Energy Conversion and Management 94 (2015) 293–299

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Numerical investigation on the combustion characteristics of methane/air in a micro-combustor with a hollow hemispherical bluff body

Li Zhang [a,b,*], Junchen Zhu [b], Yunfei Yan [a,b], Hongliang Guo [b], Zhongqing Yang [a,b]

[a] Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, Chongqing 400030, PR China
[b] College of Power Engineering, Chongqing University, Chongqing 400030, PR China

ARTICLE INFO

Article history:
Received 26 September 2014
Accepted 6 January 2015

Keywords:
Micro-combustor
Hollow hemispherical bluff body
Numerical investigation
Combustion characteristics
Blow-off limit

ABSTRACT

The combustion characteristics of methane in a cube micro-combustor with a hollow hemispherical bluff body were numerically investigated. The blow-off limit, recirculation zone length and methane conversion rate were examined. The results illustrate that the blow-off limit of the micro-combustor with a hollow hemispherical bluff body is 2.5 times higher than that without bluff body, which are 24.5 m/s and 9.5 m/s at the same equivalence ratio ($\phi = 1$), respectively. With the use of hollow hemispherical bluff body, methane conversion sharply increases from 0.24% to 17.95% at 3 mm along the inlet-flow direction, where is the location of bluff-body, which is not affected by equivalence ratio and inlet velocity. The recirculation zone size has determined influence on residence time of the mixture gas, which increases with the increase of inlet velocity. Methane conversion rate is determined by equivalence ratio and inlet velocity. Methane conversion rate firstly increases and then decreases when the equivalence ratio and inlet velocity increase, reaching the maximum value (97.84%) at $\phi = 1$ and 0.02 m/s. Methane conversion rate sharply increases from 45% to 97.84% when the inlet velocity increases from 0.008 m/s to 0.02 m/s.

1. Introduction

With the fast development and intensive applications of Micro Electro-Mechanical Systems (MEMS), it is urgent to develop new micro combustors with small volume, light weight and high power density. Micro devices have been playing a key role on human life for aviation, spaceflight, automobile, biomedicine, environmental regulation, military affair and so on, such as sensors, micro medical devices, micro-pumps, micro-motors [1]. The combustion stability and efficiency directly affect the performance of MEMS. The availability of efficient micro-combustors could significantly enhance the functionality of MEMS for portable equipment, because they require high energy density and low recharge time. Therefore, many scholars try to develop some efficient systems in micro-scale in which the combustion energy is used to meet the need of high-power density applications [2–4].

Aiming at solving the existing problem of the micro-scale combustor, Kang et al. [5] studied on the flow, mixing and combustion characteristics of methane. Heat release from combustion has a significant impact on micro-scale combustor. In order to decrease heat release of the micro-combustor, many scholars put forward many solutions. Cao et al. [6] experimented on the low combustion efficiency of the micro-combustor, a micro heat-recirculating combustor using porous media plates is designed to study its diffusion combustion characteristics, including variations of combustion efficiency. It is confirmed that by adopting the special structure of regenerative jacket and opposite direction inlet mode of reaction gas through porous media plates, flow direction of reaction gas is opposite to that of heat loss. Three-dimensional numerical simulations of spiral counter flow Swiss roll heat-recirculating combustors were performed including gas-phase conduction, convection and chemical reaction of propane-air mixtures, solid-phase conduction and surface-to-surface radiation. These simulations showed that in 3D model, results are surprisingly similar to the experimental date [7]. Zhong and Hong [8] numerically investigated the micro-scale combustor with counter current heat transfer with Computational Fluid Dynamics (CFD), the results revealed that methane conversion rate could be increased and the combustion stability could be enhanced with catalyst, but high wall temperature of the micro-combustor would lead to catalyst deactivation. In order to solve the shortage of the micro-combustor, Zhang et al. [9] studied the characteristics of catalytic combustion, flow and heat transfer in micro-combustor, using laminar finite-rate and second-order upwind discretization model. The results demonstrated that wall temperature has determined influence on the rate of methane

* Corresponding author at: Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, Chongqing 400030, PR China. Tel.: +86 23 65103114; fax: +86 23 65111832.
E-mail address: lizhang@cqu.edu.cn (L. Zhang).

http://dx.doi.org/10.1016/j.enconman.2015.01.014
0196-8904/

conversion than other factors. Catalytic and regenerative structure can increase the efficiency of micro-scale combustor, but catalytic is easy to lose activity under higher temperature and regenerative structure increases complexity of the micro-scale combustor. By applying bluff body in the micro-combustors, the stability of the flame and combustion efficiency was considerably improved. Equilateral triangle shape and V-shape bluff bodies have been commonly developed, which are simulated in 2D model. The shortage of the 2D model simulation is that the data of the simulation cannot accurately reflect the real situation due to the simplify of 3D model. Fan et al. [10,11] studied on the shape and size of bluff body, results showed that there was the recirculation zone behind the bluff body due to the interaction of the mixture gas, which prolonged the residence time of mixture gas to make the reaction carried out adequately. Yan et al. [12–14] studied on the combustion characteristics of methane/air, the results revealed that the combustion of methane/air could be improved by added hydrogen into the mixture gas. Hydrogen is easy to burn, to the heat release of which can contribute to the combustion of methane.

