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Full Length Article

Flame stability analysis of the premixed methane-air combustion in a two-layer porous media burner by numerical simulation

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ABSTRACT

The flame stabilization within a two-layer porous burner was investigated numerically in the present study. Two-dimensional model was implemented to simulate the premixed methane-air combustion process. The governing equations including the radiative transport equation and separate energy equations for the solid and gas phases were solved by using the finite volume method. In order to validate the utilized model, the gas and solid temperature profiles within the burner were compared to the experimental temperature distribution and good agreement was observed. The results proved that the stability limit and flame temperature within a porous burner can be controlled by the equivalence ratio of the incoming mixture. Heat recirculation study showed that high convective heat recirculation occurred at low equivalence ratios caused higher stable inlet velocities. The radiative recirculation efficiency was almost constant over the stability limit at constant equivalence ratio while this parameter decreased with increasing equivalence ratio. Also, the effect of outlet diameter of the burner on the flame stabilization suggested that the optimum outlet diameter eventuating the highest flame stability limit was double the amount of inlet diameter. The study of the effect of the length of first porous layer on the flame status showed that the optimum ratio of preheat zone to combustion zone length was 0.33 to reach the highest burner operating range.

1. Introduction

Flame situation controlling has an effective role in pollutant emission and efficiency of porous burners. Increment of flame stability limit by heat recirculation based on the excess enthalpy theory was introduced more than four decades ago [1]. The primary experimental studies investigating the flame stability were done on burners containing a package of ceramic tubes [2–4]. Heat recirculation mechanism occurring in the porous inert media burner causes some exceptional properties such as high burning rate [5], low pollutant emissions [6], and high flammability limits [7]. The process of flame stabilization in porous inert medium (PIM) depends on the amount of heat generation, heat recirculation, and heat loss. Numerical study of flame stabilization within porous media firstly was done on a one-layer porous matrix by considering the solid and gas conduction, solid radiation and convection between the gas and solid phases [8]. Since the one-layer porous burners are prone to flashback, two-layer porous matrix was implemented in order to avoid flashback and control the flame stability [8]. Two-layer porous medium consists of two porous zones with different thermo-physical properties. Incoming mixture is preheated in the first layer called preheat zone and the flame is formed in the second layer called combustion zone. Flame propagation in PIM is characterized by the modified Peclet number, $Pe = S_L d_m c_p \rho_g / \lambda_g$ where S_L is the laminar flame speed, d_m is the average pore diameter, c_p is the specific heat capacity of mixture, ρ_g and λ_g are density and thermal conductivity of gas mixture respectively. Several researchers studied the effect of structure and material of porous matrix on flame stabilization and pollutant emission in porous burners [9–12]. Analysis of heat transfer modes occurring in porous burners showed the role of heat recirculation in augmentation of flame stability limit [13]. Experimental and numerical studies demonstrated the effect of equivalence ratio on the flame status and stability range in PIM [14–19]. Bakry et al. experimentally studied premixed methane-air combustion in a divergent porous burner. They investigated the effect of diverse pressure and temperature conditions on flame temperature, NOx pollutant concentration, and location of flame stabilized. The results showed that increasing the pressure and temperature of inlet mixture moved the stable flame downstream and caused increase in flame temperature and NOx emission [20]. The effect

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Nomenclature

Parameter	Explanation, Unit
u	Axial velocity, m/s
v	Radial velocity, m/s
T	Temperature, K
ρ	Fluid Density, kg/m^3
g	Gas phase, –
s	Solid phase, –
ε	Emissivity, m
φ	Equivalence ratio, –
σ	Stephan-Boltzman constant, 5.67×10^{-8} $W/m^2 K^4$
D_o	Outlet diameter, m
Φ	Porosity, –
h_v	Volumetric heat transfer coefficient, $W/m^3 K$
Y	Mass fraction, –
P	Static pressure, Pa
μ	Viscosity, W/mK
R	Radiation, –

