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Numerical investigations on thermal performance of double-layer four-channel micro combustors for micro-thermophotovoltaic system

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ABSTRACT

In order to extend the output power of the micro-thermophotovoltaic system, it is necessary to assemble multiple single-channel micro combustors into a multiple-channel micro combustor. As a result, how to assemble multiple single-channel micro combustors into a multiple-channel micro combustor comes to be an interesting issue. In this work, the counterflow combustion concept is used in a double-layer four-channel micro combustor, and three representative double-layer four-channel micro combustors are designed. Extensive numerical investigations are conducted to compare the thermal performance of the three different double-layer four-channel micro combustors under various hydrogen mass flow rates, hydrogen/air equivalence ratios and solid materials. Moreover, the purely counterflow double-layer four-channel micro combustor is compared with the counterflow single-layer double-channel micro combustor in our previous work under various H_2 mass flow rates, hydrogen/air equivalence ratios and solid materials. It is found that the purely counterflow double-layer four-channel micro combustor can keep more uniform wall temperature. And the purely counterflow double-layer four-channel micro combustor has better thermal performance compared with that of the counterflow single-layer double-channel micro combustor. Moreover, some critical values are given for keeping the merit of the purely counterflow double-layer four-channel micro combustor.

1. Introduction

With the applications of micro electromechanical systems in different areas, there is a huge demand for the micro power generation systems [1]. The micro-thermophotovoltaic (MTPV) system as a popular and simple system is an alternative project to support energy for the micro electromechanical system [2]. As presented in Fig. 1, it can be seen that the MTPV system mainly consists of micro combustor (emitter), filter and PV cell [3]. The micro combustor is the key component of the MTPV system, which significantly affects the final energy conversion efficiency [4]. As a result, how to improve the thermal performance of micro combustors comes to be an interesting and challengeable issue [5].

Recently, many advanced techniques and methods such as catalytic combustion, porous media combustion, bluff-body combustion, flameless combustion, external heating method and electricity field are proposed and employed. In catalytic combustion, Yan et al. [6] used Rhodium catalyst to improve the stable combustion limit of premixed methane/air combustion in a heat recuperation micro-combustor. Lu et al. [7] used platinum catalyst to inhibit homogeneous reaction and enhance the combustion efficiency in the micro combustor. Chen et al. [8] investigated the effects of combustor dimensions on the combustion stability and combustor performance for optimizing the parallel plate micro-channels with platinum catalytic. In porous media combustion, Yang et al. [9] employed SiC porous media foam in a micro modular combustor for increasing the wall temperature. Pan et al. [10] investigated the effects of porous media materials on flame stability and conversion efficiency of micro combustors. It was found that SiC was still one of the most suitable porous media materials. Li et al. [11] enhanced the heat transfer and flame stabilities of premixed hydrogen/air flames in a planar micro-combustor by partially filled with porous medium. In bluff-body combustion, Bagheri et al. [12] investigated the effects of bluff-body shapes on combustion characteristics and flame stability of lean premixed hydrogen/air flame in a micro-combustor. It was indicated that wall-blade bluff body was the best choice. Wan et al. [13] improved the blow-off limit of lean H_2/air premixed combustion in a planar micro-channel with a bluff body. Fan et al. [14] improved the blow-off limit of CH_4/air premixed flame in a micro Swiss-roll combustor with a bluff-body. In flameless combustion, Hosseini et al. [15] investigated the micro-flameless combustion for reducing the negative

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Nomenclature

$A_{w,i}$	surface area of grid cell i on the outer wall (m^2)
d_1	diameter of the combustion channel at the inlet (mm)
d_2	diameter of the combustion channel at the outlet (mm)
$\overrightarrow{D_j}$	diffusion flux of species j (kg/(m^2·s))
E_f	total fluid energy (J/kg)
h_j	enthalpy of species j (J/kg)
h_0	natural convection heat transfer coefficient (W/(m^2·K))
I	unit tensor
k_{eff}	effective conductivity (W/(m·K))
k_w	thermal conductivity of wall (W/(m·K))
L_1	total length of the single-channel micro combustor (mm)
L_2	step length of the single-channel micro combustor (mm)
L_3	width and height of the single-channel micro combustor (mm)
p	gas absolute pressure (Pa)
Q_{loss}	total heat loss (W)
R_j	net production rate of species j by chemical reaction (kg/(m^3·s))
$\overline{R}_{T,w}$	mean nonuniformity coefficient of wall temperature
S_f^h	fluid enthalpy source term (W/m^3)
T	temperature (K)
T_0	ambient temperature, 300 K
$T_{w,i}$	temperature of grid cell i on the outer wall (K)
$\overline{T}_w$	mean wall temperature (K)
u	specific internal energy (J/kg)
$\vec{v}$	velocity vector (m/s)
x,y	radical coordinate (mm)
Y_j	mass fraction of species j
z	axial coordinate (mm)

