12], and Horsman and Daun [13] as well as the yttria-stabilized ZrO_2/Al_2O_3 and ZrO_2-toughened mullite foam burners by Ellzey et al. [14,15]. The above results indicate that the upstream section should have low thermal conductivity, low volumetric heat transfer coefficient, and high radiative extinction coefficient, whereas the downstream section should have high conductivity, high volumetric heat transfer coefficient, and an intermediate radiative extinction coefficient.

Silicon carbide is another desirable material for porous burners because of its high thermal conductivity and emissivity as well as superior thermal shock resistance, which has led to its extensive use in the combustion zone of porous burners [16–23]. Malico et al. [16,17] and Farzaneh et al. [18,19] theoretically studied a porous burner filled with 3 and 5 mm Al_2O_3 spheres in the preheating and heat-exchanger zones, and 10 PPI SiC ceramic foam in the combustion zone. Malico et al. [20–22] recently presented a three-dimensional numerical model of a two-layer porous burner that comprises 10 PPI SiC porous foam preceded by a perforated Al_2O_3 plate. Mishra et al. [23] analyzed the heat transfer in a two-dimensional rectangular porous radiant burner comprising a preheating zone made of Al_2O_3 and a combustion zone made of SiC. They concluded that smaller pore diameters must be used to avoid flashback, and that the flame front should move upstream when the burner radiates to a high-temperature environment or when solid conductivity and convective heat transfer coefficient increases.

High-temperature metallic matrix has also been studied. Only a few stainless steel materials such as nickel-based and iron–chromium–aluminum foams have been considered [24–26] because of their lower temperature resistance. Vogel and Ellzey [24] investigated a two-section burner made of FeCrAl metallic foam which showed that the flame is stabilized at or near the interface between the upstream and downstream sections of the porous media in both subadiabatic and superadiabatic conditions. Gauthier et al. [25,26] theoretically and experimentally studied the premixed combustion of natural gas–hydrogen mixtures in a porous burner made of open cell nickel–chromium–aluminum foam. The results showed that substituting a portion of the natural gas by hydrogen in a porous burner reduces the pollutant emissions of carbon monoxide (CO) and nitrogen oxides (NO_x) and the quantity of produced carbon dioxide (CO_2).

A comprehensive comparison between high-temperature metallic foam and its ceramic counterparts under a fixed condition has not been conducted because burner geometrical shapes and operation conditions differed among published studies. The current study evaluated the performance of high-temperature metallic foam and its ceramic counterparts by comparing different foam materials in the same burner. The effects of the properties of different materials (Al_2O_3, ZrO_2, SiC, and FeCrAl) on flame stability limits, flame temperatures, pressure drops, and pollutant emissions were studied.

2. Experimental setup

The experimental apparatus is shown in Fig. 1, and the burner structure is shown in Fig. 2. The apparatus comprised a porous burner, supply system of fuel/air, and a system for data acquisition. The burner was a corundum tube with an internal diameter of 50 mm and length of 200 mm, packed with 3 mm Al_2O_3 beads in the upstream and alternatively packed with Al_2O_3, ZrO_2, SiC, or FeCrAl in the downstream. The burner wall was insulated by a 20 mm-thick Kaowool high-temperature insulation material layer. Methane (99.5% pure) and air flows were regulated using two mass flow controllers (C10Smart-Trak, Sierra Instruments, USA) to satisfy the required conditions at a fixed equivalence ratio of $\varphi = 0.6$. Laboratory air was supplied using a compressor connected to an air storage tank for pressure stabilization and then passed through a dry machine for filtration and drying prior to introduction into the experimental apparatus. The burner had nine B-type thermocouples (TC1 to TC9) located along the length at 1.25 cm intervals. The pressure drop across the porous media was measured using a pressure transducer (Rosemount 3051, Rosemount, USA). All signals for thermocouples and pressure transducer were recorded using an Agilent data acquisition system. Exhaust gas was collected using a stainless steel probe placed at the top of the burner, and the concentrations of HC, CO, and NO_x in the exhaust gases were measured using a gas analyzer (Testo 350 Pro, Testo Inc., Germany). Uncertainty analyses were conducted for temperature measurement, flame speed, and equivalence ratio using root-sum-squares method by Moffat [27]. The uncertainties of the temperature measurement, flame speed, and equivalence ratio were 8.59 °C, 1.08%, and 2.1%, respectively. The pressure drop had an uncertainty of 1.5 Pa, and the CO, NO_x, and HC emission measurements had uncertainties of 2, 2, and 10 ppm according to the manufacturer. The detailed parameter definitions, uncertainty analysis, and experimental procedure can be found in the study of Gao et al. [28].

3. Results and discussion

The performance of a porous burner is influenced by the material used and its pore size. Pore size determination is based on Fu et al. [29], and the correlation can be calculated using the following equation:

$$d_p = \frac{\sqrt{4\varepsilon/\pi}}{25.4\omega} \tag{1}$$

where ε is the porosity, which is defined as the fraction of the total volume if the medium that is occupied by void space in Nield and Bejan [30]. The pore density ω refers to the PPI value. The radiative extinction κ coefficient is related to the pore diameter and can be obtained based on the experimental correlation by Hsu and Howell [31] in the following equation:

$$\kappa = \frac{3(1-\varepsilon)}{d_p} \tag{2}$$

Thermal conductivities of different foams were measured using a Hot Disk thermal analyzer (Hot Disk AB, Uppsala, Sweden). The thermal conductivity, radiative extinction coefficient, pore size, and pore density of the four materials are summarized in Table 1. The flame stability limits, flame profile, flame temperature, and polluted emissions for Al_2O_3, ZrO_2, FeCrAl, and SiC are discussed. The effect of pore density of SiC foam on combustion performance is also discussed.

Materials can influence preheating effect of the premixed fuel/air mixture, which is an important factor for flame stabilization in porous burners. The operating envelope of different materials for 10 PPI foams is obtained as indicated in Fig. 3 and can be divided into three categories: blow-off (above the upper stability limit), stable, and flashback/quenching categories (below the lower stability limit). In the blow-off category, flow velocity is sufficiently high to push the flame toward the downstream direction until flame detachment occurs. In the stable category, flame is stabilized at the interface or immediately downstream. In the flashback/quenching category, flame speed is sufficiently high to penetrate the flame holder layer in the upstream direction and consequently ignite the mixture in the mixing chamber, such that the heat produced by the flame does not offset the heat losses and the flame cannot be sustained. When the flame is stable, the mean flow velocity is equal to flame speed. The maximum stable velocity