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Research Paper

Effects of noncircular air holes on reacting flow characteristics in a micro can combustor with a seven-hole baffle

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HIGHLIGHTS

- The six-lobed flame is obtained by the annular positions of air holes.
- Strong recirculating regions are developed for the baffles with noncircular air holes.
- The axis-switching phenomenon is confirmed for the square or triangular hole baffle.
- The axis-switching flow makes the lobed flame stronger.
- The flame length reduction by the axis-switching is about 15 times the fuel diameter.

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ABSTRACT

Turbulent reacting flows in a CH_4–air micro can combustor with a baffle plate of seven holes are numerically investigated by the Reynolds Stress Model. In order to examine the effects of baffle configurations on the flow structure, the type of air hole is adopted as circle, square, and triangle. The flame zone strongly depends on the relative positions of air and fuel holes, and the flames are developed to a lobed form depending on the number of air holes. Also, when the circular air hole is changed to square or triangular hole, the development of the central recirculation is more obvious for the reacting flows. Such flow structures promote the decay of the streamwise velocity and increase the turbulent mixing. As a result, the triangular hole baffle gives the shortest flame length. It is recognized that the axis-switching phenomenon is included in the three-dimensional flow development. So to investigate the axis-switching effect on the flow and thermal field, two inlet boundary conditions are tested for the triangular hole baffle. The result shows that the axis-switching flow contributes to the shorter flame length. For the modified inlet without the axis-switching, the flame length becomes twice the original size of the axis-switching condition. Additionally, the combustion efficiency is discussed by the conversion rate and heat loss.

1. Introduction

Today, small scale devices such as microrobots, notebook computers and micro vehicles are becoming more and more important, and the demands for high-powered energy source are increasing rapidly. So, in recent years, considerable efforts have been made to develop efficient batteries for portable electronics [1]. As a result, the battery concept is realized variously for all sorts of devices. Among them is a combustion based power device. It is well known that power generation devices using hydrocarbon fuels have much higher energy densities than electrochemical storages. In such devices, energy generation from micro-combustion process is a general way, but the related researches are still challengeable.

In order to develop small scale combustors, we have to overcome the various difficulties of heat losses, flame quenching, friction losses, etc. The major problem of a small combustor is caused by the high surface to volume ratio. As the ratio increases, heat loss through combustor walls becomes more significant [2]. As a result, flame oscillation, flame instability, and flame quenching can be accelerated. Also, when the size of combustion chamber is small, its Reynolds number is too small for the development of turbulent coherent structures and the flame zone does not grow extensively to sustain stable combustion. In ways to solve these problems, several studies [3–11] suggested employing a turbulator such as bluff body, disc-type stabilizer and baffle that can promote turbulent components. For premixed combustors, Wan et al. [3,4] insisted the extension of blow off limit by a triangular bluff body in a planar micro-channel. Also, Wan et al. [5] showed that the cavities in a mesoscale channel have a strong effect in flame stabilization due to the preferential diffusion and preheating effects. Fan et al. [6,7] analyzed the differences of blow off limit in a bluff body combustor of

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H_2/air in terms of the recirculation and flame stretching. These results are based on the generation of various vortices to increase the residence time of reactants. In general, the fast mixing of fuel and oxidizer achieving efficient combustion greatly depends on the recirculating flows. So, the introduction of flow recirculation is critical for the combustor of non-premixed flames. According to Chen and Driscoll [8], the flames behind a bluff body were five times shorter than the simple jet flame by developing various vortices. Also, Bagheri et al. [9] showed that the flame structure and blow off limit are strongly coupled to the recirculation zone behind the bluff body in a micro combustor of lean premixed hydrogen–air. Yang et al. [10] investigated reacting flow structures related to the mixing mechanism for a doubly concentric bluff-body burner. On the other hand, in a micro combustor with baffle plate, Yahagi et al. [11] showed that the flow structure behind the baffle plate is strongly coupled to the reacting flows which can be classified into a diffusion flame, a lifted diffusion flame, a turbulent premixed flame, and a partially diffusion turbulent premixed flame. From these studies, it is accepted that the combustion characteristics are greatly influenced by recirculating flows.

From a literature survey, flow recirculation inside a combustor can be formed by swirl vane, bluff body, baffle, etc. One of them is a baffle plate with multiple jet flows. From geometric characteristics, the baffle plate provokes three dimensional flows caused by the jet flows. Large flow recirculation regions are formed near the combustor wall and downstream the center jet. For the development of a micro combustor operating at low Reynolds numbers, many studies [11–17] proposed a baffle plate to enhance the flow mixing. They showed that the three dimensional recirculating flows enhance the fuel–air mixing for the low Reynolds number condition. On the other hand, the reacting flows in a micro combustor with a baffle plate were investigated experimentally by Yahagi et al. [11] and Moghtaderi [17]. From their results, we found that the vortex structures and location have a strong influence on the flame structure and its position. Therefore, the flame stability in a micro combustor is closely correlated with the evolutions of recirculating flows. Much recent research for the baffled combustor has been conducted on the flow structures to enhance the flow mixing. Such flows are characterized by three-dimensional features in spite of low Reynolds numbers, and it depends on many geometrical factors of the number of jets, jet diameter, nozzle configuration, etc. Some of them are available in the literature, but we cannot fully understand reacting flows of micro combustor. So, many works still remain to be studied.

