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The effect of the blockage ratio on the blow-off limit of a hydrogen/air flame in a planar micro-combustor with a bluff body

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ABSTRACT

We recently developed a micro-combustor with a bluff body, which has a demonstrated 3- to 5-time extension in the blow-off limit. In the present work, the dimension effect of the bluff body on the blow-off limit (indicated by the blockage ratio, ζ) was investigated with a detailed H_2/O_2 reaction mechanism. The results indicate that the blow-off limits for $\zeta = 0.3$, 0.4 and 0.5 are 20, 31 and 36 m/s, respectively. Analyses reveal that for $\zeta = 0.3$, flame blowout occurs due to insufficient recirculation zone size. However, flame blowout occurs due to the stretching effect in the shear layers when $\zeta = 0.4$ and 0.5. Calculations indicate that the three cases have negligible differences in heat loss because the high temperature zones are located in the combustor centers; therefore, their effects on the combustor walls are mitigated.
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1. Introduction

With the fast development of micro-electro-mechanic system (MEMS) technology, various micro- and meso-scale devices and systems, such as micro gas turbines, propulsion systems, robots and portable electric devices, are continuously emerging. Conventional batteries have several disadvantages, such as short life spans, long recharging periods and low energy densities. Combustion-based micro-power sources are considered a competitive alternative to batteries, particularly due to their use of hydrocarbon fuels, which results in significantly higher energy densities [1,2]. The micro-combustor is a key component of micro-power generation systems. This component converts the chemical energy of fuels into thermal energy through combustion. Thus, the development of micro-combustors with a wide and stable operational range has attracted increasing attention over the last decade.

However, maintaining stable combustion in a micro-combustor is challenging. The increased heat loss and wall radical capture due to the large surface area-to-volume ratio make it difficult to sustain a stable flame at small scales [1–3].

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Another critical problem is the shortened residence time of the gaseous mixture in the combustor. Many unstable flames have been reported to date [4–11]. For instance, flames with repetitive extinction and ignition (FREI) of a premixed methane/air mixture were observed in both straight channels and curved ducts [4,5]. This combustion mode was later numerically reproduced by other researchers [6,7]. In addition, Kumar et al. [8,9] and Fan et al. [10–15] observed some special flame patterns, such as a rotating spiral-like flame, in a heated radial micro-channel.

Considerable efforts have been made to improve the flame stability in micro- and meso-scale combustors. Thermal management methods, such as heat recirculation and heat loss control, are good ways to overcome the negative effect of heat loss and thus sustain a stable flame in small devices [16–21]. The “Swill-roll” structure is a good example of heat recirculation that has been implemented to stabilize flames in micro- and meso-scale combustors [16–19]. The combustion characteristics of premixed H_2/air in a planar micro-combustor with a stainless steel mesh were experimentally studied by Li et al. [20]. These researchers’ work indicated that flames can be effectively anchored by the inserted porous media. Jiang et al. [21] developed a miniature cylindrical combustor with a porous wall that could effectively stabilize the flame in the combustor chamber by reducing the heat loss and preheating the cold feed mixture.

In addition, catalytic combustion is an excellent way to stabilize flames at small scales because the catalyst can accelerate the reaction and suppress radical depletion at the wall [22,23]. Boyarko et al. [24] investigated the catalytic combustion of a hydrogen/oxygen mixture in platinum tubes with internal diameters of 0.4 mm and 0.8 mm for micro-propulsion applications. Zhou et al. [25] studied catalytic micro-combustors made of quartz, alumina ceramic and copper through experimental observations and CFD simulations. Their results showed that these three combustors perform differently. Choi et al. [26] investigated the combustion characteristics of a sub-millimeter catalytic combustor with a platinum catalyst on a porous ceramic support. The results of this study showed that catalytic combustion is applicable to sub-millimeter scale combustors. Di Benedetto et al. [27,28] studied a micro-combustor which was divided into two parts: a first catalytic part and a second non-catalytic part. The results show that this scheme allows operating at high inlet velocity and maintaining high combustion efficiency. In addition, they investigated the effect of cross-sectional geometry on the thermal behavior of catalytic micro-combustors. It demonstrates that the square cross-section micro-rector is more resistant to extinction than the cylindrical channel. Kaisare et al. [29] analyzed the stability and performance of platinum-catalyzed micro-reactors for lean propane-air combustion. It is found that the transverse heat and mass transport strongly depend on the inlet flow rate and the thermal conductivity of the solid material. Karagiannidis et al. [30] investigated the hetero-/homogeneous steady combustion and the stability limits in methane-fueled catalytic micro-reactor. The results showed that the stability limits of catalytic micro-reactors were wider than those reported for non-catalytic systems.

Utilizing the recirculation zone of the flow field is another effective way to stabilize flames in micro-combustors. Yang et al. [31] and Pan et al. [32] developed micro-combustors with a backward-facing step. Their experimental results showed that this step is useful to control the flame position and widen several operational ranges, namely the inlet velocity and the H_2/air ratio. Khandelwal et al. [33] investigated the flame stability of premixed methane/air in micro-combustors with two backward steps. Their results showed that flames can be stable for wide ranges of the inlet velocity and equivalence ratio. Wan et al. [34] developed a micro-combustor with a bluff body that can extend the blow-off limit by 5-fold over the straight-channel combustor. The recirculation zone and shear layers are widely known to affect the flame stability in the bluff body combustor. The bluff body dimension (indicated by the blockage ratio, ζ) significantly influences the characteristics of the flow field and thus the flame stabilization in the micro-combustor. For the present work, we numerically investigated the dimension effect of the bluff body on the blow-off limit of premixed H_2/air flames. The underlying mechanisms are discussed with respect to the flow field near the bluff body and the heat loss from the outer walls.

2. Numerical methods

2.1. *Geometrical model*

Fig. 1 schematically shows the longitudinal cross-section of the bluff body micro-combustor. The total length of the combustor (L_0) is 16.0 mm. The width (W_0) and height (W_1) of the combustor chamber are 10 mm and 1 mm, respectively. The thickness of combustor wall (W_3) is 1 mm. The cross-sectional area of the bluff body is an equilateral triangle, which is symmetrical with respect to the upper and lower walls. The distance from the vertical surface of the bluff body

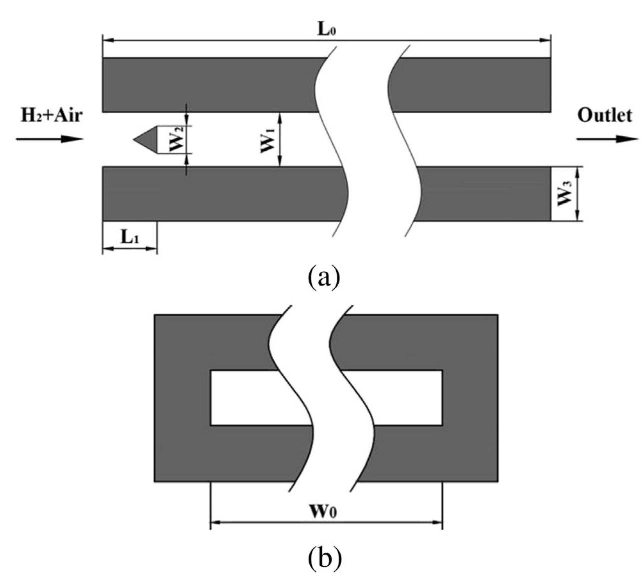

Fig. 1 – Schematic diagram of the micro-combustor with a bluff body: (a) longitudinal cross-section of the combustor, (b) combustor exit.

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