Applied Thermal Engineering 62 (2014) 13–19

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Effect of bluff body shape on the blow-off limit of hydrogen/air flame in a planar micro-combustor

Aiwu Fan*, Jianlong Wan, Yi Liu, Boming Pi, Hong Yao, Wei Liu

State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China

HIGHLIGHTS

- Effect of bluff body shape on blow-off limit of a micro-combustor was investigated.
- Blowout occurs due to flame stretching for triangular and semicircular bluff bodies.
- Triangular bluff body has a lower blow-off limit due to stronger flame stretching.
- Heat losses have a negligible effect on the difference of blow-off limit.

ARTICLE INFO

Article history:
Received 4 May 2013
Accepted 6 September 2013
Available online 19 September 2013

Keywords:
Micro-combustor
Bluff body
Blow-off limit
Recirculation zone
Flame stretching
Heat losses

ABSTRACT

We recently developed a micro-combustor with a triangular bluff body, which has a demonstrated 5-time extension in the blow-off limit compared to straight channel. In the present work, the effect of bluff body shape on the blow-off limit was investigated with a detailed H_2/air reaction mechanism. The results show that the blow-off limits for the triangular and semicircular bluff bodies are 36 and 43 m/s respectively at the same equivalence ratio of 0.5. Analyses reveal that flame blowout occurs due to the stretching effect in the shear layers for both the triangular and semicircular bluff bodies. Moreover, it is found that the triangular bluff body has a smaller blow-off limit because of the stronger flame stretching as compared with the semicircular case. Calculations indicate that the two cases have negligible differences in heat losses because the reaction zones and high temperature regions are located in the combustor centers. Therefore, the heat losses have a negligible effect on the difference in the blow-off limit of the two micro-combustors.

1. Introduction

With the rapid progresses of MEMS technology, various micro- and meso-scale devices and systems, such as micro propulsion systems, gas-turbines, robots, and portable electric devices, have continuously appeared [1,2]. As conventional batteries have disadvantages of low energy densities, short life spans and long recharging periods, the combustion-based micro-power generation devices are regarded as a potential alternative due to the much higher energy densities of hydrocarbon fuels [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 [3,4]. Many unstable micro-flames have been reported to date [5–19]. For instance, Maruta et al. [5] experimentally observed a flame with repetitive extinction and ignition (FREI) in a 2-mm-diameter tube. Richecoeur and Kyritsis [6] identified the similar phenomenon in a 4-mm-diameter curved duct. This combustion mode was later numerically re-produced by other researchers [7–9]. After that, flame splitting phenomenon during the FREI processes was numerically predicted [10] and experimentally confirmed [11]. Additionally, Kumar et al. [12,13] and Fan et al. [14–19] observed some special flame patterns, such as the rotating spiral flame in a heated radial micro-channel.

Considerable efforts have been made to improve the flame stability in micro- and meso-scale combustors. Thermal managements, such as heat recirculation and heat loss control, are good ways to suppress the negative effect of heat losses and thus sustain a stable flame in small devices. The “Swill-roll” structure is a good

* Corresponding author. Tel.: +86 27 87542618; fax: +86 27 87540724.
E-mail addresses: faw@hust.edu.cn, faw_73@163.com (A. Fan).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.09.010

example of heat recirculation that has been implemented to stabilize flames in micro- and meso-scale combustors [20–22]. Combustion characteristics of premixed H_2/air in a planar micro-combustor with stainless steel mesh [23] or SiC porous media [24] were experimentally studied. It is shown that the flame can be effectively anchored by the inserted porous media. Jiang et al. [25] developed a miniature cylindrical combustor with a porous wall. The flame can be stabilized in the combustor chamber due to the reduction of heat losses and the preheating effect on the cold fresh mixture.

Utilizing the flow recirculation zone of the flow field is another effective way to stabilize flame in micro-combustors. For instance, Yang et al. [26] and Pan et al. [27] developed a micro-combustor with a backward facing step. The experimental results showed that this structure is useful to control the flame position and widen the operation ranges of inlet velocity and H_2/air ratio. Khandelwal et al. [28] investigated the flame stability of CH_4/air mixture in micro-combustors with two backward steps. They verified that stable flames exist in these micro-combustors for wide ranges of inlet velocity and equivalence ratio. Wu et al. [29] proposed a modified design of the micro-gas turbine originally developed by the MIT group [30]. They added an additional wafer to regulate the velocity distribution and direction near the combustor entrance. Their numerical results indicate that the improved design significantly extends the operating range of mass flow rate, which may lead to higher power density of the micro-combustor. Wan et al. [31] developed a micro-combustor with a triangular bluff body which can extend the blow-off limit by more than five times as compared with the straight channel. Very recently, Fan et al. [32,33] investigated the effects of the bluff body dimension and the solid material on the blow-off limit of this micro combustor. It is shown that the dimensionless size of the bluff body (called the blockage ratio and defined as $\zeta = W_2/W_1$) should be larger than 0.3 to achieve a good performance of flame stabilization [32]. Moreover, it is revealed that 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 [33]. In addition to the bluff body dimension and the solid material, the geometric shape of the bluff body would also significantly influence the characteristics of the flow field and thus the flame stabilization ability in the micro-combustor. Therefore, in the present work, we are dedicated to investigating the effect of bluff body shape on the blow-off limit of a lean H_2/air flame. The results are analyzed in terms of the flow field near the bluff body and heat losses from the outer walls of the combustor.

