Fuel 158 (2015) 361–371

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Numerical study of diffusion filtration combustion characteristics in a plane-parallel packed bed

Jun-Rui Shi [a], Ben-Wen Li [b,*], Yong-Fang Xia [a], Peng-Fei Chen [a], You-Ning Xu [a], Hong-Sheng Liu [b]

[a] The Key Laboratory of Clean Combustion for Electricity Generation and Heat-Supply Technology Shenyang Institute of Engineering, Shenyang 110136, Liaoning Province, China
[b] Institute of Thermal Engineering, School of Energy & Power Engineering, Dalian University of Technology, Dalian 116024, Liaoning Province, China

HIGHLIGHTS

- Diffusion filtration combustion with a detailed gas-phase reaction mechanism.
- The numerical model can successfully predict the flame shape.
- Diffusion filtration combustion remains characteristics of diffusion combustion.
- Convective heat transfer & thermal conductivity do not influence flame height.
- Mass dispersion has significant influence on the flame structure.

ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form 21 May 2015
Accepted 22 May 2015
Available online 1 June 2015

Keywords:
Diffusion flame
Filtration combustion
Flame shape
Flame height
Combustion

ABSTRACT

Numerical investigations on characteristics of diffusion filtration combustion are conducted in a plane-parallel packed bed. A detailed gas-phase reaction mechanism is used, and mass dispersion in packed bed is also taken into account. Attention is mainly focused on the combustion characteristics and the influencing factors, such as the gas and solid temperature profiles in the burner, the influences of solid thermal conductivity, mass dispersion and convective heat transfer between the gas and solid phases on the flame shape. The predicted results are compared with the available experimental and analytical data. For different gas mixture velocities and pellet diameters, the numerical model can successfully predict the flame shape. The predictions show that the diffusion combustion in packed bed remains the essential characteristics of normal diffusion combustion, although the solid properties can affect the flame structure. Compared with premixed combustion in porous media, there are two high temperature zones, which belong to gas and solid separately. These two high temperature zones locate at different positions in the burner. Results show that, the flame height remains almost the same with the increasing of thermal conductivity of solid but almost does not depend on the convective heat transfer between the solid and gas phases. In contrast, mass dispersion imposes significant influence on the flame structure. Higher mass dispersion will lead to the reduction of flame height but the increase of flame width.

1. Introduction

Researches on filtration combustion (combustion in porous media) have mainly been focused on gas premixed type during the last decades due to a large number of applications [1–6]. Meanwhile, gas diffusion combustion as the basic combustion element has been extensively investigated and some significant developments have been made. For example, the flame shape, the species distribution, as well as the soot formation under gravity and micro-gravity, were studied experimentally, theoretically and numerically [7–15]. However, the diffusion filtration combustion, which combines several outstanding features of both the diffusion combustion and the filtration combustion, was not highlighted in the literature [16].

Up to now, knowledge of characteristics of the diffusion filtration combustion is still limited. Kamiuto and Ogawa [16] experimentally investigated the shape of the diffusion flame in cylindrical packed beds. Subsequently, Kamiuto and Miyamoto [17] experimentally and analytically studied the flame shape of diffusion combustion in a plane-parallel packed bed. The flame structure was viewed by gradually adding the alumina pellets with a height of 5 mm per time from the above of the burner. A theoretical flame sheet model, in which the horizontal mass dispersion

* Corresponding author. Tel.: +86 13664102228.
E-mail addresses: heatli@hotmail.com, heatli@dlut.edu.cn (B.-W. Li).

http://dx.doi.org/10.1016/j.fuel.2015.05.055
0016-2361/

Nomenclature

c	specific heat, kJ/kg K
D_p	dispersion coefficient, cm^2/s
D^d	thermal dispersion coefficient, cm^2/s
h_v	convective heat transfer between the solid and gas phases, W/m^3 K
p	pressure, Pa
T	temperature, K
T_g	gas temperature, K
$\mathbf{v}$	velocity vector, m/s
u_0	vertical velocity at inlet, m/s
v	vertical velocity, m/s
y	horizontal coordinate, m
Y	mass fraction
d	diameter of spheres, m
D_i	diffusion coefficient of species i, cm^2/s
h_i	the molar enthalpy of species i, kJ/kg
L	flame height, m
P_0	ambient pressure, Pa
T_0	ambient temperature, K
T_s	solid temperature, K
u	vertical velocity, m/s
v	horizontal velocity, m/s
W_i	molecular weight of species i, kg/kmol
x	vertical coordinate, m
Y_{in}	mass fraction at inlet

