



Numerical investigation of filtration gas combustion in a mesoscale combustor filled with inert fibrous porous medium

Yi Liu, Aiwu Fan*, Hong Yao, Wei Liu

State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China



ARTICLE INFO

Article history:

Received 23 December 2014
Received in revised form 18 June 2015
Accepted 23 July 2015
Available online 5 August 2015

Keywords:

Mesoscale combustor
Filtration gas combustion
Fibrous porous media
Flame instability
Standing wave

ABSTRACT

Filtration gas combustion in a mesoscale combustor filled with inert fibrous porous media was numerically investigated. Downstream propagating combustion wave and standing combustion wave were obtained in the simulation. The predicted flame stability diagram agrees well with experimental results in the literature. Moreover, it was found that the downstream propagating flame changes its shape and transforms from one stable state to another stable state in a short duration after ignition, while the flame shape of the standing wave remains unchanged. Furthermore, combustion efficiency of both combustion waves increases with time and a nearly complete conversion can be achieved spontaneously due to the strong heat recuperation. It is also demonstrated that heat conduction in the tube wall has a crucial effect on flame behaviors and combustion efficiency. On one hand, for a bigger wall thermal conductivity, the downstream propagating wave moves with a larger speed; on the other hand, a high combustion efficiency can be expected for a smaller thermal conductivity.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Microscale and mesoscale combustions have drawn extensive attention in the past decades due to the rapid development of micro-electromechanical systems (MEMS) [1,2]. However, there are some critical challenges to sustain a stable combustion in miniature combustors. Tremendous efforts have been made to achieve a complete reaction in combustors [3–12].

It is well known that filtration gas combustion (FGC) in inert porous media has been proved to be a good approach to broaden the flammability limits. Weinberg [13] pointed out that super-adiabatic combustion could be realized with efficient heat recuperation. Takeno [14–16] first applied porous medium to combustion to realize the excess enthalpy flame, which revealed that the application of porous media greatly extended the flammability limits and increased the burning velocity. After that, Zhdanok [17] investigated the propagation of stable combustion wave in porous media experimentally and theoretically. It was found that the reactive transfer was characterized by a thermal wave related to porous medium and by a reaction wave velocity. The super-adiabatic reaction temperature and self-propagating reactions can be

obtained if the thermal wave velocity coincides with the reaction wave velocity.

However, the flame presented in porous media can be unstable, which is an obstacle to the application of FGC in industry. There are many perturbations in flow field and temperature field due to the chaotic characteristics of porous media. Babkin [18] paid much attention to flame instability and concluded that the combustion wave velocity was a function of the mixture velocity, equivalence ratio and combustor size. Hot spots, inclination of flame front, splitting flame and other instabilities present in porous medium combustion are also investigated by many researchers [19–23].

Instead of the conventional porous media such as ceramic foam, alumina pellets and metal fibers, Yang et al. [24] used a kind of ceramic fiber of high porosity to investigate the FGC. Fig. 1(a) shows the direct photo of micro-fibrous medium, which is composed of SiO₂ (28%) and Al₂O₃ (72%). Micro-fibrous medium with a mean pore diameter (d_p) of 4 μ m is uniformly packed in a tube of 8-mm inner diameter (D), as shown in Fig. 1(b). Detailed property parameters are shown in the Section 2.2. Peculiar flame propagation features were experimentally discovered in this special porous medium. In addition to the upstream and downstream propagating combustion wave, a specific standing wave regime was observed, whereas only one standing wave point exists in normal porous media. Yang et al. [24] used a two-temperature, 1D analytical model to analyze the peculiar phenomenon. Though this model captured some features observed in the experiment, it failed

* Corresponding author at: State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China. Tel.: +86 27 87542618; fax: +86 27 87540724.

E-mail addresses: faw@hust.edu.cn, faw_73@163.com (A. Fan).

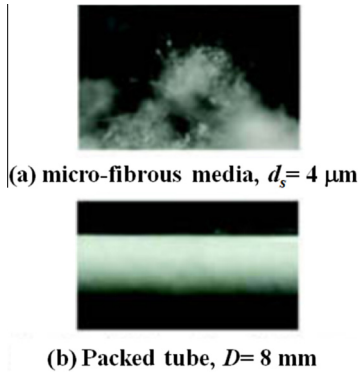


Fig. 1. Direct photos of micro-fibrous medium and the packed tube.

to reproduce the standing wave regime in the whole interval of filtration gas velocity due to the over-simplification of the analytical model.

Following the above work [24], Fursenko et al. [25] conducted a further numerical study of the combustion in fibrous porous media. They used a 2D thermo-diffusion model with 1D flow and a sub-model with 2D filtration hydrodynamics aiming at clarifying the physical mechanisms that are governing flame propagation (Note: The “thermo-diffusion model” is a simplified model in which the density of gaseous mixture is treated as a constant, i.e., the velocity profile does not change in the presence of combustion. Thus, the momentum equation is not included in this model. In contrast, in the “hydrodynamic model”, density variation is considered and the momentum equation has to be solved simultaneously with other conservation equations). It was found that the hydrodynamic instability was of great importance to the flame dynamics under moderate and high filtration velocities, but was negligible under low filtration velocities. The moving wrinkles on the flame front under high filtration velocities were obtained by the model, which could be associated with splitting flame structure revealed in previous experiments [24]. Moreover, the standing combustion wave regime was also captured under some conditions. Although this 2D model captured different combustion wave regimes more successfully than the 1D model [24], some defects still exist in the 2D model. For instance, the effect of heat conduction in the tube wall, which is expected to play a significant role in microscale and mesoscale combustions, was neglected in their model. In addition, they used a one-step, global reaction mechanism for the CH₄/air combustion. As a result, the predicted flame stability diagram did not match well with the experimental results, as can be seen from the comparison between the predicted and measured results of the quartz tube with a 8-mm inner diameter [25].