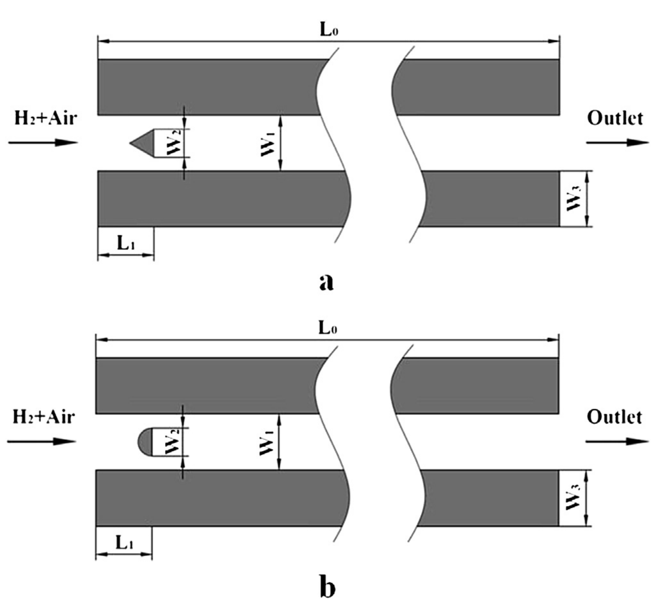

Fig. 1. Schematic diagram of the vertical cross sections of micro-combustors with a bluff body of different shapes: (a) equilateral triangle, (b) semicircle.

2. Numerical simulation method

2.1. Geometrical model

The schematic diagram of micro-combustors with a bluff body of different cross-sections, i.e., equilateral triangle and semicircle, is depicted in Fig. 1. The total length (L_0) and height (W_1) of the combustor chambers are 16.0 mm and 1.0 mm, respectively. The thickness of combustor walls (W_3) is 1.0 mm. The side lengths of the triangle (W_2) and the diameter of the semicircle (W_2) are the same of 0.5 mm. The bluff body is symmetrically located with respect to the upper and lower walls of the micro-combustor. The width of the bluff bodies is the same as that of the combustor chamber. The distance from the vertical surfaces of the triangle and semicircle to the combustor entrance (L_1) is 1.0 mm.

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 [34]. On the other hand, the mixing of various kinds of species is enhanced due to the small space and large concentration gradients in the micro-combustor. Therefore, turbulence models are expected to be better than the laminar model in reflecting the enhanced mixing and its effect on combustion characteristics. This has been confirmed by some researchers [21,31,35]. For example, Zhang et al. [35] reported that the turbulence model can get a much better prediction than the laminar model as compared with their experimental data. Kuo and Ronney [21] also suggest that it is more appropriate to predict the combustion characteristics in micro-combustors by using a turbulence model when the Reynolds number is larger than 500. In our case, the corresponding inlet velocity for Re = 500 is about 8.0 m/s. As the main purpose of the micro bluff body combustor is to extend the blow-off limit, which is larger than 8.0 m/s for H_2/air mixture at the equivalence ratio of 0.5 (refer to subsection 3.2). Besides, in our previous work [31], the predicted blow-off limit adopting the realizable k–epsilon turbulence model showed a reasonable agreement with experimental data. Therefore, we use the same model in the present paper. As heat conduction in the solid wall might affect the combustion significantly, the heat transfer in both of the combustor walls and the bluff body is considered in the present computation.

2.3. Computation scheme

Hydrogen and air are selected as fuel and oxidant, respectively. Quartz is used as the solid material. The detailed reaction mechanism reported by Li et al. [36] is applied to model the combustion of H_2/air mixtures. It consists of 13 species and 19 reversible elementary reactions. The surface reaction effect is not considered in CFD simulation because the micro-combustors could be processed via special measures which make the surfaces inert [37]. The thermodynamic and transport properties of the gaseous species could be found in the CHEMKIN databases [38,39].

Uniform velocity and concentration distributions of H_2/air mixture are specified at the inlet of micro-combustor. The mixture