International Journal of Heat and Mass Transfer 66 (2013) 72–79

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Interactions between heat transfer, flow field and flame stabilization in a micro-combustor with a bluff body

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ARTICLE INFO

Article history:
Received 13 April 2013
Received in revised form 5 July 2013
Accepted 8 July 2013
Available online 31 July 2013

Keywords:
Micro-combustor
Bluff body
Blow-off limit
Heat conduction
Flow field
Flame stretching
Heat losses

ABSTRACT

We recently developed a micro bluff body combustor. Both experimental and numerical investigations demonstrated that the bluff body can significantly extend the blow-off limit. In the present paper, the effect of solid materials (i.e., quartz, stainless steel, and SiC) on the blow-off limit of this micro-combustor was investigated numerically. The results show that the blow-off limit of the quartz combustor is the largest, while that of the SiC combustor is the smallest. The underlying mechanisms were analyzed in terms of the interactions between the flow field, heat transfer processes and flame stabilization. It is demonstrated that when the thermal conductivity is small (i.e., quartz), less heat is conducted to the upstream walls, the fresh mixture is not sufficiently preheated and the gaseous volume does not expanded so significantly. Therefore, the flame stretching effect is weaker than the other two cases and thus a larger blow-off limit is achieved. Moreover, for the stainless steel and SiC micro-combustors, a larger thermal emissivity (i.e., SiC) results in a bigger 'total heat loss ratio' and a smaller blow-off limit. In summary, a solid material with relatively low thermal conductivity and emissivity is beneficial to obtain a large blow-off limit for the micro bluff body combustor. The present study also demonstrates that both flow and heat transfer processes, as well as their interactions, play an important role in flame stabilization of the micro bluff body combustor.

1. Introduction

With the rapid development of micro-electro-mechanic system technology, many types of small devices, such as micro-aircrafts, robots, gas turbines, engines, and portable electronic devices have continuously appeared. As the electrochemical batteries have disadvantages of short life spans, long recharging periods and especially their low energy densities, combustion-based power sources are considered to be potential alternatives in the future due to the much higher energy densities of hydrocarbon fuels [1,2]. Therefore, combustions under micro- and meso-scales have attracted increasing attention during the last two decades [1,2].

However, there are several challenges to maintain stable flames in micro-combustors. The most important one is the increased heat losses due to large surface area-to-volume ratio [1–3]. By far, various kinds of unstable flames have been reported [4–15]. For instance, flames with repetitive extinction and ignition (FREI) of premixed CH_4/air mixture were observed in both straight channel and curved duct [4–6]. This combustion mode was later numerically reproduced [7–11]. In addition, some special flame patterns, such as rotating Pelton-wheel-like flames, spiral flame, and X-shaped spinning flames, were observed in micro- and meso-scale channels [12–17].

Up to now, tremendous efforts have been made to stabilize the flame in micro-combustors. Thermal managements, such as heat recirculation and heat losses control, are good approaches to overcome the negative effect of heat losses and sustain a stable flame in micro-combustors [18–25]. The "Swiss-roll" combustor which can utilize the thermal energy of burned hot gases to preheat the fresh mixture is an effective method in increasing flame speed and extending flammability limits of micro-combustors [18–20]. The thermal properties of the solid material play a significant role in flame stability of micro "Swiss-roll" combustors [18]. Stainless steel mesh was used by Li et al. [21] to anchor premixed H_2/air flame in a micro thermal photovoltaic system. Shi et al. [22,23] investigated combustion characteristics in the combustors with porous media. Jiang et al. [24] developed a miniature cylindrical combustor with porous wall. Flame can be stabilized in the combustor chamber due to the reduction of heat losses and preheating effect on the cold fresh mixture. Taywade et al. [25] utilized an external heating cup for heat recirculation in a three-step micro-combustor. It is shown that heat recirculation significantly enhances the flame stability.

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0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.07.024

Utilizing the recirculation zone is another effective way to stabilize flame in micro-combustors. Yang et al. [26] and Pan et al. [27] developed micro-combustors with a backward facing step. The experimental results showed that the step is useful in controlling flame position and widening operational ranges. Khandelwal et al. [28] investigated premixed CH_4/air flame in micro-combustors with two backward steps. Their results showed that a stable flame can occur in wide ranges of inlet velocity and equivalent ratio. Wu et al. [29] proposed an improved design of a micro gas turbine engine which was originally developed by the MIT group [30]. They added an additional wafer of micro channel to regulate the velocity distribution and direction near the combustor entrance. Their numerical results indicate that the improved design can significantly extend the operating range of mass flow rate, which may lead to higher power density of the micro-combustor. Very recently, Fan and co-workers [31,32] developed a planar micro-combustor with a bluff body. The main concern of their work is the blow-off limit, which is an important index of the combustion limit, i.e., the largest inlet velocity before flame is blown out of the combustor. The experimental results show that the blow-off limit of H_2/air flame is extended by five times as compared with the straight channel. Numerical results of the blow-off limit also show reasonable agreement with the experimental data. This work demonstrates that the micro-combustor with a bluff body has a strong ability in flame stabilization. Veeraragavan and Cadou [33,34] showed that heat recirculation through combustor walls has a crucial effect on the temperature distribution and burning velocity in micro-combustors. The serial papers by Vlachos and co-workers [35–37] demonstrate that a high thermal conductivity of the walls leads to a large blow-off limit for the straight channel. Motivated by those works [33–37], we were dedicated to numerically investigate the effect of solid material on the blow-off limit of premixed H_2/air flame in the micro bluff body combustor. The underlying mechanisms were discussed from viewpoints of the interactions between the flow field near the bluff body, heat conduction in solid walls, heat losses from the outer walls, and flame stabilization.

