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Research Paper

Non-premixed lean flame characteristics depending on air hole positions in a baffled micro combustor

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HIGHLIGHTS

- The vortices are changed by the air hole position and global equivalence ratio.
- The highest reaction rate is observed for the specific baffle.
- The flame shape varies from the jet flame to the M−shape flame.
- The seven-hole baffle has a best configuration for efficient combustion.

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ABSTRACT

Compared to a premixed micro combustor, non-premixed micro combustor has the advantage of being able to control more easily the fuel-air mixing with reducing flame flashback. To find an efficient micro combustor based on the non-premixed combustion, non-premixed flame characteristics of CH_4-air in a baffled micro combustor are numerically studied. Among many factors of the combustor with a seven-hole baffle, the air hole position and air-fuel ratio are important parameters in understanding the combustion characteristics of non-premixed micro combustor. So, to investigate the relation of the combustion efficiency and flame characteristics under different geometrical conditions, six air hole positions of the baffle and five air-fuel ratios are selected. Various simulations based on the Reynolds Stress Model and detailed chemical mechanism of GRI 3.0 are performed. The results show combustion characteristics depending on recirculating flows and the relation between baffle configurations and flame structures for efficient combustion. The stoichiometric zone strongly depends on the relative positions of air and fuel holes. As the air holes of the baffle are away from the fuel hole, the center of dominant vortices is moved from near the inner combustor wall to the combustor center. So, the combustion efficiency can be maximized for the baffles of air hole positions having the center recirculation in addition to non-negligible wall recirculations. To examine this feature, turbulent flows for many combustors with different baffles are analyzed. Even though the air hole diameter changes, the efficient condition of air hole position is nearly fixed at two-thirds of the combustor radius. Another crucial factor in a non-premixed micro combustor is the equivalence ratio which can be linked to the operating condition. So, the geometrical effects are examined for different equivalence ratios. As the equivalence ratio decreases, the flame shape varies from the jet flame to the M−shape flame. As a result, the flame length decreases and the flame temperature increases. From such results, flame characteristics and various flame shapes are discussed with the global equivalence ratio and the effects of air hole position. So, the best baffle configuration is explored for the combustion efficiency. Also, the development of wall recirculations is analyzed with the wall heat transfer from the viewpoint of a heat emitter.

1. Introduction

Recently, energy demands are diversified for small scale devices due to technology advances. So, various efforts have been made to get new energy sources. Particularly, the combustion based device is very attractive, because it has higher energy density than conventional batteries [1]. In such a small device, the combustion is usually realized in a micro combustor. In general, the micro combustor has special characteristics that are not observed in the reacting flows of a large combustor [1–2]. Many studies have been performed to overcome the clear limitation of micro combustors. The related problems are heat losses, flame quenching, laminarization of fluid flows, etc. due to millimeter or sub-millimeter scale.

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Nomenclature

$D_{i,m}$	diffusion coefficient of species i, m^2/s
h	total enthalphy, kJ/kg
h_i	static enthalpy of species i, kJ/kg
J_i	diffusion flux, kmol/(m^2·s)
LHV	lower heating value of methane, kJ/kg
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
S_{ij}	strain rate tensor
T	temperature, K
T_w	outer wall temperature, K
T_∞	ambient temperature, K
U	streamwise velocity, m/s
U_c	streamwise velocity at center of baffle exit, m/s
U_i	velocity components, m/s
$\overline{u_i u_j}$	Reynolds stress, m^2/s^2
Y_i	mass fraction of species i
Z	mixture fraction
Z_{st}	stoichiometric mixture fraction

Greek letters

η	combustion efficiency
κ_f	thermal conductivity of fluid, W/(m·K)
μ	dynamic viscosity, (N·s)/m^2
ρ	density, kg/m^3
Ω_{ij}	vorticity tensor

Among others, the heat loss is a major feature of a micro combustor to be examined. If we accomplish the best design in the aspect of combustion efficiency, the heat loss increases oppositely because of the increase of heat flux on the combustor wall.

