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Investigation of bluff-body micro-flameless combustion

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ABSTRACT

Characteristics of lean premixed conventional micro-combustion and lean non-premixed flameless regime of methane/air are investigated in this paper by solving three-dimensional governing equations. At moderate equivalence ratio ($\varnothing = 0.5$), standard k–ε and the eddy-dissipation concept are employed to simulate temperature distribution and combustion stability of these models. The effect of bluff-body on the temperature distribution of both conventional and flameless mode is developed. The results show that in the premixed conventional micro-combustion the stability of the flame is increased when a triangular bluff-body is applied. Moreover, micro-flameless combustion is more stable when bluff-body is used. Micro-flameless mode with bluff-body and 7% O_2 concentration (when N_2 is used as diluent) illustrated better performance than other cases. The maximum temperature in premixed conventional micro-combustion and micro-flameless combustion was recorded 2200 K and 1520 K respectively. Indeed, the flue gas temperature of conventional mode and flameless combustion was 1300 K and 1500 K respectively. The fluctuation of temperature in the conventional micro-combustor wall has negative effects on the combustor and reduces the lifetime of micro-combustor. However, in the micro-flameless mode, the wall temperature is moderate and uniform. The rate of fuel–oxidizer consumption in micro-flameless mode takes longer time and the period of cylinders recharging is prolonged.

1. Introduction

1.1. Development of micro-scale combustion

Recently, the demand for lightweight and compact energy resources has significantly increased because high energy density could not be supplied by traditional batteries. The demand for compact energy is expected to be increased due to development of electronic devices and thus micro-power will be required to supply energy of these enhanced functionalities [1,2]. Since the energy density (per unit mass or unit volume) of hydrocarbon fuels is much greater than the traditional batteries, micro-power generation based on combustion of hydrocarbons has been more considered. Furthermore, the negative impacts of conventional batteries on the environment upon disposal highlight the necessity of emergence of new micro-power generation methods for micro-electro-mechanic-systems (MEMS) [3]. Although, the package of combustion based micro-power generation could be significantly shrank, the demanded power is not compromised if the chemical energy of the fuel is utilized efficiently. Despite the low efficiency of micro-combustion systems, the priorities of combustion based micro-power generating in a few Watts within an extremely small volume was noticed [4]. In order to address the raising demand for small-scale electricity sources, various micro-combustion-based power generators have been developed. Hence, enhancement of flame stability and thermal efficiency of micro-combustors has become new challenge in combustion investigations [5,6]. The fundamental concepts of combustion characteristics of micro-scale combustors play crucial role in the improvement of system efficiency and optimization of the design. Since combustor volume is reduced in micro-scale combustion, conspicuous radical destruction and heat loss from micro-combustor walls are expected. Accordingly, application of micro-thermophotovoltaic (TPV) power generation in MEMS has been enhanced. Elimination of moving parts, high reliability and highly robust of TPV are the main characteristics of TPV which makes it suitable for application in commercial electronic devices [7]. In the recent years, conspicuous progress has been obtained in micro-scale combustion experimentally and numerically. These investigations have helped to understand the fundamentals of micro-combustion in terms of flammability limits, flame stability, emitter and thermal efficiency. Application of micro-combustion systems in MEMS was successfully experimented by Waitz et al. [8] in micro-turbines and Yang et al. [9] in the TPV in the last decade. Since the ratio of surface to the volume of micro-combustor is higher than regular combustors, the possibility of thermal quenching in micro-combustors is very high

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Nomenclature

μ_t	turbulent viscosity
P_k	turbulence kinetic energy production
P_b	effect of buoyancy
Y_M	the contribution of the fluctuating dilatation to the overall dissipation rate
$T_{s,o}$	outer surface temperature
T_∞	ambient temperature set at 300 K
h	natural convection coefficient considered constant value 5 $\mathrm{W/m^2\,K}$
σ	Stefan–Boltzmann constant (= $5.67 \cdot 10^{-8}\ \mathrm{W/m^2\,K^4}$)
ε	solid surface emissivity
C_ξ	volume fraction constant (= 2.1377)
ν	kinematic viscosity
C_τ	time scale constant (= 0.4082)
σ_k	turbulent Prandtl numbers for k
σ_ε	turbulent Prandtl numbers
S_k, S_ε	user-defined source terms
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	constants
G_k	the generation of turbulence kinetic energy due to the mean velocity gradients
G_b	the generation of turbulence kinetic energy due to buoyancy
$\vec{J}_j$	diffusion flux of species j
k_{eff}	effective conductivity
Y_M	the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