of gravity and pressure difference on the premixed methane-air combustion were studied numerically by Lutsenko et al. [21]. For this purpose, they investigated a homogeneous porous burner in vertical and horizontal situations. They reported that the gravity and pressure difference had significant effects on the direction of combustion wave propagation. Qu et al. [22] experimentally perused combustion of diverse fuels in a two-layer porous burner. They used of methane, propane, and hydrogen as fuels in their experiments. The aim of their work was to investigate the effect of fuel on the flame stability, temperature distribution within the burner, flame temperature and pollutant emissions. Results demonstrated that the flame stability limit increased with increasing the equivalence ratio for methane, propane and hydrogen while, hydrogen had the highest limit of flame stability among these three fuels. Gao et al. [23] examined the premixed methane-air combustion in a two-layer porous burner. They compared diverse structures of alumina including foams, beads, and honeycombs as porous medium in their experiments. The flame stability limits, temperature distribution, pressure drop, and pollutant emissions were investigated. Results indicated that at same inlet conditions, the flame temperature of the foams was considerably lower than that of two other structures. Combustion of premixed methane-air in a two-zone catalytic alumina pileup-pellets burner was experimentally investigated by Qu et al. [24]. They showed that the flame stability limits increased by increasing the equivalence ratio and pellet diameter. The comparison of inert and catalytic burners showed that the axial temperature distribution was more uniform in catalytic burners than that of inert burners. Also, the pollutant emissions of both catalytic and inert burners were discussed. Vandadi et al. [25] numerically studied a two-layer porous burner with a heat exchanger. The heat exchanger consisted of radiant rods for preheating the incoming air of the porous burner. They proved that preheating the combustion air increased the radiant burner efficiency over 45%.

The focus of this study is on the flame stabilization and flame dynamics of the premixed methane-air combustion in a two-layer porous burner. This work intends to develop a numerical scheme to accurately simulate the combustion processes and flame situation in porous medium. The effect of inlet velocity and fuel-equivalence ratio on the flame stability limits and heat transfer modes are perused. Also, the influence of dimensions of burner on the performance are studied. As a distinction from previous numerical studies [13–14,25–28], the ultra fuel-lean combustion in porous medium is modeled in present work, and flame stability limits and temperature distribution under this condition are investigated. The governing equations are solved in a two-dimensional axisymmetric model. In order to quantify the radiation heat flux in the solid matrix, the finite volume method is used to solve the radiative transport equation. Non-equilibrium thermal condition between the gas and solid phases is considered and heat recirculation processes through the burner are discussed. Predicted results indicated that the present numerical scheme is able to preciously simulate the behavior of the premixed combustion, flame stabilization and heat transfer modes in the porous medium.

2. Model specifications

Two-layer porous media burner which has 140 mm length is composed of two porous sections with different porous materials. The preheat zone consists of alumina spheres of 5 mm diameter and the combustion zone is made up of 10 PPI (Pores Per Inch) SiC ceramic foam. The inlet and outlet diameters are 40 mm and 74 mm, respectively. This porous burner was tested by Durst et al. [29] at LSTM-University of Erlangen-Nuremberg and is shown schematically in Fig. 1. The thermo-physical properties of alumina spheres and SiC ceramic foam are summarized in Table 1 [30].

3. Numerical modeling

3.1. Assumptions

The following assumptions are used in numerical modeling [10]:

(1) The solid matrix radiates as a gray homogeneous medium.
(2) The reactants and products of combustion are considered as incompressible ideal gases.
(3) Catalytic effects of the solid matrix are ignored.
(4) The buoyancy effects and gaseous radiation are neglected.
(5) The Dufour and Soret effects are not considered.
(6) Radiative gray, no-slip and adiabatic conditions are considered for the burner wall.

3.2. The governing equations

Due to the symmetric geometry of the burner, Two-dimensional axisymmetric model was implemented to simulate the combustion of premixed methane-air. The reacting flow through the porous matrix was considered as a Newtonian, steady and laminar flow. Under these assumptions, the governing equations are expressed as:

Continuity equation [31]:

$$\nabla \cdot \left(\rho_g \phi \vec{v}\right) = 0 \tag{1}$$

where ϕ is the porosity of the porous medium and $\vec{v}$ represents the velocity vector of gas mixture within the burner.

Momentum equation [31]:

$$\rho_g \vec{v} \cdot \nabla \vec{v} = -\nabla p + \mu \nabla^2 \vec{v} - R_P \tag{2}$$