To increase the combustion efficiency, several studies [3–6] introduced a bluff body for premixed combustors. For a planar micro-combustor, Wan et al. [3] and Fan et al. [4] showed that the blow-off limit and the combustion efficiency are considerably improved by a bluff body. Fan et al. [5] investigated the extended blow off-limit of the micro Swiss-roll combustor with a triangular body. Also, Bagheri et al. [6] examined combustion characteristics in a micro-combustor with different shapes of bluff body (circle, ellipse, diamond, semicircular, half ellipse, triangle, crescent, arrowhead and wall-blade). They proposed that the wall-blade type is a best configuration in a view of emitter. It can be considered that such results are mainly due to changes in the flow structure behind a bluff body.

Unlike these studies, the baffle plate for non-premixed combustors was explored recently [7–10]. Moghtaderi et al. [7] proposed that the multi-hole baffle has significant effects on the flow structure and mixing patterns in a micro-reactor. Yahagi et al. [8] experimentally studied the reacting flows inside a micro-combustor with a baffle plate. Also, Choi et al. [9] and Choi and Park [10] showed flow and heat transfer characteristics of a micro combustor by a large-eddy simulation. From those studies, we found that recirculating flows have important roles for the development of stable flame. In general, the mixing and heat transfer in a combustor are enhanced by the configuration generating the reversed flows and also the flame residence time is increased. So, the flammable limit of the combustor is extended. Such features are more clear for the non-premixed combustor, because the combustion process depends on the mixing state of fuel and air. However, the intensive study related to the effect of combustor geometry on the flow fields and flame properties leaves still much to be studied. Recently, Kim and Park [11] showed that the flame zone of a micro combustor with a seven-hole baffle is described by the stoichiometric condition of the six-lobed shape. On the other hand, Choi and Park [10] showed that the amount of heat loss via combustor wall is reduced by the change of air hole size. Those are strongly coupled with the fuel-air mixing zone reliant on the air hole location. Accordingly, the combustion efficiency is very sensitive to the geometrical variation of air hole, and for that reason, we can consider annularly placed air holes as a key parameter in the micro combustor with a baffle.

On the other hand, as the combustion efficiency increases, the wall heat flux becomes stronger naturally. In a micro combustor, the heat loss is an adverse factor to be improved. However, it gives an effective way for a power generation device like thermo-photovoltaic (TPV) system. According to the previous studies [12–13], the TPV system consists of micro combustor, emitter of combustion heat, and the photovoltaic cell arrays. For a high-performance TPV, the combustion heat is effectively transferred to the combustor wall. To increase the wall heat flux in the micro combustor, many methods using a backward facing step [14], elliptical tube [15], rectangular rib [16], and double-channel combustor [17] have been tried. On the other hand, Kim and Park [11] proposed a baffled micro combustor based on the non-premixed flame. From their results, we can form a heat emitter for TPV system based on the baffled micro combustor as Fig. 1. In this combustor, the six-lobed flame induced by the multi-holed baffle plate has an important function from both sides of combustion efficiency and wall heat transfer. And, it is strongly related to the baffle configuration.

In the present study, the micro combustor with a seven-hole baffle is studied for the relation of the combustion efficiency and flame characteristics under different geometrical conditions. Since this combustor is an important component for a power generator based on the hybrid system of the micro gas turbine and the solid oxide fuel cell, this kind of research is really worthwhile for the various development of micro combustor. Toward this end, the micro combustor of Kim and Park [11] is selected as a baseline configuration. In the combustor, a multi-holed baffle is introduced to improve the combustion efficiency. To see variable characteristics of stoichiometric zone, the air hole position of the baffle is changed for six cases. In general, the inlet air-fuel ratio has a critical effect on the peculiar development for a non-premixed flame. So, it needs to get flame characteristics of the baffled combustor for different inlet air-fuel ratios. In order to examine local flame structures in terms of heat transfer and flow development, the inlet air-fuel ratio of methane-air mixture is changed for five values. From the results, the combustion efficiency is discussed with flame structures depending on the variation of air hole position. A specific feature of the wall heat flux is investigated for baffle geometrical characteristics.

2. Numerical procedure

2.1. Governing equations

For unsteady turbulent flows, the governing equations of continuity, momentum, species, and energy can be expressed as

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