Obviously, it is an idea condition for the application of filtration gas combustion that the flame can be stabilized in porous media. The stable flame is beneficial for the operation of burners based on FGC. Motivated by the above works [24,25], our objective has been to numerically reproduce the flame stability diagram of the 8-mm diameter tube obtained by Yang et al. [24] as a first step, and then reveal more detailed information of the FGC, such as combustion wave velocity and combustion efficiency. Special attention was also paid to the heat conduction effect of the tube wall on the characteristics of the FGC in the mesoscale tube filled with fibrous porous media.

2. Numerical method

2.1. Geometric model

A 2-D axisymmetric model was applied to simulate the filtration gas combustion, as schematically illustrated in Fig. 2. The

combustor has an internal radius of $r = 4$ mm and is filled with fibrous porous media. Differing from the simulation conducted in [24,25], heat conduction in the solid wall was taken into account in the present work. The wall thickness (δ) is 1 mm and the length (L) of the combustor is 200 mm.

2.2. Governing equations

In order to simplify the calculations, the following hypotheses are introduced:

- (1) The gas phase is treated as incompressible and with constant physical properties.
- (2) Porous medium is uniformly filled in the combustor and they are non-catalytic.
- (3) Dispersion effects in the species and energy equations are negligible and not considered.

Under these assumptions, conservation equations of the gas and porous medium are expressed as follows.

Continuity equation:

$$\frac{\partial}{\partial t}(\varepsilon \rho_g) + \frac{\partial}{\partial x}(\varepsilon \rho_g u) + \frac{1}{r} \frac{\partial}{\partial r}(\varepsilon \rho_g r v) = 0 \quad (1)$$

where ε is the porosity of porous media, ρ_g is the density of the gas, u and v are the axial and radial velocity components, respectively. The ideal gas equation of state for a multi-component mixture is solved to obtain gas densities.

Momentum equations:

$$\begin{aligned} \frac{\partial}{\partial t}(\varepsilon \rho_g u) + \frac{\partial}{\partial x}(\varepsilon \rho_g u u) + \frac{1}{r} \frac{\partial}{\partial r}(\varepsilon \rho_g r u v) \\ = -\varepsilon \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\mu r \frac{\partial u}{\partial r} \right) + S \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\varepsilon \rho_g v) + \frac{\partial}{\partial x}(\varepsilon \rho_g u v) + \frac{1}{r} \frac{\partial}{\partial r}(\varepsilon \rho_g r v v) \\ = -\varepsilon \frac{\partial p}{\partial r} + \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\mu r \frac{\partial v}{\partial r} \right) + S \end{aligned} \quad (3)$$

where p is the hydrostatic pressure and μ is the dynamic viscosity. The last term S in either equation is the source term, which includes viscous loss and inertial loss caused by porous medium.

Species conservation equation:

$$\begin{aligned} \frac{\partial}{\partial t}(\varepsilon \rho_g Y_i) + \frac{\partial}{\partial x}(\varepsilon \rho_g Y_i u) + \frac{1}{r} \frac{\partial}{\partial r}(\varepsilon \rho_g Y_i r v) + \frac{\partial}{\partial x}(\varepsilon \rho_g Y_i V_i) \\ + \frac{1}{r} \frac{\partial}{\partial r}(\varepsilon \rho_g Y_i r V_i) = \varepsilon \omega_i W_i \end{aligned} \quad (4)$$

where Y_i , V_i , ω_i and W_i are the mass fraction, diffusion velocity, molar rate of production and molecular weight of i th species, respectively.

Energy equation for gaseous mixture:

$$\begin{aligned} \frac{\partial}{\partial t}(\varepsilon \rho_g c_g T_g) + \frac{\partial}{\partial x}(\varepsilon \rho_g c_g T_g u) + \frac{1}{r} \frac{\partial}{\partial r}(\varepsilon \rho_g c_g T_g r v) = \frac{\partial}{\partial x} \left(\varepsilon \lambda_g \frac{\partial T_g}{\partial x} \right) \\ + \frac{1}{r} \frac{\partial}{\partial r} \left(\varepsilon \lambda_g \frac{\partial (r T_g)}{\partial r} \right) + h_v (T_s - T_g) - \varepsilon \sum_i \omega_i W_i h_i \end{aligned} \quad (5)$$

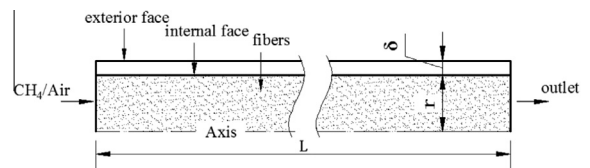


Fig. 2. Schematic of the combustor filled with fibrous porous media.

Download English Version:

<https://daneshyari.com/en/article/7056095>

Download Persian Version:

<https://daneshyari.com/article/7056095>

[Daneshyari.com](https://daneshyari.com)