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Numerical investigation on flame blow-off limit of a novel microscale Swiss-roll combustor with a bluff-body

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A B S T R A C T

A micro Swiss-roll combustor with a bluff-body was proposed for the first time. It is demonstrated that this improved design can greatly extend flame blow-off limit by reducing the flame stretch effect. The flame stabilization ability of this new combustor made of quartz, stainless steel (SS) and silicon carbide (SiC) was numerically investigated using a three dimensional, steady state, k-epsilon turbulence model. The results show that at an equivalence ratio of 0.5, the blow-off limits of quartz combustor, SS combustor and SiC combustor are 40 m/s, 50 m/s and 35 m/s, respectively. Comprehensive analyses were conducted under an inlet velocity of 20 m/s. It was revealled that the heat loss rates for quartz, SS and SiC combustors were 153 W, 108 W and 185 W, respectively. The SS combustor has the best heat-recirculation effect, followed by quartz combustor and SiC combustor. The lengths of recirculation zones are 4.35 mm, 3.4 mm and 3.37 mm for SiC combustor, quartz combustor and SS combustor, respectively. In summary, the heat loss rate is the chief factor responsible for the flame blow-off limit of this novel Swiss-roll combustor. It acts together with the heat-recirculation effect and flow-recirculation effect to determine the flame blow-off limit.

1. Introduction

Since the beginning of this century, the development of combustion-based micro-power-generation-devices has attracted extensive attention because hydrocarbon fuels have a much higher energy density than traditional batteries [1]. Recent progresses in both technical and fundamental aspects were summarized by Ju and Maruta [2] in 2011. Also, the development in micro power generators was reviewed by Chou et al. in the same year [3]. However, in micro channels, the thermal-coupling between flame and wall, such as heat-recirculation, can exert significant effects on flame stability. For instance, Veeraragavan [4] revealed that high axial thermal conductivity allows the burner to withstand greater heat loss. Kang and Veeraragavan [5] found that orthotropic walls can expand the operating envelope of micro-combustors. In addition, the increased heat-loss ratio and the reduced residence time may results in various unstable combustion modes. Flames with repetitive extinction and ignition were experimentally observed in micro-channels with temperature gradient by Maruta et al. [6]. Recently, Alipoor and Mazaheri [7] confirmed the repetitive extinction-ignition dynamics for lean premixed hydrogen-air combustion in a heated microchannel. They also identified flame bifurcation in repetitive extinction-ignition dynamics within the same configuration [8].

Heat recirculation is a frequently adopted strategy to enhance flame stability in small combustors. Adding porous media into microscale combustors is a direct heat-recirculating method. Jiang et al. [9] designed a miniature combustor with a porous wall to reduce heat-loss and preheat incoming fresh mixture. Pan et al. [10] studied the combustion characteristics of hydrogen/oxygen (H_2/O_2) mixtures in micro porous media combustor. They found that porous material with low heat capacity and high thermal conductivity led to better temperature distribution on the wall. Li et al. [11] discovered that a porous material with an effective thermal conductivity of the same order of magnitude with the wall thermal conductivity is helpful to stabilize flames in micro channels. Liu et al. [12] reported that the stationary flame regime in a mesoscale tube filled with ceramic fibers was expanded if the solid wall had a lower thermal conductivity, but the flame cannot be stabilized in the tube with a diameter less than 4 mm [13].

The Swiss-roll configuration is an indirect heat-recirculating method which was first proposed by Lloyd and Weinberg [14].

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Ronney and co-workers [15] found that combustion could be sustained in a low temperature "flameless" mode in microscale Swiss-roll combustors. Mixtures well below the conventional lean flammability limit could be burned even at mean flow velocities 30 times the stoichiometric laminar burning velocity. Kim et al. [16] examined the combustion characteristics of miniature Swiss-roll combustors made of different materials. They found that as the heat loss increased, the flammable regime became narrower. Chen and Buckmaster [17] investigated the parametric effects on combustion and extinction in microscale Swiss-roll combustors. They showed that as the Reynolds number or equivalence ratio increases, the reaction rate increases and the reaction front moves away from the center of the Swiss-roll combustor towards the inlet. Vijayan and Gupta [18] investigated the flame dynamics and heat transfer characteristics of a mesoscale heat-recirculating combustor. They reveal that the walls have significant effect on the global flame structure, flame location and flame dynamics. Thermodynamics of premixed combustion in a heat-recirculating micro combustor was studied by Rana et al. [19]. It was demonstrated that the second law efficiency is almost invariant with heat loss from the combustor. Bagheri and Hosseini [20] examined the impacts of inner/outer reactor heat recirculation on the characteristics of a micro-combustor. They found that the inner reactor profoundly affects flame stability while the outer reactor presents a higher range of emitter efficiency. Shirsat and Gupta comprehensively reviewed the progress in heat recirculating meso-scale combustors [21].

