



Experimental investigation and numerical analysis on the blow-off limits of premixed CH₄/air flames in a mesoscale bluff-body combustor



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ABSTRACT

It is challenging to maintain a stable flame in miniature combustors. In the present work, a mesoscale bluff-body combustor was developed. The flame blow-off limits of CH₄/air mixtures were experimentally obtained, which showed that the bluff body can effectively expand the flame stabilization limit. The flame anchoring mechanisms of this mesoscale bluff-body combustor were studied through 3D numerical simulation. It is revealed that a flow recirculation zone is formed behind the bluff body and its area increases with the increase of inlet velocity. Moreover, the incoming fresh mixture can be preheated by both the upstream channel wall and the front and side walls of the bluff body, which leads to an earlier initiation of chemical reactions. Furthermore, the local equivalence ratio grows larger than that of the incoming pre-mixture due to preferential transport effect, which favors the flame stabilization, especially for relatively leaner mixtures. Besides, the dynamic process of flame blow-off was numerically reproduced, which demonstrates that the excessively large strain rate is responsible for flame extinguishment at high inlet velocity. In conclusion, the present work revealed the complex interactions between flow field, mass and heat transfer processes, and chemical reactions in the mesoscale bluff-body combustor.

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1. Introduction

With the rapid development of micro-electromechanical systems technology, the demand for micro power generation devices becomes increasing urgent. The current power sources for portable electronics and micro propulsion systems are conventional electrochemical batteries. However, the batteries have some disadvantages, including a long recharging period, low energy density and short life span. The micro power generation apparatuses utilizing combustion energy are considered promising alternatives due to the much higher energy densities of hydrocarbon fuels [1,2]. A wide stable operational range of miniature combustors is vital to the whole power generation system.

However, it is challenging to maintain a stable flame in small combustors. In the first place, the large surface-area-to-volume ratio leads to a sharp increase in heat losses when the combustor dimension is reduced. Moreover, the residence time of gaseous

mixture may be insufficient to achieve a complete combustion. Owing to those adversities, various unstable flame behaviors occur in microscale and mesoscale combustors [3–8]. For instance, flames with repetitive extinction and ignition (FREI) were experimentally observed by Maruta et al. [4] and numerically studied by Alipoor and Mazaheri [5,6]. Pelton-wheel-like flame and spiral flame were reported by Kumar et al. [7]. Richécœur and Kyritsis [8] studied flame oscillations with sound emission in curved mesoscale ducts. Hence, it is crucial to develop effective flame stabilization technologies under small scales.

By far, various approaches have been developed to improve flame stability in microscale and mesoscale combustors. Heat management is a frequently adopted strategy to stabilize flames in small combustors [9,10]. Kuo and Ronney [11] investigated combustion characteristics in a heat-recirculating type “Swiss-roll” combustor, and found that the operational limits of inlet velocity can be obviously extended. Wan et al. [12] developed a microscale combustor with preheating channels and a plate flame holder. A large blow-off can be obtained for lean CH₄/air flames. Wang et al. [13] reported that inert porous media can significantly expand the operating ranges of gas flow rate and equivalence ratio of CH₄/air

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mixture. Jiang et al. [14] developed a miniature combustor with a porous wall that can enhance the flame stability by reducing the heat loss and preheating the fresh mixture. Veeraragavan [15] studied the flame propagation characteristics in the narrow channels with enhanced wall thermal conduction, and the results showed that a material with orthotropic thermal conductivity can improve the flame stabilization. In addition, the catalytic combustion has been demonstrated to be a good way to stabilize the flame in small combustors. Boyarko et al. [16] confirmed that the catalytic combustion is applicable to sub-millimeter scale combustors. Chen et al. [17] investigated the characteristics of the heterogeneous and homogeneous interaction in a micro-tube, and the results showed that the heterogeneous reactions had sustaining and competing effects on homogeneous combustion. Li et al. [18] studied the effect of catalyst segmentation on the combustion of $H_2/CO/CH_4$ blended fuel. They pointed out that the heterogeneous reaction in the prior catalyst segment produced active chemical radicals and induced the homogeneous reaction. Baigomohammadi et al. [19,20] showed that an inserted wire and a catalytic segmented bluff body have significant effects on flame stability and flame location within the microscale combustor.

Forming a recirculation zone or a low-velocity zone in microscale combustors is another effective way to stabilize the flame. Yang et al. [21] studied the flame stability in microscale combustors with a backward facing step. Khandelwal et al. [22] experimentally investigated the flame behaviors in a microscale combustor with three rearward steps. Their results showed that the flame can be anchored with expanded flammability limits. Akram and Kumar [23] studied the combustion behaviors of CH_4 -air mixture in mesoscale diverging channels, which showed an enhancement of the blow-off limit compared to the straight channel. Nair et al. [24] used a diverging channel to measure the laminar burning velocity of liquid petroleum gas-air mixtures. Wan et al. [25–28] developed microscale and mesoscale cavity-combustors which can increase the blow-off limit by several times compared with that of the straight channel.