Greek symbols

λ	thermal conductivity, W/m K
λ_{rad}	radiation conductivity, W/m K
ε	porosity
σ	Stephan–Boltzmann constant
λ_{eff}	effective thermal conductivity, W/m K
ρ	density, kg/m^3
ω_i	reaction rate of species i, kmol/m^3 s
μ	dynamic viscosity, Pa s

Subscripts

g	gas
s	solid

effect in porous media can be taken into account, was presented. However, the vertical dispersion diffusivity was ignored. Several parameters which affect the flame shape were evaluated and discussed. It is shown that the flame sheet model can capture the flame shape for different pellet diameters and mixture velocities. However, the predicted flame widths were in general smaller than those of experimental results, this discrepancy between the prediction and experimental data was attributed to the neglecting of thermal radiation [17].

The proportionality between the laminar jet flame height and the fuel mass flow rate is a classical relation of combustion science [10]. However, in diffusion filtration combustion, Dobrgeo et al. [18] suggested that, the diffusion mixing rate does not depend on the flow rate and the pellet size, and this conclusion may be utilized to control the heat release rate and the flame height. Thereafter, Dobrego et al. [19] numerically studied the diffusion filtration combustion radiative burner using a two-dimensional two-temperature model with a simple chemical reaction mechanism. In their model, the dispersion coefficients of species were taken into account with different expressions for vertical and horizontal directions, respectively. High stability of the flame was verified at an equivalence ratio of 0.2 for the proper geometry of the fuel–air feed system.

The dispersion phenomena can lead to enhancement of heat and mass transfer in packed bed. Most of the studies focused on the premixed combustion in porous media [1–6,20,21]. Henneke and Ellzey [1] presented simulation of the lean gas premixed combustion in a packed bed, their one-dimensional model included both the thermal and species dispersions proposed by Wakao and Kaguei [22]. The coefficients of species and thermal dispersions were described as $0.5P_eD_i$ and $0.5P_e\alpha$, respectively. Here D_i is the molecular diffusion coefficient and P_e is the Peclet number, α is the thermal diffusivity. Results showed that the gas-phase dispersion is important only at higher equivalence ratios for premixed combustion in porous media. The same treatment for species and thermal dispersions was performed in other literature [4,19–21].

In 1856, Darcy [23] proposed the pressure loss of water flowing through a packed bed. Ergun [24] assumed that the whole pressure loss through a fluidized bed is due to the sum of viscous and kinematic forces. By testing a variety of material and flow rates, Ergun concluded that his own equation is valid for a wide range of Reynolds's number. An extension of Darcy's equation is commonly known as Brinkman's equation [25]. However, for the simulations of low-velocity filtration combustion, most of investigators ignored the pressure loss in packed bed due to the relatively low *Re* in their studies [1,2,4,5,21].

As reviewed above, only few researches have been devoted to study the diffusion flame structures and the combustion characteristics in porous media. Because of the existence of porous media in the combustor, the properties of solid skeleton may influence the flame structure, but this problem has not been solved yet. Further, the diffusion filtration combustion combines some features of both the diffusion combustion and the premixed combustion in porous media [19]. In addition, the diffusion combustion is an important issue in both safety and technology of industrial processes. Those encourage us to explore the combustion characteristics of diffusion filtration combustion.

This work aims to simulate the experimental cases [17] using a two-dimensional two-temperature model with detailed chemical reaction mechanism, further, to gain physical understanding of the diffusion filtration combustion characteristics, the gas and solid temperature distributions. Then we examine the flame shape in the plane-parallel packed bed. Finally, the effects of several parameters, such as the solid thermal conductivity, the convective heat transfer between solid and gas, and the mass dispersion on flame structure are evaluated. In order to emphasize and clarify the contains of present investigation, the effects of mass fraction of fuel, the inlet velocity of gas mixture and the pellet diameter, etc., on the flame structure are not discussed individually in this study.

2. Physical model

A plane-parallel diffusion filtration combustor reported by Kamiuto and Miyamoto [17] is considered in this study, in which the N_2-diluted methane and O_2 are separately injected into the combustor filled with 2.02 mm or 3.18 mm alumina pellets. To save computation cost, 2-D computations are performed. Fig. 1 shows the schematic of the computational zone, which includes an extended region in the upstream side with a height of 40 mm.

To simplify the problem, the following assumptions are made:

(1) Inert homogeneous and optically thick porous media are assumed. The solid radiation is taken into account using the Rosseland approximation.