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Effect of thermal conductivity of solid wall on combustion efficiency of a micro-combustor with cavities

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ABSTRACT

We recently developed a micro cavity-combustor which has a strong ability in flame stabilization and is promising to be used in micro power generation apparatus for MEMS and micro propulsion systems. In the present paper, the effect of wall thermal conductivity on the combustion efficiency of lean H_2/air flame was numerically investigated. It is shown that the decrease of combustion efficiency is due to flame-tip opening at high velocity. For the convenience of quantitative comparison, a "flame-splitting limit" was defined as the critical velocity when the combustion efficiency drops to 80%. It is very interesting to find that the flame-splitting limit exhibits a non-monotonic variation with the wall thermal conductivity. The analysis reveals that, for a larger thermal conductivity, the heat recirculation effect on the fresh mixture is better, which leads to higher flow velocity at the cavity exit; therefore, the flame front suffers stronger stretching effect and is splitted at a lower velocity. However, for a smaller thermal conductivity, the flow velocity in the central region of far downstream becomes faster, which results in stronger flame-stretching effect and smaller flame-splitting limit. In summary, a moderate thermal conductivity is advantageous to achieve high combustion efficiency.

1. Introduction

With the rapid development of MEMS (Micro-Electro-Mechanical Systems) technology, the demand for micro power generation devices and systems becomes more and more urgent. The current primary power sources for portable electronics are conventional electrochemical batteries. However, batteries have some disadvantages including a short life span, long recharging period and low energy density. Micro power generation apparatus utilizing combustion energy are considered to be promising alternatives due to the much higher energy densities involved in the hydrocarbon fuels [1,2]. A high combustion efficiency of the micro combustor is vital for the whole energy conversion system.

However, there exist some challenges to maintain a stable combustion in micro-combustors. At first, the large surface-area-to-volume ratio leads to a drastic increase of heat-loss ratio when the combustor is scaled down. Moreover, the residence time of gaseous mixture flowing through the combustor is very short, which sometimes makes it very hard to achieve a complete combustion [2]. Due to those problems, various unstable flames occur in micro- and meso-scale combustors [3–5]. Hence, it is vital to develop flame stabilization technologies under small scales.

By far, many methods have been applied to promote flame stability in micro- and meso-scale combustors. Heat management is a frequently-used method to stabilize flame in small combustors. Kuo and Ronney [6] studied the combustion characteristics in heat-recirculating type "Swiss-roll" combustors, and results showed that the heat recirculation effect can significantly extend the operational limits of inlet velocity. Cao and Xu [7] pointed out that the micro-flame can be stabilized in a micro annular combustor with a wide operating range. Li et al. [8] inserted porous media into micro planar combustor to anchor flame, and higher and uniform wall temperature distribution was achieved. Jiang et al. [9,10] proposed a miniature combustor with porous wall which can enhance flame stability due to the reduction of heat-loss amount and the preheating effect of fresh mixture. Moreover, catalytic combustion is a good way to stabilize flame under small scales. Wang et al. [11] investigated the catalytic combustion for premixed hydrogen/air mixture in a micro-tube made of alumina ceramic, and the catalyst can improve the flame stability remarkably. Li et al. [12] studied the effect of catalyst segmentation on $H_2/CO/CH_4$ blended fuel, and results revealed that the catalytic reaction can produce active radicals and release heat to induce the homogeneous reaction. To form a recirculation zone or low-velocity zone in the flow field is another effective way to stabilize flame in micro-combustors.

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Yang et al. [13,14] investigated flame stability in micro-scale combustors with one backward facing step. They found that flames can remain stable in different combustors configurations over wide ranges of inlet velocity and equivalence ratio. Khandelwal et al. [15] experimentally studied the flame stabilization in a micro combustor with three rearward steps, and the flame can be anchored with improved flammability limits. Wan et al. [16] developed a micro combustor with bluff body which can greatly enlarge the flame blow-off limit. Later, Hossein and Wahid [17] studied flameless combustion in a micro bluff-body combustor. They found that the wall temperature is moderate and uniform in the flameless mode, and the fuel-oxidizer consumption rate is lower than conventional combustion.

Hydrogen is considered to be a good fuel for micro combustors due to its high burning rate and heat value. Recently, our group [18] studied the combustion characteristics of lean H_2/air flames in a micro cavity-combustor with a 1.0-mm height. The flame-tip opening phenomenon, which usually occurs in stretched premixed flames with a sub-unity Lewis number [19], was confirmed at high inlet velocities. The flame-tip opening leads to large amount of fuel leakage and a sharp decrease of combustion efficiency. For the convenience of a quantitative comparison, a "flame-splitting limit" was defined as the critical inlet velocity when the combustion efficiency drops to 80% [18]. Very recently, we [20] examined the impact of combustor height on the flame-splitting limit of lean H_2/air flames in this micro cavity-combustor. It is very interesting to find that the flame-splitting limit exhibits a non-monotonic dependence on the combustor height. It is well known that heat conduction in the solid wall plays a vital role in combustion performance of micro-combustors [21,22], therefore, in the present work we numerically investigate the effect of thermal conductivity of solid wall on the combustion efficiency of lean H_2/air flame in this micro cavity-combustor.

