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Investigation of the structural and reactants properties on the thermal characteristics of a premixed porous burner

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ABSTRACT

Porous burners offer attractive features such as competitive combustion efficiency, high power ranges, and lower pollutant emissions. In the present study, the thermal characteristics of a porous burner are numerically investigated for a range of operating conditions and design specifications within a practical range. The premixed flame propagation of a methane/air mixture in a ceramic porous medium is simulated through an unsteady, one-dimensional model. The combustion process is modeled using a suitable single-step chemical kinetics. The reaction location is not predetermined, thus the flame is allowed to float within the solid matrix or to run off from either side of the porous medium. The numerical results indicate that flame stability and thermal characteristics of the burner are strongly dependent on the inlet mixture specifications and the solid matrix structural properties. For a fixed value of the inlet firing rate, the combustion products temperature will increase by an increase in the inlet gas temperature, an increase in the matrix porosity, or by a decrease of the matrix pore density. Among the geometrical properties, the burner length has virtually no effect on the burner performance. An increase in the solid matrix porosity or burner firing rate will increase the efficiency of the preheating zone, while increasing the inlet gas temperature or matrix pore density will cause a reduction in this efficiency. Simulation results also suggest that in order to prevent flame blow-out or flash-back, critical values of the burner settings and design parameters must be avoided.

1. Introduction

Interest in the development of advanced combustion systems has been motivated by the need for more efficient heat transfer with lower emissions. Among many options, the process of gas combustion in an inert porous medium has been given special attention. Enhanced efficiencies, higher power densities, higher dynamic power ranges, high compactness and controlled pollutant emissions are of the characteristics of porous burners, which have made them superior to conventional free-flame burners [1,2].

High heat capacity, conductivity and emissivity of the solid matrix in comparison to a gas phase cause the distinctive properties of combustion in porous media. Heat from the high temperature post-flame zone serves to heat the porous solid in the preheating zone with radiation and conduction heat transfer mechanisms through the solid medium, which in turn convectively preheats the incoming reactants. The regenerative internal heat feedback mechanism results in several interesting characteristics relative to a free burning flame, namely higher burning speeds, extension of the lean flammability limit and ability to burn fuels that have a low energy content.

The inception point in the study of porous burners may date back to the early 1970's. In 1971, Weinberg [3] proposed several heat recirculating burners, where the flue gases were partially used in the preheating of the reactants by using a heat exchanger. Inserting a porous highly conductive matrix into the flame location to make a more effective transfer of heat from the solid to the reactants was first suggested by Takeno and Sato [4]. Another early analysis was performed by Echigo [5] to investigate the ability of converting some of the enthalpy of a non-reacting hot gas for radiative transfer from a porous medium through which the gas was flowing. Since then, especially over the last two decades, considerable efforts have been made in the development and applications of porous media combustion and heat recirculation technology; see, for example, reviews in [6,7].

The solid region of a porous burner can be divided into two zones: the preheating and reaction zones. In the preheating zone the solid-phase temperature exceeds the gas temperature, while in the reaction zone the combustion reaction causes a considerable increase in the gas phase temperature. In comparison to a premixed laminar free flame, the preheating zone in a porous burner

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Nomenclature

A	pre-exponential factor (m^3/kg s)
C	specific heat (kJ/kg K)
C_p	constant-pressure specific heat of gas mixture (kJ/kg K)
d	diameter (m)
D	diffusion coefficient (m^2/s)
E_a	activation energy (kJ/kmol)
FR	inlet firing rate (kW/m^2)
H	volumetric convective heat transfer coefficient (kW/m^3 K)
HV	heating value (kJ/kg)
k_G	fuel consumption rate (kg/m^3 s)
L	solid matrix length (m)
$\dot{m}$	mass flux (kg/m^2 s)
n	refractive index
N	total number of species
Nu	Nusselt number
PPC	pore density (1/m)
Pr	Prandtl number
Re	Reynolds number
R_u	universal gas constant (8.315 kJ/kmol K)
t	time (s)
T	temperature (K)
u	velocity (m/s)
V	diffusion velocity (m/s)
Y	mass fraction
x	axial distance (m)
X	igniter length (m)