due to the extremely high heat loss from flame [10]. Therefore, stability of the flame in combustors with sub-millimeter size has become a new challenge [11]. Indeed, the stability of the flame in micro-scale combustors is influenced by absorption and destruction of generated combustion radicals [12]. Hence, feasibility of using catalyzed combustion [13] as well as application of external heat [14] and heat recirculation [15] were experimented. It was found that flame stability in micro-scale combustors depends strangely on the heat recirculation through combustor walls [16]. Preheating the reactants via heat transfer from high temperature region broads the reaction zone in micro-scale combustion [17]. To decrease heat loss to the ambient and impalement heat recirculation to the unburned zone, specific material should be selected. Therefore, material selection in micro-scale combustors is vital due to strong thermal coupling between reacting mixture and micro-combustor walls. Maruta et al. [18] pointed out that flame instabilities in non-premixed micro-scale combustion could be attributed to the interaction between flame structure and flame flow, heat loss and mass transfer limitations. Flame stability and characteristics of non-premixed sub-millimeter combustor was investigated by Prakash et al. [19]. The source of flame instabilities in premixed combustion of narrow channels was investigated by Sánchez-Sanz et al. [20]. Since the size of combustor shrinks to sub-millimeter in micro-scales, some combustion parameters such as flame ability, flame stability, flame thickness, heat loss, flow field and thermal efficiency are changed. Therefore, the role of numerical and computational investigation has been more highlighted in micro-combustion due to difficulty of measuring various quantities in such limited circumstance in experimental investigations. The impacts of various parameters such as combustor size, the geometry of combustor and boundary conditions on the flame temperature of hydrogen-air premixed micro-combustion were investigated by Li et al. [21] numerically. The authors stipulated that flame temperature in micro-scale combustion could be influenced by the mixture flow rate, the size and the geometry configuration of micro-combustor. Karagiannidis et al. [22] confirmed that a wide range of flammability could be offered in catalytic micro-combustors. The effects of equivalence ratio as well as inlet velocity on the structure of the premixed CH_4/air flame in micro-scale size were investigated by Feng et al. [23] computationally. It was found that the position of the flame is shifted to the downstream in high inlet velocities. Indeed, the highest flame temperature could be achieved in stoichiometric condition.

1.2. Flameless combustion technology

The commencement of flameless combustion research traced back to about 1990s, mainly attributed to the augmentation of the environmental concerns. Depletion of fossil fuel resources and anxieties about environmental issues conducted combustion research community to find environmentally friendly combustion technology and optimized fuel consumption [24]. Flameless combustion [25] or so-called moderate intensive low oxygen dilution (MILD) combustion [26] or high temperature air combustion technology (HITAC) [27] has been developed in the resent years because of its ability to combine high performance of combustion with extremely low pollutant formation [28]. The uniform temperature inside the chamber emerges perfectly stirred reactor circumstances. Since the peak of temperature reduces in flameless mode and hot spots are eliminated, NO_x formation reduces dramatically [29]. Indeed, low emission of flameless mode is attributed to the air dilution by inert gases such as CO_2 and N_2 [30,31]. In flameless combustion, the temperature of inlet diluted oxidizer is higher than self-ignition of the fuel, therefore ignition is eliminated [32]. Due to the significant potentials of the flameless mode to deal with various fuels, implementation of flameless combustion in micro-scale power generation could solve dilemma problems in micro-combustions and thus application of this model of combustion in micro-scale combustors could enhance combustion stability and thermal efficiency [33,34]. In the flameless mode, the reaction zone is distributed throughout the chamber consequently; the fluctuations of temperature are eliminated and uniform low temperature is observed. Furthermore, low oxygen concentration, elimination of audible and visible flame, low level of soot formation are the main characteristics of flameless mode [35]. Sine flameless mode shows complicated performance, analytical and computational investigation of this regime has received more attention especially in macro-scale combustors. Kim et al. [36] compared different reaction mechanisms in natural gas flameless combustion by using four different global reaction mechanisms and setting standard k–ε model and the eddy-dissipation concept (EDC). Dally [37] stipulated that based on the numerical results of centerline temperatures of the combustor achieved by adoption of k–ε and flamelet model, this settings are in good agreement with experimental results for CH_4 flameless combustion. Christo and Dally et al. [38] pointed out that it is necessary to consider differential diffusion effects in CFD modeling due to of calculations accuracy and the numerical results of eddy dissipation concept (EDC) solver shows higher accuracy. Hosseini and Wahid [39] investigated various aspects of biogas flameless combustion numerically. It was found that reaction time and Damköhler number plays crucial role in the computational settings. Although, characteristics of flameless combustion in macro-scale combustors have been developed numerically and experimentally, few documents could be found about micro-scale flameless mode. In the present paper, micro-flameless formation, temperature distribution in the