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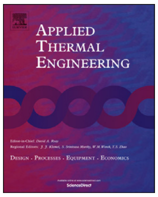

Effects of bluff body shape on the flame stability in premixed micro-combustion of hydrogen–air mixture

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HIGHLIGHTS

- The maximum flame temperature occurs when wall-blade was applied as a bluff body.
- Apart from wall blade, the maximum flame temperature was recorded at $V_2 = 20$ m/s for all cases.
- When inlet velocity of mixture increases from 20 m/s to 30 m/s, the flame temperature reduces in all studied cases.
- Emitter efficiency is very high in micro-combustor with wall-blade bluff body in lower velocities.

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ABSTRACT

Combustion characteristics and flame stability of lean premixed hydrogen–air mixture in a micro-combustor with different shapes of bluff body (circle, ellipse, diamond, semicircular, half ellipse, triangle, crescent, arrowhead and wall-blade) under various physical and chemical circumstances were investigated by solving two-dimensional governing equations. The blow-off limit of different bluff bodies, combustion efficiency, wall temperature and exhaust gas temperature of micro-combustor were examined. The results illustrate that in moderate equivalence ratio ($\varnothing = 0.5$) and low velocity ($V = 10$ m/s), the maximum flame temperature occurs when a wall-blade is applied as a bluff body. When the inlet mixture velocity increases from $V_1 = 10$ m/s to $V_2 = 20$ m/s, the flame temperature of the micro-combustion rises in all cases. Apart from the wall-blade, the maximum flame temperature was recorded at $V_2 = 20$ m/s for all cases and when the inlet velocity of the mixture increased from 20 m/s to 30 m/s, the flame temperature reduced in all studied cases. Therefore, the flame of micro-combustor with wall-blade bluff body is more stable than other cases. Moreover, the mean wall temperature of the micro-combustor with wall-blade bluff body is highest. Emitter efficiency is very high in the micro-combustor with wall-blade bluff body in lower velocities.

1. Introduction

Today, micro-power-generation based on micro-combustion technique is developed widely due to rising demand for portable power devices, development of micro-electro-mechanic system (MEMS) technology and the disadvantages of traditional batteries such as their low power density, heavy weight, long recharging time and short charging duration. The availability of efficient micro-combustors could significantly enhance the functionality of MEMS for portable equipment, because they require high energy density and low recharge time. The high energy densities of various fuels utilized in micro-combustors could be a great opportunity to introduce combustion-based micro-power-generation as an alternative technique for conventional batteries [1,2]. It was demonstrated that, by using liquid hydrocarbon fuels, even when just 10% of energy conversion efficiency was considered, the energy generated from a micro-combustor is six times higher than that of batteries. Therefore, hydrocarbon fuel based micro-combustors can substitute batteries to generate a much higher energy density for the development of micro-electromechanical equipment for micro-propulsion, biomedical applications, telecommunication and chemical sensing [3]. Altogether, heat loss from the combustor walls is higher in micro-scale combustors because the ratio of surface area to the volume of micro-combustor increases and thus the combustion efficiency decreases by micro-combustor size reduction and residence time mitigation [4]. On the other hand, the