2. Numerical method

2.1. Geometrical model

The cross section of the micro bluff body combustor is schematically shown in Fig. 1. 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 section of the bluff body is an equilateral triangle with a side-length W_2. The bluff body is symmetrically located with respect to the upper and lower walls, and the distance from the vertical surface of the buff body to the combustor inlet (L_1) is 1 mm. The size of the bluff body is indicated by a dimensionless parameter, i.e., the blockage ratio $\zeta = W_2/W_1$. As the aspect ratio (W_0/W_1) of the combustor chamber is very large (10:1), we adopted a two dimensional model in our numerical simulation to reduce the computation load.

2.2. Mathematical model

As the characteristic length of the combustor chamber is still sufficiently larger than the molecular mean-free path of gases flowing through the micro-combustor, fluids can be reasonably considered as continuums and the Navier–Stokes equations are still suitable in the present study [38]. It is well known that the combustion is a very complicated process involving flow, heat transfer and chemical reactions. According to the classic book by Williams [39], the flame instability usually has two major types, i.e., thermo-diffusion instability and hydraulic instability. Many other factors, such as the interactions among heat, mass transfer and chemical reactions may also trigger a turbulent combustion. For the combustion under micro- and meso-scales, these interactions can be greatly enhanced due to the small space of the combustor chamber. Therefore, the flame isprone to be turbulent in micro-combustors and it is not suitable to judge a flame is a laminar one or a turbulent one just by the Reynolds number. We can list many experimental examples to support this. For instance, Kumar et al. and Fan et al. observed many kinds of unstable flame patterns, such as rotating Pelton-wheel-like flames, spiral flame, X-shaped spinning flame in micro- and meso-scale channels [12–15,23,26–28]. In these cases, the *Re* at the inlet port is controlled to be in the laminar regime, however, the flames are not laminar ones. Our recent experimental investigations on CH_4 combustion in the small bluff body combustor also demonstrated that the flame transited to a turbulent mode with flame pulsation and noise emission at a relatively low *Re* of 175. (Note: these data have not been published yet.) In addition,many researchers [19,40,41] have reported that using a turbulent model can better predict the micro-combustion behaviors above a certain Re. Their conclusions have been confirmed by experimental data. For example, Zhang et al. [40] reported that the turbulence model can get a much better prediction than the laminar model as compared with their experimental data. Ivan and Ahsan [41] showed that using a turbulent model

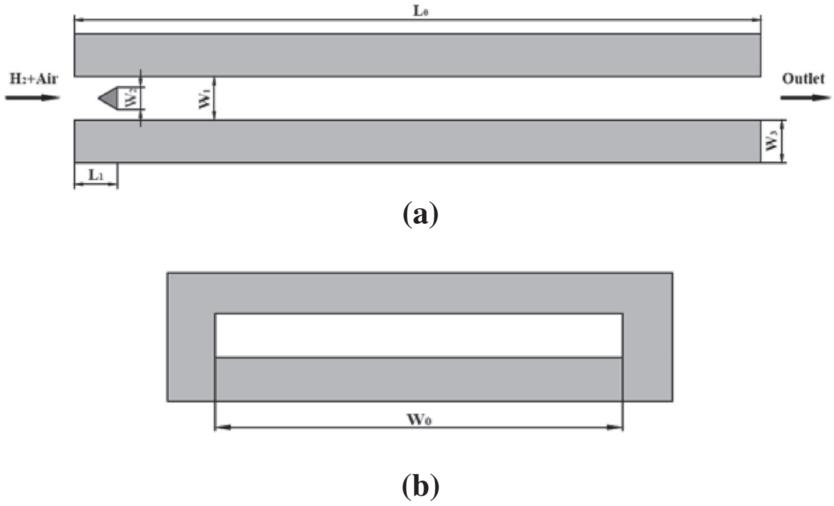

Fig. 1. Schematic diagram of the micro bluff body combustor [31]: (a) longitudinal cross section of the combustor, (b) combustor exit.