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Effect of reduced pressures on the combustion efficiency of lean H_2/air flames in a micro cavity-combustor

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ABSTRACT

The effect of reduced pressures (i.e., $p = 1.0$ atm, 0.8 atm and 0.5 atm) on the combustion efficiency of lean H_2/air flames in a micro-combustor was investigated in this work. We found that the combustion efficiency increases as the pressure is reduced from 1.0 atm to 0.8 atm, and then decreases when the pressure is further reduced from 0.8 atm to 0.5 atm. Numerical analyses reveal that when the pressure is reduced to 0.8 atm, the laminar burning velocity, the heat release rate and the effective Lewis number are increased, while the stretch rate is decreased. The combined effects of these aspects retard the occurrence of "flame tip opening" and lead to a higher combustion efficiency. When the pressure is further reduced to 0.5 atm, the fuel supply and heat release amount are significantly reduced, resulting in much lower temperature level and weaker reaction intensity. Meanwhile, the heat-loss ratio is almost doubled. Therefore, the combustion is completely extinguished in the downstream channel and a large amount of fuel leaks out without burning. As a consequence, the combustion efficiency decreases drastically.

Introduction

Microscale combustors for micro-power generation and micro-propulsion systems have received extensive attention in the past decades due to the much higher specific energy of hydrocarbon fuels compared to conventional electrochemical batteries [1]. However, it is a tough task to sustain a stable flame with high combustion efficiency because of the increased heat-loss ratio resulting from a large surface-area-to-volume ratio [2]. Moreover, the residence time is also significantly reduced at small scales, which might lead to an incomplete conversion of the fuel.

Various strategies have been put forward to improve the flame stability in micro-combustors. Heat-recirculating type configurations, which can reuse part of the heat released and reduce the heat loss, are frequently employed. For instance, the "Swiss-roll" structure [3–5] and porous media [6,7] were applied to micro-combustors for flame stabilization. Other structures include planar micro-combustors with parallel separating plates [8] and miniature combustors with a porous wall [9]. Recently, Wan et al. [10] investigated the flame blowout limit of a micro-combustor with preheating channels and a plate flame holder. They found the optimum length of the flame holder at which a largest blowout limit was obtained.

Catalytic combustion is a viable way to attenuate the radical-quenching effect of wall surfaces [11]. Maruta et al. [12] investigated catalytic combustion of CH_4/O_2 mixture in a tube coated with platinum catalyst. Suzuki et al. [13] explored

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catalytic combustion of butane in a micro-combustor with tailored porous alumina. Chen et al. [14] designed segmented catalyst with inert intervals to improve the effect of catalytic combustion. Li et al. [15] numerically studied the effects of catalyst segmentation with wall cavities on the combustion characteristics of CH_4/O_2 mixture. Their results confirm that the catalytic reaction plays a positive role in micro combustion. The effects of heterogeneous–homogeneous interaction on the homogeneous ignition in hydrogen-fueled catalytic micro-reactors were numerically investigated by Chen et al. [16]. Tang et al. [17] investigated combustion characteristics of three hydrocarbon fuels in a micro-planar combustor. They found that under the same chemical energy inputs, the external wall temperature distribution of methane case is most uniform and the average wall temperature is also the highest among the three fuels. Yan et al. [18] numerically studied hydrogen-assisted catalytic combustion of methane. It is shown that the ignition temperature decreases considerably when hydrogen content of the blended fuel is increased with a fixed equivalence ratio.

Forming a recirculation zone or a low velocity zone in the flow field is an effective measure to anchor the flame in micro flow reactors. For example, Yang et al. [19] experimentally investigated H_2/air combustion in a converging–diverging micro tube and found that the range of inlet velocity for stable combustion was significantly expanded. Wan et al. [20] and Fan et al. [21] developed micro bluff-body combustors which can greatly increase the blow-off limit of lean H_2/air flames. Recently, Wan et al. [22] experimentally explored the flame stability of CH_4/air mixtures in a mesoscale channel with wall cavities. It was shown that the flame blow-off limits were several times the corresponding burning velocities of incoming mixtures. As for lean H_2/air flames in micro-channels with wall cavities, although large blow-off limits can also be achieved, they [23,24] found that the “flame tip opening phenomenon” occurred at relatively high inlet velocities.

