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The effect of a perforated plate on the propagation of laminar hydrogen flames in a channel – A numerical study

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ABSTRACT

Laminar hydrogen flame propagation in a channel with a perforated plate is investigated using 2D reactive Navies-Stokes simulations. The effect of the perforated plate on flame propagation is treated with a porous media model. A one step chemistry model is used for the combustion of the stoichiometric H₂–air mixture. Numerical simulations show that the perforated plate has considerable effect on the flame propagation in the region downstream from the perforated plate and marginal effect on the upstream region. It is found to squeeze the flame front and result in a ring of unburned gas pocket around the flame neck. The resulting abrupt change in flow directions leads to the formation of some vortices. Downstream of the perforated plate, a wrinkled “M”-shape flame is observed with “W” shape flame speed evolution, which lastly turns back to a convex curved flame front. Parametric studies have also been carried out on the inertial resistance factor, porosity, perforated plate length and its location to investigate their effects on flame evolution. Overall, for parameter range studied, the perforated plate has an effect of reducing the flame speed downstream of it.

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Introduction

Hydrogen is a clean substitute for fossil fuels and seen as a potential energy carrier for the future. However, hydrogen has a wide flammability range from 4% to 75% and high reactivity with a laminar flame speed around 6 times that of typical hydrocarbon fuels. The commercial exploitation of hydrogen will inevitably involve its transportation through pipelines from the point of production or delivery to the point of demand. While the research has been ongoing elsewhere on the

related issues of hydrogen embrittlement and adding hydrogen to the existing natural gas pipeline network, the present study is conducted in the context of using porous plate type of flame arresters to enhance safety during pipeline transmission and in process equipment.

Accidental ignition of fuel in pipelines can lead to explosions and in some cases transition from deflagration-to-detonation (DDT). As such, flame arrestors are frequently used in industry to enhance safety. A common type arrester is based on the quenching effect of the porous material, which depends on the pore characteristic dimensions and the flame

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properties (i.e., the flame thickness and laminar burning velocity) [1,2]. Insight of the quenching mechanism will be of assistance towards increasing the effectiveness of such arresters.

Among the literature, some experimental work has been carried out on flame interaction with porous media. Khanna et al. [2] studied methane combustion in a porous medium burner with porosity of 0.87 upstream and 0.84 downstream. Ellzey and Goel [3] measured carbon monoxide and nitric oxide emissions of fuel/air mixture using a two stage porous media burner. Tseng and Howell [4] studied combustion of liquid fuels in a porous radiant burner. These studies focused on burner flames. For propagating flames, Babkin et al. [5], Pinaev [6] and Makris et al. [7] investigated steady flame and detonation propagation in vertical tubes filled with sand and spherical beads. Flame propagation in porous media at speed greater than 5 m/s was found to produce a local pressure rise ahead of the flame. Johansen et al. [8–10] investigated flame propagation in a horizontal channel filled with spherical beads and found that flame propagating above the bead layer had a higher speed than the speed of sound in the combustion products [9]. Ciccirelli et al. [10] found that flame of a stoichiometric hydrogen-air mixture accelerated rapidly in a 7.62 cm square cross-section channel filled with 1.27 cm diameter beads.

A number of numerical investigations on flame interaction with porous media have also been reported. Zhou and Pereira [11] investigated one-dimensional combustion on a porous burner using detailed reaction mechanism of methane/air. Malico et al. [12] simulated a flame in a 10 kW porous burner. Zhao et al. [13] numerically studied the CH₄/air premixed gas combustion in a porous media burner using detailed chemistry. Zheng et al. [14] performed numerical studies on flame inclination in porous media combustors.

However, none of these were conducted in the context of the flame arresting potential of the porous materials. Overall, relatively little study has been carried out about flame interaction with porous media, especially for low speed flame propagation in a channel obstructed with perforated plate. Depending on the pore characteristic dimensions and the flame characteristics, the porous material might have a quenching effect rather than accelerating the flame as in the case investigated by Ciccirelli et al. [10]. In the present, we aim to gain insight of the flame and porous plate interaction in a channel through numerical study, focussing on the effect of the porous plate with pore characteristic dimensions on the flame structure and propagation mechanism. Such study does not directly address the potential quenching mechanism but shades light on the changing flame behaviour when going through a perforated plate. Such fundamental understanding will serve as the basis towards investigating the quenching mechanism of perforated plates.

Numerical modelling

Governing equations and numerical schemes

The following assumptions are made in order to represent the perforated plate as porous media:

- (1) The perforated plate is non-catalytic and homogeneous.
- (2) Radiation heat transfer from the wall, gas and the perforated plate are also neglected.
- (3) The porosity variation near the tube wall is not considered.

Based on the above assumption, the governing equations can be described as follows:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{U}) = 0 \quad (1)$$

Momentum conservation equation:

$$\frac{\partial \psi \rho \bar{U}}{\partial t} + \nabla \cdot (\rho \bar{U} \bar{U}) = -\nabla p + \nabla \cdot \bar{\tau} + S_d \quad (2)$$

Energy conservation equation:

$$\frac{\partial (\psi \rho h_s + (1 - \psi) \rho_p h_{s,p})}{\partial t} + \nabla \cdot (\rho \bar{U} h_s) = \frac{dp}{dt} + \bar{\tau} : \nabla \bar{U} + \nabla \cdot \left[k_{\text{eff}} \nabla T + \sum_{i=1}^{NS} \rho D h_{si} \nabla Y_i \right] + \dot{q}''' \quad (3)$$

Species conservation equation:

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho \bar{U} Y_i) = \nabla \cdot (\rho D \nabla Y_i) + S_i \quad (4)$$

where ρ and ρ_p are the gas and porous media densities. \bar{U} is the velocity and t is time. The ratio $Y_i = \rho_i / \rho$ denotes the i -th species mass fraction. NS is the total number of species. p , T and h_s denote pressure, temperature and sensible enthalpy, respectively. h_{si} is the sensible enthalpy of the i -th specie. $k_{\text{eff}} = \psi k_g + (1 - \psi) k_p$ where k_g is gas thermal conductivity and k_p is porous media thermal conductivity. $\rho D = \mu = \frac{k_g}{C_p} = z_0 T^{0.7}$ [15,16], where D , μ , C_p and z_0 are the diffusion coefficient, viscosity coefficient, specific heat capacity at constant pressure and transport constant, respectively.

$\bar{\tau} = \mu \left[\left(\nabla \bar{U} \right) + \left(\nabla \bar{U} \right)^T - \frac{2}{3} \left(\nabla \cdot \bar{U} \right) I \right]$, where I is unit vector. $h_{s,p}$ denotes the sensible enthalpy of porous media. ψ is the porosity of the perforated plate. S_d is composed of two parts, a viscous loss term and an inertial loss term due to the perforated plate and can be expressed as

$$S_d = - \left(\mu D + \frac{1}{2} \rho \left| \bar{U} \right| F \right) \bar{U} \quad (5)$$

where F is the inertial resistance factor, and can be viewed as a loss coefficient per unit length along the flow direction due to the effect of porous media.

Based on the mass interaction law, the mass production/sink rate of the i -th species due to gas reaction can be derived as:

$$S_i = \nu_i W_i \dot{\omega} \quad (6)$$

where ν_i and W_i denotes the stoichiometric coefficient and molar weight of the i -th species. $\dot{\omega}$ denotes the molar production rate of product per unit volume.

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