Greek letters

ε	wall emissivity
μ	molecular viscosity (Pa·s)
μ_j	chemical potential of species j (J/kg)
ρ	density of gas (kg/m^3)
σ	Stephan-Boltzmann constant, 5.67 × 10^{-8} W/(m^2·K^4)

effects of the conventional micro-combustion on the lifetime of micro-combustor. In external heating method, Zhao et al. [16] mitigated the combustion oscillation by an electrical heater. In external electricity field, Gan et al. [17] investigated the electro-spraying characteristics of ethanol in a small-scale combustor under combined electric field. Then, Gan et al. [18] investigated the combustion characteristics of ethanol flame in small-scale by alternating current electric field. It was shown that the upper stability limit is greatly improved. In other fields, E et al. [19] varied the inlet pressure to achieve a high and uniform wall temperature and the proper inlet pressure was verified by Field Synergy Principle. Zuo et al. [20] used Orthogonal Experimental Design and Fuzzy Grey Relational Analysis to understand the effects of various factors on the emitter efficiency of micro-cylindrical combustor.

Moreover, the improvement of the micro combustor structure offers another way to improve thermal performance of the micro combustors. Vijayan et al. [21] experimentally and numerically investigated the propane/air flame in meso-scale Swiss-roll ceramic combustors. It was found that flame was well stabilized. Furthermore, Vijayan et al. [22] examined the acoustic emissions and preheat temperatures of propane/air flame in meso-scale Swiss-roll ceramic combustors. It was suggested that flame-acoustic interactions had significant effects on flame dynamics. Yang et al. [3] compared the wall temperature of the micro circular tube combustors with and without the heat recuperator. It was found that the wall temperature of the micro combustor with a heat recuperator was more uniform and high. Then, Yang et al. [23] inserted a block in the micro planar combustor for increasing the mean wall temperature and its uniformity. Jiang et al. [24] compared the thermal performances of the micro-combustor with and without baffles. Results showed that the mean wall temperature was improved due to that the heat from exhaust gas was recycled to preheat the cold H_2/air mixture. Zuo et al. [25] improved the micro-cylindrical combustor with a rectangular rib. Results show that the inserted rectangular rib makes a recirculation region at the back of the rectangular rib, enhancing the heat transfer between the back part of the combustor wall and the burned gas. Then, Zuo et al. [26] modified the cavity of the micro-cylindrical combustor, reducing the radical thermal resistance between the combustor wall and the flame. Finally, Zuo et al. [27] developed a micro elliptical tube combustor, enhancing the heat transfer between the combustor wall and the hot gas by adjusting the major/minor axis length ratio of the cross section. Akhtar et al. [28] compared the energy conversion of the curved micro-combustor and the straight micro combustor. It was suggested that the curved micro-combustor had higher conversion efficiency. Tang et al. [29] separated the large and single combustion channel into multiple and small combustion channels. Results showed that the wall temperature of the micro combustor was greatly improved. Su et al. [30] added the number of combustion cavity to improve the radiation efficiency of the combustor. Then, Su et al. [31] improved the traditional single-channel micro combustor into a multiple-channel micro combustor for more uniform and higher wall temperature.

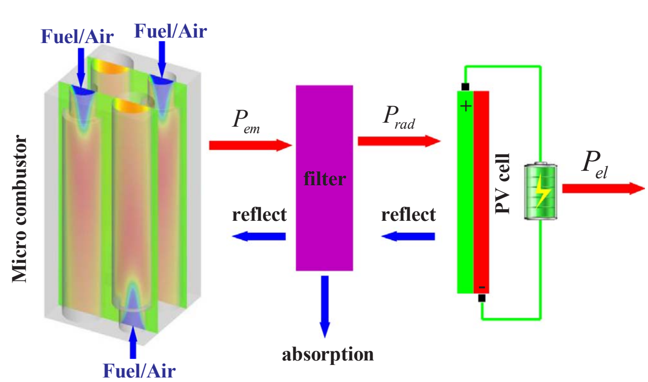

Fig. 1. Schematic diagram of a MTPV system.

Based on the above literature review, it is well known that many scholars have done experimental and numerical works to develop micro combustors with high thermal efficiency, combustion efficiency and blow-off limit. However, the works on how to assemble multiple single-channel micro combustors into a multi-channel for obtaining better thermal performance are rare. In our previous work, the thermal performance of counterflow and coflow double-channel micro combustors is compared. Results show that the counterflow double-channel micro combustor owns better thermal performance [32]. In this work, in order to verify the effectiveness of the counterflow combustion concept in a double-layer four-channel micro combustor, three representative double-layer four-channel micro combustors are designed and compared under various H_2 mass flow rates, H_2/air equivalence ratios and solid materials. Moreover, the purely counterflow double-layer four-channel micro combustor is compared with the counterflow single-layer double-channel micro combustor in our previous work [32] under various H_2 mass flow rates, H_2/air equivalence ratios and solid materials.