Once the “flame tip opening phenomenon” occurs, the fuel leaks from this gap and leads to a sharp drop in the combustion efficiency. Due to complicated interactions between heat and mass transfer, fluid flow and chemical reactions, some geometrical parameters and thermophysical properties of the walls show non-monotonic effects on the combustion efficiency [25,26]. In the present work, we investigate the effect of reduced pressures on the combustion efficiency of lean H_2/air flames in the micro-combustor with wall cavities. Owing to the inconvenience to conduct experimental detection in the narrow channel of 1.0-mm separation, we adopt numerical method to examine and analyze the complicated phenomena and processes which occur in this micro-combustor with wall cavities.

Numerical methods

Geometric model

The micro-combustor with dual cavities is schematically shown in Fig. 1. The length (L_0), width (W_0) and height (W_1) of the channel are 18 mm, 10 mm and 1 mm, respectively. The wall thickness (W_3) is 2 mm. The distance (L_1) from the channel inlet to the vertical cavity wall is 3 mm. The length (L_2) and depth (W_2) of the cavity are 3 mm and 1 mm, respectively. The acute angle (θ) between the ramped cavity wall and interior channel wall is 45°. The origin of the coordinates is also illustrated in Fig. 1a.

Mathematical model

Here, we first assess the suitability of the Navier–Stokes equations. For this, we calculate the Knudsen number, $K_n = L_g/L_c$, where L_g is the mean free path of gas and L_c is the characteristic dimension of the micro-channel (i.e., channel height, W_1). It comes out that the orders of magnitude of K_n are 10^{-5} for both H_2 and O_2, which are two orders less than the criterion of 10^{-3} [27]. Hence, the Navier–Stokes equations are still applicable to the current work. Kuo and Ronney [5] reported that a satisfactory prediction of the combustion characteristics in micro-combustors can be obtained using the “*k-epsilon*” turbulence model when $Re > 500$. Our previous work [23] also verified the suitability of the “*k-epsilon*” turbulence model through a comparison between predicted and measured data. Thereby, this model is employed in the present work. Meanwhile, because the effects of heat recirculation and heat loss play an important role in combustion characteristics in micro-channels, the heat conduction in the solid walls is considered in the computation. Furthermore, due to the large aspect ratio (W_0/W_1 = 10:1) of the micro-combustor, a two-dimensional, steady-state model is used to reduce the computational load.

Computation scheme

The quartz glass was chosen as the solid material whose density (ρ), thermal conductivity (λ_s), specific heat capacity (c_p) and surface emissivity (ε) were 2650 kg/m^3, 1.05 W/(m K), 750 J/(kg K) and 0.92, respectively [28]. Our previous work [23] showed that for lean mixtures with an equivalence ratio of $\phi < 0.5$, the flame was prone to tip opening. Therefore, $\phi = 0.4$ was chosen in this paper. The density of gaseous mixture was computed using the ideal gas assumption, with the specific heat, viscosity and thermal conductivity obtained from a

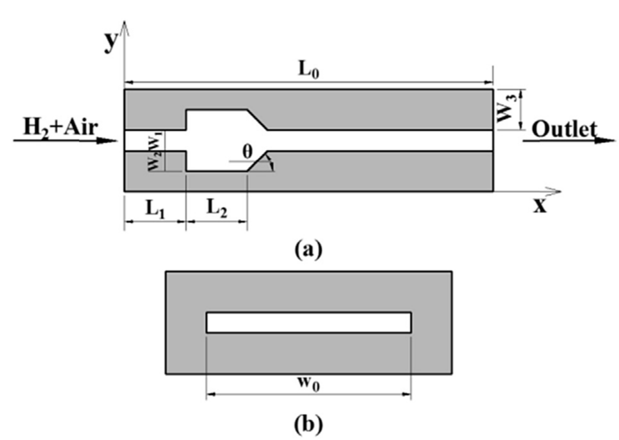

Fig. 1 – Schematic diagram and coordinates of the micro-channel with dual cavities: (a) longitudinal cross section, (b) combustor exit.