Greek symbols

α	excess air fraction
β	extinction coefficient (1/m)
ϕ	solid porosity
λ	thermal conductivity (kW/m K)
ρ	density (kg/m^3)
σ	Boltzmann constant (5.672×10^{-11} kW/m^2 K^4)
$\dot{\omega}$	reaction rate (kg/m^3 s)
Φ	equivalence ratio

Subscripts

cond	conduction
eff	effective
g	gas phase
k	*kth* species
km	*kth* species in gas mixture
p	pore
rad	radiation
s	solid-phase
v	volumetric

is much more effective. The thermal performance and pollutant formation in a porous burner are strongly affected by the length of the matrix preheating zone and the capability of this region in heat recirculation through the solid-phase. An efficient preheating zone causes an effective transfer of heat between the two phases and increases the reactants temperature entering the reaction zone considerably.

In an analytical work using a prescribed flame location Yoshizawa et al. [8] showed that temperature profiles and burning velocities are highly dependent upon the optical and structural properties of the porous matrix. Excess enthalpy flames were predicted due to the presence of the solid-phase. According to their modeling, the single most important solid property governing the flame behavior is the absorption coefficient. In practice, the absorption coefficient can be increased by reducing the mean pore size of the matrix [7].

A numerical investigation of premixed combustion within a highly porous inert medium was reported by Hsu et al. [9]. The simulated burner was a 0.08-m long partially stabilized zirconia cylinder. An improved description of the thermophysical properties of the solid was used in the modeling; however, the flame location was arbitrarily prescribed. It was found that the preheating effect increased strongly with increasing convective heat transfer and with increasing effective thermal conductivity of the solid. The volumetric convective heat transfer was expected to increase with increasing number of cells per unit length of the porous matrix, but the absorption coefficient decreased with increasing cell size and decreasing cell density.

Mohamad et al. [10] numerically studied combustion and heat transfer in a porous matrix burner consisting of a packed bed of ceramic particles with two rows of embedded cooling tubes. They used a two-dimensional model, single-step kinetics, and a single energy equation for the solid and gas phases by assuming that the gas and the solid matrix are in thermal equilibrium. Radiative heat transfer was modeled using a diffusion approximation. The effects of firing rate, excess air and particle diameter on the thermal performance of the burner were examined. The predicted results showed that the flame location is a strong function of the excess air and is also sensitive to the uncertainty in the activation energy.

A one-dimensional theoretical study of the heating effectiveness of a composite porous radiant burner (PRB) was conducted by Kulkarni and Peck [11]. A parametric study was carried out to determine the effect of the radiative and structural properties of the two porous layers on the burner performance. Calculations indicated that a significant improvement in the radiative output of a PRB can be attained by optimizing the burner properties upstream and downstream of the flame. Generally, the upstream layer should be of lower porosity, shorter length, and higher optical thickness than the downstream layer.

Mital [12] proposed both experimental and theoretical models for combustion and heat transfer in a two-stage porous burner to study the thermal characteristics of reticulated ceramics. His burner was composed of a diffuser layer (DL) and a flame support layer (FSL). The DL was made from cordierite with a porosity of 0.73 and 19 mm thickness. The FSL was 2-mm thick with a porosity of 0.83. It was observed that the flame was stabilized in the middle of the FSL. Fu [13] attempted to improve the approximate analytical model proposed by Mital. In a comprehensive parametric study, he showed that temperatures of both the solid and the gas in the flame support layer increased with an increase in the firing rate because the chemical heat release rate and the convective heat transfer rate increased with the firing rate.

Barra and Ellzey [14] analyzed heat recirculation in a two-layered porous burner using a one-dimensional model. It was concluded that the burner length does not significantly affect the amount of heat recirculated. In addition, the relative importance of conduction and radiation are unchanged. They suggested a bilayer solid structure to improve the flash-back resistance of the burner.

Several design and setting parameters of a porous burner have considerable influence on the performance of its preheating zone. Because of the strong impact of heat transfer characteristics of the preheating zone on the overall thermal efficiency of a porous burner, an accurate study of the thermal performance of this zone