Although the effects of micro-combustor structure and operating condition on combustion characteristics of micro combustion have been noted, the impacts of a cube micro-combustor with a hollow hemispherical bluff body have not been properly studied. Spherical surface can reduce the gas flow resistance and hollow hemisphere can prolong the recirculation zone. The paper focuses on the combustion characteristics of methane/air in a 3D micro-combustor model and compares the methane conversion rate and blow-off limit between micro-combustor with and without bluff body, and then investigates the combustion characteristics in order to optimize the structure and the combustion characteristics of the burner.

2. Physical model and mathematical model

2.1. Physical model

The 3D numerical models of cube micro combustor (20 mm length, 8 mm width, 5 mm height) with and without a hollow hemispherical bluff body are depicted in Fig. 1, which were constructed using FLUENT. Numerical calculation of the present problem included solutions of the momentum, energy, species available in FLUENT [15]. The cross-sectional view of the studied bluff body located at the entrance of micro-combustor (3 mm from the entrance). The radius and thickness of the hollow hemispherical bluff body are 2 mm and 0.1 mm, respectively. The bluff body was symmetrically located with respect to the micro-combustor. The combustion of methane/air was carried out in a micro combustor, which was packed with Rh catalyst on the inner wall of the combustor.

2.2. Mathematical model

Surface catalytic reactions are merely considered in the calculation. As the size of the reactor is small and the flow velocity of the mixture gas is low, the fluid volume is neglected and heat dissipation effect and gas radiation in the process of reaction have not been taken into account either. A similar application was adopted in the literature of Zhang et al. [16]. Nonetheless, equations for conservation of continuity, momentum, and energy are used in control volume. The mathematical model could be described by the following equations, which has been used in another literature [17] The governing equations in Cartesian coordinates include:

Continuity equation:

$$\frac{\partial(\rho u_j)}{\partial x_j} = 0 \tag{1}$$

where ρ is the density of the gas mixture, u is the velocity.

Composition equation:

$$\rho u_j \frac{\partial Ys}{\partial X_j} = \frac{\partial}{\partial X_j}\left(D\rho \frac{\partial Ys}{\partial X_j}\right) + Rs \tag{2}$$

where Y_i corresponds to the mass fraction of the ith species in micro premixing chamber, D is diffusion coefficient and Rs refers to the consumption or decomposition rate. Both surface species and gas phase species can be generated and consumed by surface reactions. The consumption or decomposition rate Rs is defined as below:

$$Rs = \sum_{k=1}^{Ks} \upsilon_{sk} k_{sk} \prod_{i=1}^{Ng+Ns} [X_i]\, \upsilon''_{ik} \tag{3}$$

where υ_{sk} is stoichiometric coefficient in forward direction of the combustion k, Ks is the total number of elementary surface reactions, υ''_{ik} is stoichiometric coefficient in negative direction of the combustion k, k_{sk} is forward rate coefficient of the combustion k. Ns is the number of surface species and Ng is the number of gas phase species. $[X_i]$ is the molar concentration of surface species i. k_{sk} is calculated by Arrhenius reaction source of the reaction k as below:

$$k_{sk} = A_k T^{\beta k} \exp\left(-\frac{Ea}{RT}\right) \prod_{i=1}^{Ns} \Theta_i^{\mu_{ik}} \exp\left[\frac{\varepsilon_{ik}\Theta_i}{RT}\right] \tag{4}$$

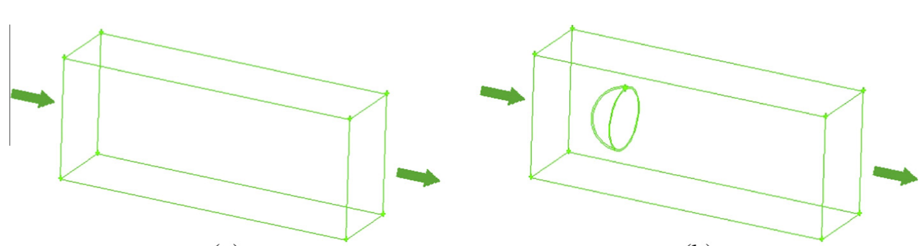
where A_k is the pre-exponential factor, Ea is the activation energy of reaction k, β_k is the temperature exponent, Θ_i is the surface coverage rate of species i, ε_{ik} and μ_{ik} are surface coverage parameter. In addition, $[X_i]$ is written as below:

$$[X_i] = \Gamma \Theta_i \tag{5}$$

Here, Γ is surface site density of the catalyst. The value of 2.72×10^{-9} mol cm^{-2} is used for the Rh catalyst in this paper. The surface of the catalytic is described by its coverage with adsorbed species and temperature. The temperature is based on the governing equation for enthalpy as below:

Momentum equation:

$$\frac{\partial}{\partial X_j}(\rho u_j u_i) = -\frac{\partial p}{\partial X_j}\left[\mu\left(\frac{\partial u_i}{\partial X_j} + \frac{1}{3}\frac{\partial u_j}{\partial X_i}\right)\right] \tag{6}$$



(a) (b)

Fig. 1. Structural diagram of the micro-combustor: (a) without a hollow hemispherical bluff body, (b) with a hollow hemispherical bluff body.