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Numerical investigation on combustion characteristics of methane/air in a micro-combustor with a regular triangular pyramid bluff body

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ABSTRACT

Combustion characteristics of methane/air in a micro-combustor with a regular triangular pyramid bluff body were numerically investigated. Results reveal that the blow-off limit of the micro-combustor with a regular triangular pyramid bluff body is 2.4 times of that in the micro-combustor without bluff body. With the increase of inlet velocity, the recirculation zone expands and preferential transport effect behind the bluff body is intensified. Therefore, the local equivalence ratio in the recirculation zone increases when $\Phi = 0.8$, but the growth trend of local equivalence ratio is not obvious when the inlet velocity exceeds 10 m/s. When $\Phi < 1.0$, adding small amount of hydrogen into gas mixture can speed up the significant elementary reaction, leading to an increase of methane conversion. It's found that both the methane conversion rate and the temperature behind the bluff body reaches the highest when blockage ratio increase to 0.22.

Introduction

With the fast development and intensive applications of Micro Electro-Mechanical Systems (MEMS), lightweight and compact energy resources have been gradually stepped into aviation, military, healthcare and even our daily life [1]. Applications of compact energy are expected to increase due to the development of electronic devices, which mainly depends on the development of micro-powers [2,3]. The efficiency and stability of the combustion have a decisive effect on the performance of MEMS. Since the energy density of hydrocarbon fuels is much greater than the traditional batteries, the

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Nomenclature

Y_s	mass fraction of species
D_s	diffusion coefficient of species
R_s	consumption or decomposition rate species
V_{sk}	stoichiometric coefficient in forward direction of surface reaction
k_s	total number of elementary surface reactions
V''_{ik}	stoichiometric coefficient in negative direction of reaction
k_{sk}	forward rate coefficient of reaction
A_k	pre-exponential factor
Ea	activation energy of reaction
β_k	temperature exponent
Θ_i	surface coverage rate of species
ε_{ik}	surface coverage parameter
μ_{ik}	surface coverage parameter
N_s	number of surface species
N_g	number of gas phase species
[Xi]	molar concentration of surface species
Γ	surface site density of the catalyst
f_i	body force
μ	viscosity of the mixture
h	enthalpy
q	heat of reaction
λ	thermal conductivity
R	universal gas constant
Φ	equivalence ratio of the inlet mixture
$M_{CH_4} \cdot in$	mass flow rate of methane at the entrance of the combustor
$M_{CH_4} \cdot out$	mass flow rate of methane at the exit of the combustor
A/F	actual ratio of air/fuel in the inlet mixture gas
A_0/F_0	stoichiometric air/fuel ratio
Φ_{local}	equivalence ratio of the rear of the bluff body

combustion of hydrocarbons has been extensively studied in the field of micro-power generation [4–7]. Fernandez-Pello pointed out that the energy density of typical hydrocarbon fuels was about 45 MJ/kg, which is several tens of times than that of a lithium battery [8]. Many studies have proved that hydrogen and methane are the most promising fuels in micro combustors.

The tiny size that shortens residence time of fuels and the large surface area-to-volume ratio that multiplies the heat loss of micro-combustors are two prominent characteristics of micro-combustor [8]. It has been proved that a short residence time of fuels and heat loss from exterior surface of combustor can significantly weaken the performance of micro-combustor [9]. Scholars have made tremendous contributions to solve these problems. In order to reduce heat loss, Tang et al. [10]. proposed a new planar combustor for micro thermo photovoltaic system, which had multi-mode heat transfer passages in the combustion channel. It was found that the new combustor could achieve a higher temperature of the radiation surface due to the enhancement of heat transfer. Cao et al. [11] studied the diffusion combustion in a micro-combustor with porous media. It revealed that porous media can improve the enthalpy of reactant and reduce the heat loss. Furthermore, Pan et al. [12] investigated the hydrogen/oxygen premixed combustion characteristics in micro porous media combustor. They figured out that porous media material with low C_p and high thermal conductivity led to better temperature distribution on the wall, which can improve the efficiency of the thermophotovoltaic (TPV) system. In order to prolong the residence time of inlet gas, some researchers proposed to add a bluff body into micro-combustor to optimize combustion characteristics [13–16]. Stability of the flame and combustion efficiency were considerably improved by using bluff body. Bagheri et al. [13] investigated effects of bluff body shape on the flame stability in premixed micro-combustion of hydrogen/air mixture via 2D CFD simulations, it's concluded that the wall temperature and combustion efficiency was improved in all cases compared with the conventional model, and they also suggested that wall-blade is better than other shape of bluff body at high inlet velocities. Fan et al. [15,16] compared combustion characteristics of gas mixture in a 2D planar micro-combustor model with and without a bluff body. The results showed that the blow-off limit of flame can be extended to several times in the micro-combustor with a bluff body than that without bluff body. Hosseini et al. [17] studied the effect of bluff-body on flameless combustion in a cylinder micro-combustor, they pointed out that micro-flameless mode with bluff-body illustrated better performance than other cases. Ran et al. [18] compared the flow field and combustion efficiency of methane in a micro-channel with concave cavity and with convex cavity, they reported that concave cavity can lead to the reflux of methane at a high velocity and convex cavity can enhance the contact between gas mixture and catalyst. Zhang et al. [19] investigated the cavity structure, position, and number of convex cavities on the catalytic combustion characteristics of methane/air in a micro-channel, they reported that increasing the normalized cavity diameter is an effective way to expand the blow-off limit. E et al. [20] proposed a cavity and backward-facing step in micro-combustor. It was found that the cavity or backward-facing step contributed to the formation of the recirculation zone, enhanced the heat recirculation and the flame stabilization. Niu et al. [21] have made a comparative study between streamline-type bluff body and non-streamline-type bluff body. The results showed that the micro-combustor with non-streamline-type bluff body performs better in the formation of recirculation zone and stability of the flame.

In addition, catalytic combustion is also an effective way to improve the performance of micro-combustors. It has been proved that catalyst can decrease the activation energy of the reactions and improve conversion rate of fuels [22–24]. Suzanne et al. [25] experimentally investigated the surface oxidation on small-scale catalytic combustion for methane/air and propane/air, and they found a sharp temperature increase occurred on the catalytic surface with simultaneous fast depletion of the combustible gas. Ran et al. [26] employed a 2D model to numerically investigate wall heat transfer characteristics of CH_4/air in the micro-tube with Pt catalyst. It's concluded that both the heat transfer along the solid structure and the total heat loss increased with increasing wall thickness. Lee et al. [27]

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