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Effect of channel gap distance on the flame blow-off limit in mesoscale channels with cavities for premixed CH_4/air flames

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HIGHLIGHTS

- Flame blow-off limit of a mesoscale channel with cavities was experimentally studied.
- The effect of channel gap distance on flame blow-off limit was numerically analyzed.
- Heat loss rate from flame to cavity wall increases with the decrease of channel gap.
- Preheating effect on fresh mixture becomes more pronounced for larger channel gaps.
- Interplay between heat transfer and chemical reactions is vital for flame stability.

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ABSTRACT

The development of simple and effective flame stabilization methods is crucial for micro- and mesoscale combustors. In the present paper, flame stability in a mesoscale channel with cavities was experimentally investigated, and the effect of the channel gap distance on the flame blow-off limit was examined. Experimental results demonstrate that the stable operational range of the combustor is extended in the presence of cavities, which act as a flame holder. Meanwhile, the flame blow-off limit increases as the channel gap distance is increased. Numerical simulation was conducted to facilitate analysis of the underlying mechanisms responsible for the differences in flame blow-off limits. Analyses reveal that effects of heat loss and heat recirculation are the two dominant factors that lead to different blow-off limits. First, the heat recirculation effect is more prominent for a larger channel gap distance, which exhibits much more intense initiation reactions. In addition, with the decrease of the channel gap distance, the heat loss rate from the flame root becomes larger, and the flame root is liable to be thermally quenched by the cavity walls. In conclusion, the fresh mixture is better preheated by the recirculated heat, and the heat loss rate from the flame root is also lower when the channel gap distance is larger. Hence, a larger flame blow-off limit can be expected for a channel with a wider gap.
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1. Introduction

Micro- and mesoscale combustion has received extensive attention in past decades, primarily due to the considerably higher energy densities of hydrocarbon fuels compared with batteries. Owing to this major advantage, combustion-based micro-power-generation devices are considered a viable alternative for providing power for micro-electro-mechanical systems (MEMS) and micro propulsion systems in the future (Fernandez-Pello, 2002; Maruta, 2011).

It is a challenge to obtain a stable flame over a wide range of operating conditions for smaller combustors. This difficulty is observed primarily because of the increased heat losses that result from the large surface-area-to-volume ratio of micro- and mesoscale combustors (Fernandez-Pello, 2002; Maruta, 2011). Another critical issue is the reduced residence time of the gaseous mixture in miniaturized combustors. Various flame dynamics have been reported hitherto (Maruta, 2011). For instance, flames with repetitive extinction and ignition (FREI) were observed in heated micro-tubes (Maruta et al., 2005). Later, similar flame dynamics were confirmed and interpreted by many other researchers (Choi et al., 2009; Fan et al., 2009; Jackson et al., 2007; Minaev et al., 2007; Nakamura et al., 2012; Pizza et al., 2008). In addition, a variety of non-stationary flame patterns, such as rotating Pelton-wheel-like flames and spiral-like flames, were observed in heated radial micro-channels (Fan et al., 2013a; Kumar et al., 2007).

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Tremendous efforts have been made to improve flame stability in micro- and mesoscale combustors. Heat recirculation is a frequently adopted method in the design of small combustors, such as the Swiss-roll combustor configuration (Kim et al., 2007; Kuo and Ronney, 2007; Rana et al. 2014) and porous media combustion (Jiang et al., 2009; Li et al., 2010). Catalytic combustion has also been demonstrated as viable in micro channels, as the catalyst can accelerate the reaction and suppress the radical depletion on the walls (Boyarko et al., 2005; Chen et al., 2007; Choi et al., 2008; Lee and Kim, 2009; Norton and Vlachos, 2004). Forming a recirculation zone or low velocity zone via structural design is another effective way to anchor the flame in small flow-reactors (Akram and Kumar, 2011; Li et al., 2012; Nehe and Kumar, 2013; Wan et al., 2012; Yang et al., 2015).

Recently, we investigated the flame behaviours of a CH_4/air mixture in a mesoscale channel with and without cavities, both experimentally and numerically (Wan et al., 2015). It is interesting that a stable symmetric flame does not occur in a straight channel without cavities, while a flame can be effectively anchored by the recirculation zone and low velocity zone in wall cavities. The blow-off limits of the channel with cavities are several times larger than the corresponding laminar burning velocities of incoming mixtures, which indicates that cavities have a strong ability to extend the operational range of the inlet velocity. The analysis demonstrated that in addition to the extension of residence time of various species, the interactions between heat and mass transfer processes, flow field, and chemical reactions play a significant role in flame stability. It can be expected that the channel gap distance also has important influences on the combustion characteristics in the mesoscale channels with cavities. Thus, in the present work, we experimentally investigated the flame blow-off limits of mesoscale cavity-combustors with different channel gap distances. Numerical simulation was conducted to facilitate analysis of the underlying mechanisms responsible for the differences of flame blow-off limits.