2. Numerical methods

2.1. Geometric model

The schematic diagram of the micro combustor with cavities is depicted in Fig. 1. The total length (L_0) is 18.0 mm. The distance between the vertical cavity wall and combustor entrance (L_1) is 3.0 mm, and the wall thickness (W_3) is 2.0 mm. The gap distance (W_1) and width (W_0) of the micro combustor are 1.0 mm and 10.0 mm, respectively. The angle (θ) between the ramped cavity wall and downstream inner wall is 45°. The length (L_2) and depth (W_2) of the cavities are 3.0 mm and 1.0 mm, respectively.

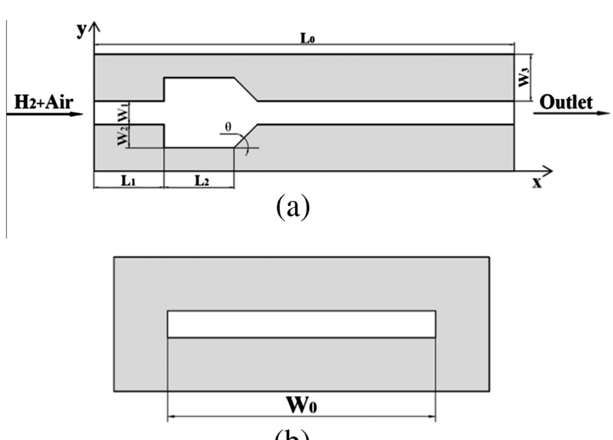

Fig. 1. Schematic diagram of the micro cavity-combustor: (a) longitudinal cross section, (b) combustor exit.

2.2. Mathematical model

Here, the value of Knudsen number, $K_n = L_g/L_c$ was first estimated, where L_g is the mean free path of gas and L_c is the characteristic scale of channel. Calculation demonstrates that the order of magnitude of K_n is 10^{-5} for both CH_4 and O_2, which is much less than the critical value 10^{-3}. Therefore, the Navier–Stokes equations are still applicable to the present work [23]. Kuo and Ronney [6] pointed out that the turbulence models are more suitable for premixed flame in micro-combustors when the Reynolds number (Re) is above 500. Our previous works [16,18,20] also verified the suitability of "realizable *k-epsilon*" turbulence model for micro combustor with bluff body and cavities. Thus, this model was adopted in the current work. For the present micro-combustor, the corresponding critical inlet velocity for $Re = 500$ is approximately 8 m/s. As the aspect ratio (W_0/W_1) of the micro-combustor is large enough (10:1), a two-dimensional steady-state model was applied. Governing equations for the gaseous mixture are shown below.

Continuity:

$$\frac{\overline{\partial(\bar{v}_x + v'_x)}}{\partial x} + \frac{\overline{\partial(\bar{v}_y + v'_y)}}{\partial y} = 0 \tag{1}$$

Momentum:

$$\frac{\partial(\rho \bar{v}_i \bar{v}_j)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\eta \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u'_i u'_j}\right) \quad (i = 1, 2) \tag{2}$$

Energy:

$$\frac{\partial(\rho v_x C_p T)}{\partial x} + \frac{\partial(\rho v_y C_p T)}{\partial y} = \frac{\partial((\lambda_f + \lambda_{ft})\partial T)}{\partial x^2} + \frac{\partial((\lambda_f + \lambda_{ft})\partial T)}{\partial y^2} + \sum_i \left[\frac{\partial}{\partial x}\left(C_{p,i} T \rho D_{m,i} \frac{\partial Y_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(C_{p,i} T \rho D_{m,i} \frac{\partial Y_i}{\partial y}\right)\right] + \sum_i C_{i,p} T R_i \tag{3}$$

Species:

$$\frac{\partial(\rho Y_i v_x)}{\partial x} + \frac{\partial(\rho Y_i v_y)}{\partial y} = \frac{\partial}{\partial x}\left(\rho D_{m,i} \frac{\partial Y_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho D_{m,i} \frac{\partial Y_i}{\partial y}\right) + R_i \tag{4}$$

where Y_i, R_i, $C_{p,i}$ denote the mass fraction, generation or consumption rate, and specific heat capacity of species *i*, respectively; while λ_f and λ_{ft} are thermal conductivity and turbulent thermal conductivity of the fluid, respectively.

Turbulence energy k and turbulence dissipation rate ε in transport equations of are given in Eqs. (5) and (6), respectively.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{5}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 E\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon\varepsilon}} \tag{6}$$

where $C_1 = \max\left(0.43, \frac{\eta}{\eta+5}\right)$, $C_2 = 1.9$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.2$.

The mixture density was calculated using the ideal gas assumption, while the specific heat, thermal conductivity and viscosity were computed from a mass-fraction-weighted average of the species' properties, which are shown below.

$$\text{Viscosities}: \quad \mu = \sum_i Y_i \mu_i, \text{with} \quad \mu_i = 2.67 \times 10^{-6} \frac{\sqrt{M_W T}}{\sigma^2 \Omega_\mu} \tag{7}$$

$$\text{Specific heat}: \quad C_{Pf} = \sum_i Y_i C_{P,i}, \quad \text{with} \quad C_{P,i} = \frac{1}{2}\frac{R}{M_{w,i}}(f_i + 2) \tag{8}$$

$$\text{Thermal conductivity}: \quad \lambda_f = \sum_i Y_i \lambda_{f,i}, \quad \text{with}$$

$$\lambda_{f,i} = \frac{15}{4}\frac{R}{M_{w,i}}\mu_i\left[\frac{4}{15}\frac{C_{P,i} M_{w,i}}{R} + \frac{1}{3}\right] \tag{9}$$