Utilizing the recirculation zone (i.e., flow recirculation) is also a classic approach to stabilize flame in micro-combustors. Yang et al. [22] found that expanded flammability limit can be obtained with the help of a backward facing step. E et al. [23] investigated the effects of inlet pressure on wall temperature and exergy efficiency of a micro-cylindrical combustor with a step. They found that the highest energy conversion efficiency and exergy efficiency were obtained at the atmospheric pressure. Recently, they conducted analysis of the micro-cylindrical combustor with a step based on field synergy thoery [24]. Wan et al. [25] developed a micro-combustor with dual cavities as flame holders, which can effectively anchor the flame root. The flame-splitting limit of H_2/air flames in the micro-cavity combustor increases as the external surface emissivity is reduced [26]. Wan et al. [27] also designed a micro bluff-body combustor in which the blow-off limit of H_2/air flames can reach up to 50 m/s at an equivalence ratio of 0.6. The blow-off limit of CH_4/flame can be significantly expanded with the presence of a plate flame holder in the combuster center [28]. Bagheri et al. [29] numerically studied that effects of bluff body shape on the flame stability of premixed H_2-air flames. The maximum flame temperature occured when wall-blade was applied as a bluff-body. Hosseini and Wahid [30] investigated flameless combustion in micro bluff-body combustors. They found that the temperature uniformity increased when a triangular bluff-body was applied. Baigmohammadi et al. [31] showed that a catalytic segmented bluff-body had significant effects on flame stability and flame location in the microscale combustor.

As reviewed above, the flammability limits (i.e., equivalence ratio range) of micro Swiss-roll combustors can be greatly extended by the heat recirculation effect of the spiral structure. But the flame cannot be effectively anchored in the combustor center because there is no flame holder [16,18], which narrows the combustible velocity range of micro Swiss-roll combustors. Therefore, in the present work, we add a bluff-body to the center of the Swiss-roll structure as a flame holder to extend the flame blow-off limit. The main body of this paper consists of two parts: we first compare the flame anchoring ability of two microscale Swiss-roll combustors with/without a bluff-body through computational fluid dynamics (CFD) simulation, and then numerically investigate the impact of solid materials on the flame blow-off limit of this new combustor. The underlying physics are analyzed in terms of the heat-loss effect, heat-recirculation effect and the recirculation zone behind the bluff-body.

2. Numerical method

2.1. Geometrical model

The microscale Swiss-roll combustor with a bluff-body is schematically shown in Fig. 1. Here, the cover is removed for clear observation of the inner configuration. The total length, width and height of the combustor are 36 mm, 30 mm and 6 mm, respectively. The channel depth is 4 mm and its width is 2 mm, which is less than the quenching distance of the stoichiometric CH_4/air mixture (~2.5 mm). The thickness of separating walls between the flow paths of fresh mixture and burnt gases is 0.5 mm, while those of the top and bottom plates are both 1 mm. The combustor center has a width of 4 mm. The cross-section of bluff-body is an equilateral triangle with a side-length of 2.5 mm, symmetrically placed at the entrance of combustion chamber. All the values of geometrical parameters are summarized in Table 1. Structured grids were

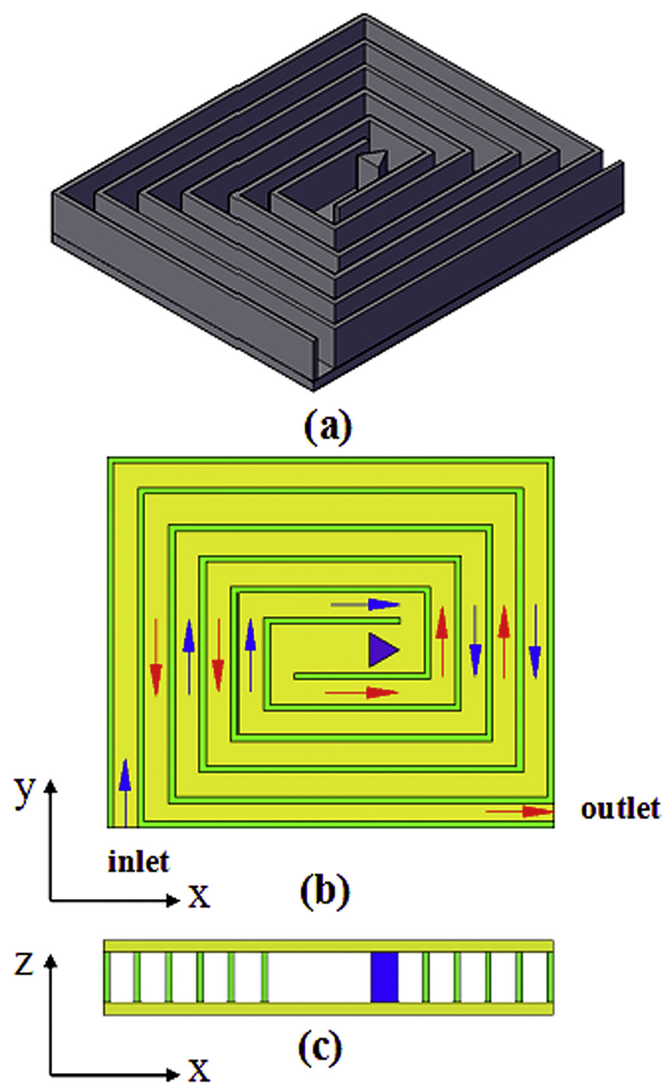

Fig. 1. Schematic of a microscale Swiss-roll combustor with a bluff body: (a) three-dimensional geometrical model, (b) horizontal cross-section, (c) vertical cross-section.