2. Experimental

2.1. Geometric parameters of the channel with cavities

The mesoscale cavity-combustor is schematically shown in Fig. 1. The length (L_0), width (W_0) and wall thickness (W_3) are 70 mm, 20 mm and 3 mm, respectively. The cavity depth (W_2) and length (L_2) are 1.5 mm and 4.5 mm, respectively, while the angle of the ramped cavity wall (θ) is 45°. The distance from the vertical cavity wall to the combustor inlet (L_1) is 10 mm. Three values (2, 3 and 4 mm) were selected for the channel gap distance (W_1). Experimental details can be found elsewhere (Wan et al., 2015).

2.2. Experimental results

Flame blow-off limits for different channel gap distances and equivalence ratios (ϕ, the ratio of the real fuel-to-air ratio to the stoichiometric fuel-to-air ratio) are shown in Fig. 2. Here, the flame blow-off limit is defined as the largest combustible velocity of a mixture with an equivalence ratio, ϕ. It is well-known that the gap distance of 2 mm is already less than the quenching distance of the stoichiometric CH_4/air mixture. Our previous experimental investigation (Wan et al., 2015) showed that a stable symmetric flame did not occur even in the straight channel with a gap distance of 4 mm, and only inclined and pulsating flames were observed in the case without wall cavities. However, the present study shows that when cavities are present in the wall, stable symmetric flames can occur in a channel that is narrower than the quenching distance of the incoming mixture. This finding indicates that the cavities have a strong ability to extend the operational range of the inlet velocity.

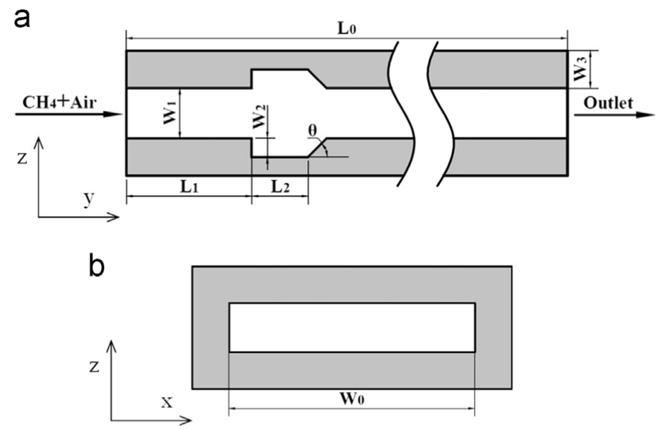

Fig. 1. Schematic diagram of the mesoscale channel with cavities: (a) longitudinal cross section, (b) vertical cross section. The origin of the coordinates is located at the channel centre.

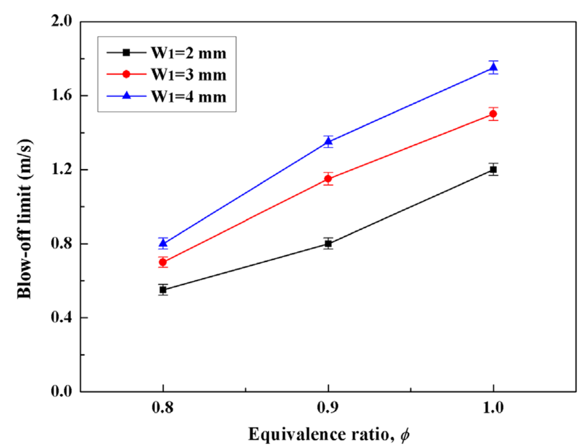

Fig. 2. Experimental results of flame blow-off limits for different channel gap distances.

Fig. 2 demonstrates that for a fixed gap distance, the blow-off limit increases with an increasing equivalence ratio, while for a fixed equivalence ratio, the blow-off limit grows larger for a larger gap distance. Furthermore, the blow-off limits are several times larger than the corresponding laminar burning velocities (one of the most important properties of premixed laminar flames, which are determined by the initial conditions of the fuel/oxidizer mixture, i.e., temperature, pressure and equivalence ratio) of the incoming CH_4/air mixture. For example, the blow-off limits of $W_1=2$ mm, 3 mm and 4 mm at $\phi=1.0$ are 1.20 m/s, 1.50 m/s and 1.75 m/s, respectively, while the laminar burning velocity is ~0.36 m/s.

3. Numerical analysis

3.1. Numerical methods

In this study, 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. Calculation demonstrates that the order of magnitude of K_n is 10^{-5} for both the CH_4 and O_2 used for the present combustor, which is much less than the critical value of 10^{-3}. Therefore, the gas mixture can be reasonably treated as a continuum, and the Navier–Stokes equations are still applicable to the present study (Beskok and Karniadakis, 1999). Because the maximal Reynolds number of the inflow is approximately 732, a three-dimensional, laminar flow, steady state model was used. Methane and air were selected as the fuel and oxidant, respectively.

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