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Effect of the length of a plate flame holder on flame blowout limit in a micro-combustor with preheating channels

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ABSTRACT

It is challenging to achieve a large blowout limit for micro-combustors due to the increased heat loss ratio and reduced residence time. For this, we recently developed a micro-combustor with a plate flame holder and two preheating channels. In this paper, the effect of the plate length (L_b = 0.5, 1.0, 2.0, 3.0, 4.0, 5.0 and 6.0 mm) on the blowout limit of CH_4/air flames was numerically investigated. The results show that the flame blowout limit increases firstly and then decreases with an increasing plate length. The largest blowout limit is obtained at L_b = 1.0 mm. Three neighboring cases, i.e., L_b = 0.5, 1.0 and 2.0 mm, are taken to analyze the underlying mechanisms responsible for this non-monotonic trend. The flame blowout process demonstrates that, the flame is extinguished due to "pinch-off phenomenon" at high inlet velocity, and the shorter the distance between the upper and lower flame fronts, the smaller the blowout limit will be. Numerical analysis reveals that the differences in flame blowout limits are a result of the combined effects of heat recirculation and local flow field at the entrance of the combustion chamber. The heat recirculation effect grows stronger with a decreasing length of flame holder, which results in a more obvious volumetric expansion at the entrance of the combustion chamber. Meanwhile, the plate flame holder has a redirection effect on the local flow field. As a result, the gaseous mixture enters the combustion chamber with a smallest acute angle in the case of L_b = 1.0 mm, which leads to a largest distance between the upper and lower flame fronts and a longest recirculation zone. Consequently, the flame blowout limit reaches a peak at L_b = 1.0 mm. The present work provides an important guideline to design such kind of micro combustors.

1. Introduction

With the rapid development of Micro-Electro-Mechanical Systems technology, the demand for micro power generation devices becomes increasing urgent. Currently, the power sources for portable electronics and micro propulsion systems are conventional electrochemical batteries. However, the batteries have disadvantages including a long recharging period, a low energy density and a short life span. Combustion-based micro power generation apparatuses are considered to be promising alternatives due to the much higher energy densities of hydrocarbon fuels [1–3]. A wide stable operational range of the micro combustor is vital to the whole energy conversion system.

Nevertheless, it is challenging to maintain a stable flame in micro combustors. In the first place, the large surface-area-to-volume ratio leads to a sharp increase in the heat-loss ratio when the combustor dimension is reduced. Moreover, the residence time of gaseous mixture is sometimes insufficient to obtain a complete combustion. Owing to those difficulties, various unstable flames occur in micro- and meso-scale combustors [4–7]. Hence, it is crucial to develop effective flame stabilization technologies for small burners.

By far, various approaches have been employed to improve flame stability in micro- and meso-scale combustors. Thermal management is a frequently adopted strategy to anchor flames in small combustors. The Swiss-roll configuration has been implemented by Kim et al. [8] and Kuo and Ronney [9] to stabilize very lean flames in miniature combustors with expanded operational limits of inlet velocity. Liu et al. [10] investigated the effect of wall thermal conductivity on the flame stability of a mesoscale channel with fibrous porous medium. Their work show that the stationary flame regime is extended with the decrease of the wall thermal conductivity. Kang and Veeraragavan [11] point out that the flame stability limit of a mesoscale combustor grows larger when it is made of thermally orthotropic material comparing to conventional isotropic material.

Another effective way of flame stabilization for miniature combustors is to form a recirculation zone in the flow field by using a

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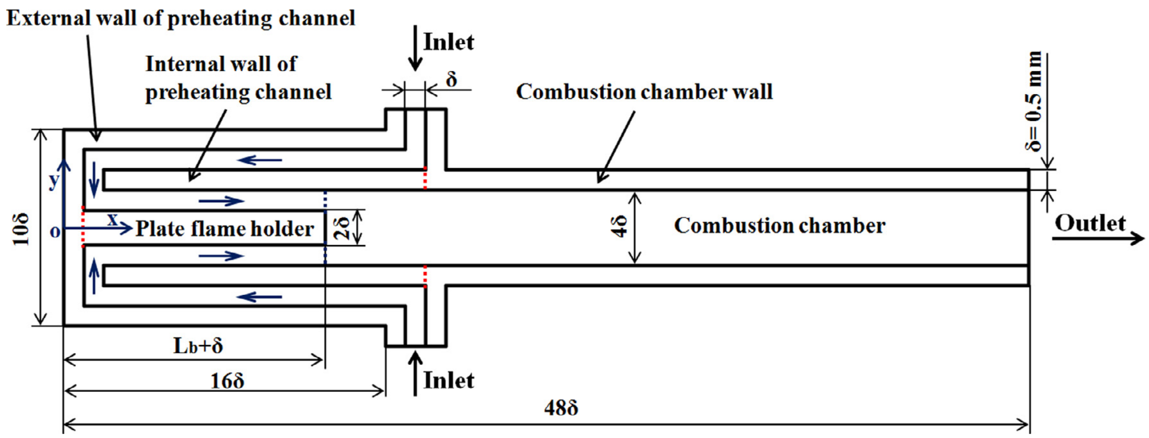