The present study focuses on the geometrical conditions of a micro combustor for better mixing and efficient combustion. The micro combustor with a baffle plate of seven circular holes is selected for a baseline. Then, several hole shapes are adopted to investigate the modification of three dimensional recirculation. In general, when the cross sections of a jet flow are noncircular, the axis-switching phenomenon is observed by the different rates of shear layer growth [18–21]. Since this kind of flows can exert a favorable influence on the flow mixing and combustion efficiency, extensive research has been conducted for noncircular jets. However, the combustion study based on the flow mixing with the axis-switching phenomenon is very rare. Toward this end, several simulations are performed for a micro combustor with a baffle plate of square and triangular holes. As a result, axis-switching phenomenon, overlapping of noncircular jet flows, and three dimensional recirculating flows are discussed under the reacting flow condition. Also, special characteristics of reacting flows in the micro combustion with multiple jets are scrutinized.

2. Governing equations and numerical methods

For incompressible turbulent flows, the continuity, momentum, and energy equation can be written as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho U_i)}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial(\rho U_i)}{\partial t}+\frac{\partial(\rho U_i U_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial U_i}{\partial x_j}-\rho\overline{u_i u_j}\right) \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial x_j}(\rho U_j h)=\sum_j\left[\frac{\partial}{\partial x_i}\left(\rho h_j D_{j,m}\frac{\partial Y_j}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_i}\left(k_f\frac{\partial T}{\partial x_i}\right) \tag{3}$$

where U_i, P, h, T, $\overline{u_i u_j}$, k_f, μ, and ρ are the velocity, pressure, total enthalpy, temperature, Reynolds stress, thermal conductivity, viscosity, and density, respectively. And h_j, Y_j, and $D_{j,m}$ are the static enthalpy, mass fraction, and diffusive coefficient of species j. For turbulent reacting flows, the Reynolds stress model (RSM) and flamelet model of the detailed mechanism GRI-mech 3.0 (53 species and 325 reaction) [22] are adopted. Also, the flamelet model of the reduced mechanism (16 species and 41 reactions) [23] and eddy-dissipation model (EDM) are selected for comparison. The SIMPLEC algorithm in FLUENT [24] is applied for the pressure–velocity coupling and the second-order upwind scheme is selected for the convection terms in all transport equations. The convergence criterion is chosen by the residuals being less than 10^{-6}. For simplicity, species transport equation for the EDM model, conservation equations of mean mixture fraction and variance for the flamelet models are omitted. The details of model functions and numerical procedure are simplified.

Fig. 1 shows the computational domain for a CH_4–air micro combustor with a baffle plate. The baffle has a fuel hole at the center and six air holes annularly. To investigate the axis-switching effect on the reacting flow, the type of air holes is changed from circular to square or triangular. The cross-sectional areas are fixed to minimize the difference of inlet momentum. So, three different baffle configurations are analyzed for the mixing and combustion characteristics. Based on the previous studies [11–16], the baseline baffle of the micro combustor is determined. The combustor diameter is $D=2.8\ mm$, and the fuel and air holes are the same diameter as $D_f=D_a=0.4\ mm$. The geometrical parameters are summarized in Table 1. The inlet condition is obtained from the fully developed profile through the separate computation of a periodic domain. The inlet temperatures of CH_4 and air are 300 K, the fuel inlet Reynolds number based on the fuel hole diameter is set to $\mathrm{Re}=3060$ [2,15]. A constant pressure outlet condition and isothermal wall boundaries are adopted.

In order to validate the present numerical procedure, several computations using the RSM model and the SKE model are performed for non-reacting/reacting jets and baffled combustor. Since the present baffle produces multiple inlet jets for the combustor, jet flows [25,26] are selected for comparison. The flamelet and EDM models are adopted for the reacting flows. Fig. 2(a) shows the centerline distributions of streamwise velocity and its fluctuation, mixture fraction, and temperature of jet flow. Here, U_c is the velocity at the jet axis. As can be seen, the RSM results are very good agreement with the experiments [25,26]. For the jet flame of Brookes and Moss [26], the EDM model shows a general feature of overpredicted temperature, but the flamelet models well reproduced the temperature evolution. The detailed data of flow field is not experimentally available for the micro combustor with the present baffle geometries. So, the predicted temperature field is compared to the image of Yahagi et al. [11] for a micro can combustor. In general, the RSM model is more reliable than the SKE model for the complex flows having various strains. This feature is tested for the micro combustor. To test the dependency of turbulence model, the result of the standard $k-\varepsilon$ model (SKE) is added. In Fig. 2(b), the SKE model underpredicts the recirculation zone and the RSM model gives a little longer flame. Considering the sizes of recirculating flow and flame