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time scale of thermal diffusion in the combustor walls becomes comparable to the time scale of combustion phenomena and the temperature of the flame begins to couple with the temperature of the combustor conducting multiple flame regimes in which both weak flame and normal flame exist. The ratio of diffusion time scale to the convection and radiation heat loss time scale, called the Biot number, governs the wall temperature of the micro-combustor coupling with the flame. When the Biot number is small, the changes in combustor wall temperature affect the small-scale combustion. When the wall temperature increases, the ignition time decreases and flameless combustion can also be observed. This flame wall coupling phenomenon may consciously extend the flammability limit via the excess enthalpy effect. In micro-combustion, when the air–fuel mixture residence time becomes close to the characteristic combustion time, extinction occurs due to incomplete combustion [5]. By applying ceramics [6], melting temperature metals [7] and quartz [8,9] in the micro-scale combustors, the stability of the flame and combustion efficiency considerably improved, while the rate of heat loss from the micro-combustor wall is still large and the micro-combustion efficiency is low. In order to improve flame stability and combustion thermal efficiency of micro-combustors, different experimental and numerical investigations have been done till now. Miesse et al. [10] measured the quenching lengths in micro-combustors made of stainless steel, quartz, alumina and cordierite to specify the impact of surface reactivity and various thermal diffusivities on the flame characteristics. It was pointed out that at surface temperatures of more than 1000 °C, the quenching distance varies with the combustor wall materials, while at lower temperatures (around 500 °C), the quenching distance is similar in different micro-combustors made of different materials. It means that at higher wall temperatures, the radical quenching plays a crucial role in flame quenching. Zhou et al. [11] investigated hydrogen–air mixture combustion in catalytic micro-combustors of different material and illustrated that higher wall thermal conductivity makes the inharmonious reaction region. Therefore, most of the hydrocarbon fuels can be applied in micro-combustors if the heat losses from the walls are controlled and fuel–air mixture is preheated. Indeed, flame sustainability can be achieved by heat recirculation through the combustor walls via conduction and efficient combustion can be obtained by micro-combustor dimension optimization [12]. In micro-combustor design, the excess enthalpy concept has been widely adopted. Kim NI et al. [13] applied the Swiss-Roll burner to stabilize the flame by energy recirculation from burned gas to the unburned mixture. As a result, in so-called super adiabatic combustion, the peak temperature of the flame at the reaction zone is higher than the maximum adiabatic flame temperature of combustion without excess enthalpy. When the maximum flame temperature is augmented, quenching cannot occur due to heat loss from walls, so the flame becomes stronger [14,15]. The effects of channel width, mixture velocity and Lewis number on the flame propagation were studied to investigate the impact of heat loss on the flame stability in channels [16–18]. Experimental results demonstrate that the flame from the mixture can be sustained in the combustors with 0.5 mm diameter [19]. The flame formation in a radial micro-channel was investigated experimentally by Fan et al. [20]. It was pointed out that flame splitting could occur in a micro-channel with fixed wall temperature. Similarly, computational studies in the micro-combustor process have been developed to simulate different parameters in these devices. Various numerical studies such as the effects of fuel–air equivalence ratio, wall thermal conductivity, mixture flow rate and heat losses from combustor walls on the flame stability were carried out [21,22]. Combustion characteristics of premixed hydrogen–air flame in a radial micro-channel were studied experimentally and numerically by Zamashchikov and Tikhomolov et al. [23]. Hydrogen–air swirling premixed flames in a micro-combustion were investigated using direct numerical simulation by Wang et al. [24] and it was explained that the majority of the flame elements lie in the laminar flame regime and the thin reaction zones regime. The effects of bluff body on blew-off limit in a micro-combustor fueled by premixed hydrogen–air were studied experimentally and numerically by Wan et al. [25]. It was stipulated that blow-off limit is extended in presence of bluff body and higher equivalence ratios. Indeed, utilization of higher mixture velocities will be applicable when bluff body is installed [26]. Although the effects of micro-combustor dimensions and operating conditions on the flame stability and combustion characteristics of micro-combustion have been noted, the impacts of different shapes of bluff body on the flame stability, emitter efficiency, wall temperature and exhaust temperature have not been properly developed. In this numerical study, the effects of the different shapes of bluff body applied at the micro-combustor entrance in different inlet velocity profiles, with respect to the fixed equivalence ratio of premixed hydrogen–air on the flame stability and efficiency of the micro-combustor – is investigated.

2. Numerical modeling

The cross-sectional view of the studied bluff bodies located at the entrance of micro-combust (1 mm from the entrance) is depicted in Fig. 1. The geometry of the micro-combustor has been selected based on experimental works proposed by Refs. [25,27,28]. The length of the micro-combustion tube is 15 mm and its diameter is 1 mm. The image formed on the surface of all the bluff bodies is 0.5 mm in the 2D simulation.

The swirl velocity of components was eliminated in this steady-state CFD study, therefore a symmetrical flow rate with respect to the centerline is modeled and the micro-combustor computational model is simplified to a 2D case. Indeed, viscous forces, pressure work and gas radiation were not taken into consideration [29]. In this simulation, the hydrogen was assumed as the fuel due to extremely high burning velocity of hydrogen in comparison with hydrocarbon fuels. In order to protect the inlet geometry, bluff bodies and combustor walls against high temperatures, lean

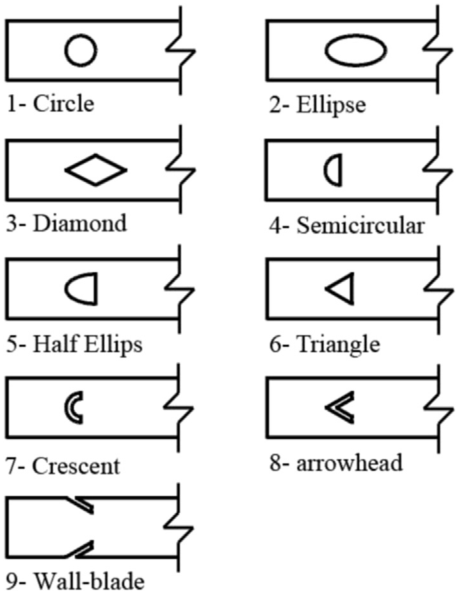

Fig. 1. The cross-sectional view of the studied bluff bodies.