Recently, we developed [29] a microscale combustor which consists of a 1.0-mm wide channel and a triangular bluff-body of 0.5-mm side-length. The experimental results showed that the blow-off limits of premixed H_2 /air flames can be greatly extended. In the present work, we designed a mesoscale combustor fitted with a rectangular bluff-body to burn CH_4 /air mixtures. The flame blow-off limits were experimentally obtained and the flame anchoring mechanisms were numerically analyzed in terms of the flow field, heat recirculation effect and preferential transport effect. Additionally, the dynamic process of flame blow-off was also numerically demonstrated.

2. Experimental

2.1. Experimental setup and method

The mesoscale bluff-body combustor is schematically illustrated in Fig. 1. The length (L_0), width (W_0) and height (W_1) of the channel are 70 mm, 20 mm and 4 mm respectively, while the wall thickness (W_3) is 2 mm. The width (W_2) and thickness (δ) of the bluff body are 2 mm and 1 mm, respectively. The distance from the combustor inlet to the front wall of bluff body (L_1) is 9 mm. Quartz glass is adopted as the solid material because it is transparent for direct flame observation and can endure a high temperature.

The experimental system is schematically shown in Fig. 2. Methane and air of high pressure were stored in two gas tanks. Their pressures were reduced to atmospheric pressure and they were fully mixed in a mixer before entering into the combustor. The inlet velocity (V_{in}) and equivalence ratio (ϕ) of gaseous mixtures

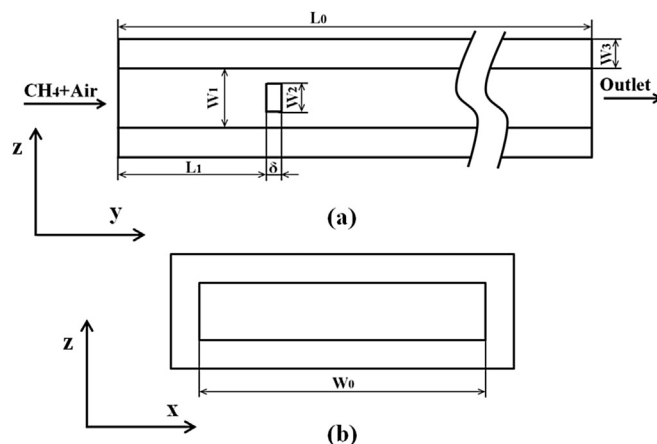


Fig. 1. Schematic of the mesoscale combustor with a rectangle bluff body: (a) longitudinal cross section, (b) vertical cross section. The origin of coordinates is located at the channel center.

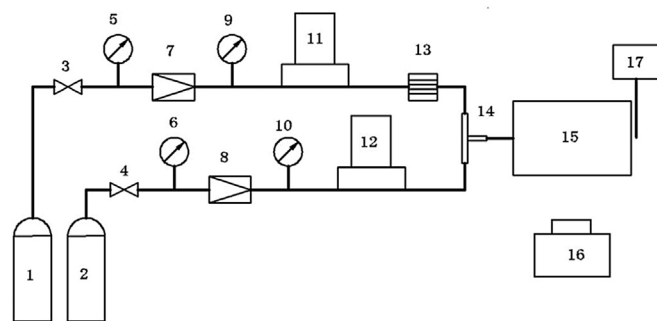


Fig. 2. Schematic of the experimental system. 1, 2: methane and air cylinders; 3, 4: manual valves; 5, 6, 9, 10: pressure gauges; 7, 8: pressure reducing valves; 11, 12: mass flow controller; 13: flash arrester; 14: mixer; 15: combustor; 16: digital video camera; 17: electric spark igniter.

were controlled by two electric-mass-flow meters (ALICAT MS type) with an accuracy of 1% over the full range. These two flow meters were connected to a computer and thus the changes of fuel and air flow rates were controlled synchronously. To eliminate the effect of inlet boundary condition on the experimental results, a fine stainless steel mesh was used to obtain a uniform velocity field at the combustor entrance. A flash-arrester was installed in the fuel line for the sake of safety. A digital video camera (Canon IXY DIGITAL 25 IS) was applied to take flame photographs with a shutter speed of 1/8 s. An electric spark with 10 kV direct-current discharge was adopted to ignite the incoming fresh mixture at the combustor exit. At the beginning of the experiment, we first ignited the fresh mixture of a certain equivalence ratio under a suitable low velocity at which the flame can be stabilized behind the bluff body. Then, we increased the inlet velocity with a step of 0.05 m/s until the flame blow-off occurred. The largest inlet velocity prior to the occurrence of blow-off is defined as the flame blow-off limit. The major purpose of our experiment is to obtain the values of blow-off limit under various equivalence ratios.

2.2. Flame blow-off limits under various equivalence ratios

Our previous experimental investigation [26] showed that symmetric stable flames did not occur in the straight channel with a gap distance of 4 mm, and only inclined and pulsating flames were observed, as depicted in Fig. 3a. However, the present study

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