Fig. 1. Schematic of the micro-combustor with a plate flame holder and two preheating channels.

flame holder. Yang et al. [12] studied the flame stability in micro combustors with a backward facing step. Khandelwal et al. [13] experimentally investigated the performance of a micro combustor with three rearward steps. Their results showed that the flame stability limits can be expanded significantly. Fan et al. [14,15] developed a micro bluff-body combustor with excellent flame stabilization performance. Recently, Wan et al. [16–18] investigated flame behaviors of CH_4/air and H_2/air mixtures in micro- and meso-scale combustors with wall cavities. It was demonstrated that the flame stability was greatly improved and stable symmetric flames were observed over a wide range of inlet velocity.

Motivated by the aforementioned works, we recently [19] developed a micro combustor with a central plate (acts as a flame holder) and two preheating channels. This configuration can make full advantages of both the flow recirculation effect and heat recirculation effect. The results show that very lean CH_4/air flames ($\phi = 0.6$) can be stabilized in the combustion chamber which is narrower than the corresponding quenching distance of the incoming mixture due to the heat recirculation effect via preheating channels. On the other hand, a large flame blowout limit can be obtained owing to the existence of a plate flame holder. For this configuration, several factors, including the lengths of both the plate flame holder and the preheating channels, and the material type of solid walls, have important effects on the overall performance of heat recirculation, local flow field and flame stability. In the present work, we are dedicated to investigate the effect of the plate length on blowout limits of premixed CH_4/air flames, which can provide a guideline to design such kind of micro-combustors. The underlying mechanisms were analyzed in terms of heat recirculation, local flow field and their combined effects.

2. Numerical methods

2.1. Geometric model

A two-dimensional, symmetric rectangular combustor with a plate flame holder and two preheating channels is schematically shown in Fig. 1. For the sake of a clear discussion, the whole combustor channel is divided into two segments, namely, the preheating channels and the combustion chamber, as indicated by the vertical blue dashed lines at the right end of the central plate. In addition, the solid wall is divided by the red dashed lines into six segments, i.e., the plate flame holder, one external wall of the preheating channels, two internal walls of the preheating channels, and two combustor chamber walls. The geometry dimensions are also given in Fig. 1. The inlet width and wall thickness (δ) are both 0.5 mm. Seven values of the plate length (L_b) are selected for comparison, i.e., $L_b = 0.5$, 1.0, 2.0, 3.0, 4.0, 5.0 and 6.0 mm, respectively. The origin of coordinates is located at the middle point of the left side of the micro combustor.

2.2. Mathematical model

We first estimate the value of 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 scale of the channel. The order of magnitude of K_n is 10^{-5} for the CH_4/air mixture, which is much less than the critical value of 10^{-3}. Hence, the gaseous mixture can be reasonably regarded as a continuum and the Navier–Stokes equations are still applicable to the present study [20]. The largest Reynolds number of the incoming cold mixture is around 430. Hence, a laminar model was used in the computation. Additionally, we used a steady-state model for most cases in which the flame is stable, and only adopted the unsteady model for near-limit cases. Considering the computational accuracy and cost, a time step of 1.0×10^{-5}s was selected. It was determined based on the requirement of the Courant number (the ratio of time step to grid size) for unsteady sate simulation [21]. Governing equations for the mixture are shown below.

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) = 0 \tag{1}$$

Momentum:

$$X\text{ direction}: \frac{\partial(\rho v_x)}{\partial t} = -\left[\frac{\partial(\rho v_x v_x)}{\partial x} + \frac{\partial(\rho v_x v_y)}{\partial y}\right] - \frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} \tag{2}$$

$$Y\text{ direction}: \frac{\partial(\rho v_y)}{\partial t} = -\left[\frac{\partial(\rho v_y v_x)}{\partial x} + \frac{\partial(\rho v_y v_y)}{\partial y}\right] - \frac{\partial p}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} \tag{3}$$

Energy:

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho v_x h)}{\partial x} + \frac{\partial(\rho v_y h)}{\partial y} = \frac{\partial\left(\lambda_f \partial T_f\right)}{\partial x^2} + \frac{\partial\left(\lambda_f \partial T_f\right)}{\partial y^2} + \sum_i \left[\frac{\partial}{\partial x}\left(h_i \rho D_{m,i} \frac{\partial Y_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(h_i \rho D_{m,i} \frac{\partial Y_i}{\partial y}\right)\right] + \sum_i h_i R_i \tag{4}$$

Species: