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Numerical investigation on hydrogen/air non-premixed combustion in a three-dimensional micro combustor

Jiaqiang E [a,b,d], Qingguo Peng [a,b,d,*], Xueling Liu [c,*], Wei Zuo [a,b,d], Xiaohuan Zhao [a,b,d], Haili Liu [b,d]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
[b] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China
[c] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University, Tianjin 300072, China
[d] Institute of New Energy and Energy-saving & Emission-reduction Technology, Hunan University, Changsha 410082, China

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ABSTRACT

In order to obtain a higher combustion efficiency and a lager heat transfer from outer wall, a new type of micro cylindrical combustor with suction pipe, mixing pipe, diffuser pipe and shrinkage pipe and the combination of cavity and backward-facing step is designed and a numerical investigation on non-premixed hydrogen/air reacting flow inside three micro combustors has been carried out at atmospheric pressure. Moreover, the combustion characteristics and working performance of micro combustors are also investigated. Results show that the cavity and the backward-facing step in micro combustor is useful for the heat recirculation and the flame stability. Moreover, the combustion efficiency and the heat transfer from outer wall can be improved by increasing the length of combustion chamber within limited range. A high and uniform outer wall temperature distribution is desirable for the L_2 micro combustor, therefore, the L_2 micro combustor is more suitable for the micro thermo photovoltaic (MTPV) system when hydrogen volume flow rate is equal to 150 mL/min and equivalence ratio φ is equal to 1.0.

1. Introduction

With the development of MEMS (Micro Electro Mechanical Systems), the micro-power system has been developed rapidly. As a key component of micro power-system, researches on micro-combustion characteristics have become a focus recently. As for the micro power-system with the small dimension and high rate of heat loss, hydrogen was regarded as one of the most promising and cleanest fuels in micro-combustion with high power density, longevity, small volume and light weight. Many prototypes of micro power devices have been built such as micro thermo photovoltaic (TPV) systems, micro fuel cells, micro gas turbines and others [1–4].

Recently, researches about micro TPV are more likely focus on combustion characteristics in micro combustor [5]. Hosseini and Wahid [6] investigated the characteristics of lean premixed conventional micro-combustion and lean non-premixed flameless regime of methane/air. Lee et al. [7] studied the combustion characteristics of premixed hydrocarbon/air micro flames at normal and elevated temperatures. Then, Zhang et al. [8] investigated combustion characteristics in a cube micro combustor with a hollow hemispherical bluff body. Tang et al. [9] analyzed the combustion characteristics with the differences in flame stabilization, temperature distribution of external wall and flammable channel-heights. Scholars also did researches on homogeneous combustion in micro combustor. Chen et al. [10] studied the hetero-/homogeneous combustion characteristics and flame stability of lean premixed propane–air mixtures over platinum in micro combustors. Wang et al. [11] investigated the catalytic combustion characteristics concerning homogeneous charge compression ignition in micro power device. As for flame, Wan et al. [12,13] investigated the flame-anchoring mechanisms in terms of interplays between flow field, heat recirculation, chemical reaction and preferential transport of species. Hossain and Nakamura [14] studied the thermal and chemical structure formed in the micro burner potentially leading to the unique stability mechanism of miniaturized jet diffusion flame via excess heat recirculation through the burner wall.

Previous studies of micro combustion had emphasized thermal performance and flame stability in combustors. Li et al. [15] analyzed the heat transport occurring in three fuel–air mixtures to

* Corresponding authors at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China (Q. Peng); Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University, Tianjin 300072, China (X. Liu).

E-mail addresses: pengqingguo317@163.com (Q. Peng), lxling@tju.edu.cn (X. Liu).

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Nomenclature

$F_{h,j}$	the energy flux of the x_j direction, W
h	the enthalpy of gas composition, J/kg
h_w	the convective heat transfer coefficient, W/(m^2·K)
$J_{l,j}$	the diffusion flux of species l in the x_j direction, kmol/(m^2·s)
$m_{H2,in}$	the inlet hydrogen mass flow rate, kg/s
$m_{H2,out}$	the outlet hydrogen mass flow rate, kg/s
M_l	the molar mass of species l
m_l	the mass fraction of species l
p	the pressure, Pa
$q_{H2,in}$	the inlet hydrogen volume flow rate, mL/min
$q_{H2,out}$	the outlet hydrogen volume flow rate, mL/min
$q_{air,in}$	the air mass flow rate, kg/s
Q_o	the heat dissipating capacity of the outer wall, W
R_l	the production rate of species l by chemical reaction, kmol/(m^3·s)
R_0	the universal gas constant, J/(mol·K)
$T_{w,o}$	the temperature of the outer wall, K
$\overline{T}_{w,o}$	the mean temperature of the outer wall, K
T_∞	the ambient temperature, K
u_i	the velocity component of x_i (i = 1,2,3) direction, m/s

Greek letters

ε	the emissivity of the wall
η	the combustion efficiency
λ_w	the thermal conductivity of the wall, W/(m·K)
ρ	the gas density, kg/m^3
σ	the Stephan-Boltzman constant, 5.67×10^{-8} W·m^2/K^4
τ_{ij}	the stress tensor, N
φ	the equivalence ratio
σ_T	the temperature variance of the outer wall, K
ΔT_{mtd}	the maximum temperature difference of outer wall, K

account for the difference of fuel property in terms of the kinetics in the cylindrical micro combustors. Vijayan and Gupta [16,17] found that positive effect of recirculation on the wall temperature and the overall energy conversion efficiency in recirculating combustors. Heat recirculation is an effective strategy to maintain combustion and to improve combustion limits in micro-scale system [18]. Yang et al. [19] conducted test to study the combustion of hydrogen–air mixture in a micro-cylindrical combustor with and without a heat recuperator. Yan et al. [20] researches on premixed combustion of a methane/air mixture in a heat recuperation micro-combustor with corundum material. Another aspect of researches on micro combustion is flame stability, Wang et al. [21] tested with its surface heat loss and flame stability controlled by wind at different temperatures. Bagheri and Hosseini [22] researched on flame stability and thermal performance of two different heat recirculation micro combustors, found that inner reactor heat recirculation micro combustor profoundly affects flame characteristic and stability, while bututer reactor heat recirculation presents a higher range of emitter efficiency. Stazio [23] investigated flame behaviors with different flow velocity. Li et al. [24] studied on fundamental flame characteristics of premixed hydrogen/air combustion in a planar porous micro combustor, found that the flame speed was in a linear relation with the inlet flow velocity.

To achieve stabilized combustion in micro combustor, some measures have been implemented. For example, backward-facing step or bluff body is a useful measure to reduce the velocity of gas locally, which is widely used in studies of micro combustor [25–27]. The turbulent micro combustion premixed bluff-body stabilized flames and 3D flame orientation were investigated by Magnotti and Barlow [28]. Lee et al. [29] and Niu et al. [30] made researches on the bluff-body stabilized flames. There also exist other useful measures to obtain stabilized flame in micro combustor. Hsueh et al. [31] established a three-dimensional model of a plate methanol steam micro-reformer and a methanol catalytic combustor with parallel flow fields and serpentine flow fields. Li et al. [32] added porous medium to enhance the heat transfer and flame stabilities.

Moreover, some structural designs of the combustors were applied to enhance the distribution characteristics of the outer wall temperature [33,34]. Hua et al. [35] performed numerical simulations to study the combustion of premixed hydrogen–air mixture in a series of chambers with the same shape aspect ratio but various dimensions from millimetre to the micron level. In order to overcome the critical heat loss and flame instability, Li et al. [36] designed a novel combustion chamber which used a percolated platinum tube as catalyst, emitter, and flame stabilizer. A hydrogen-fuelled micro combustor of simple construction was designed by Jejurkar and Mishra [37], which utilized the external thermal recirculation by a hollow nitrogen-filled tube inserted in the flame. Benedetto et al. [38] investigated into the opportunity of setting up a novel scheme of micro combustor divided into two parts the catalyst-coated wall and the catalyst absent wall. Su et al. [39] proposed a double-cavity micro combustor, Tang et al. [40] and Su et al. [41] designed multiple-channel micro combustors for the application of micro TPV system.

In order to obtain a higher combustion efficiency and a lager heat transfer from outer wall, a new type of micro cylindrical combustor with suction pipe, mixing pipe, diffuser pipe and shrinkage pipe and the combination of cavity and backward-facing step will be designed and investigated based on non-premixed H_2-air burned in a three-dimensional micro combustion. And the heat performance of burned gas and the wall will also give careful consideration. Furthermore, the effects of different geometries on the energy conversion efficiency of the micro combustor will be studied. This investigation results will offer some useful information for the design and operation of the micro-combustor, and give some reference to understand the combustion characteristics and heat performance of the micro combustor.

2. Mathematical-physical model of combustor

2.1. Physical model of micro combustor

A new type of micro cylindrical combustor is proposed as shown in the left side of Fig. 1. In order to enhance the inhalation efficiency of the gas and the mixing performance of hydrogen/air, the model is established with suction pipe, mixing pipe, diffuser pipe and shrinkage pipe. Hydrogen enters into the micro combustor by the central circular channel of suction pipe A, and air through the outer annular channel into it. The shrink-shaped suction pipe A can obtain the oblique velocities of air and hydrogen which toward the centerline. Oxygen and hydrogen are mixing in the mixing pipe B, in addition, the diffuser pipe C is set up to make dynamic pressure partly transform into static pressure which increases the pressure difference, also the suction efficiency is improved through diffuser pipe C, while the shrinkage pipe D is provided to prevent tempering. The effectively combination of