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Numerical investigations on an improved counterflow double-channel micro combustor fueled with hydrogen for enhancing thermal performance

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ABSTRACT

In this work, an improved counterflow double-channel micro combustor is designed. Computational Fluid Dynamics software Fluent is used to conduct numerical investigations on the thermal performance comparison between the old and improved counterflow double-channel micro combustors. It is found that the improved counterflow double-channel micro combustor has much higher and more uniform wall temperature compared that of the old one under various hydrogen mass flow rates, hydrogen/air equivalence ratios and solid materials. To make a quantitative comparison, the main results are presented as follows: (a) The improved combustor achieves the largest thermal enhancement at the hydrogen mass flow rate of 5.25×10^{-7} kg/s when the hydrogen mass flow rate is ranged from 5.25×10^{-7} kg/s to 9.8245×10^{-7} kg/s. Namely, the mean temperature of upper and right wall is improved by about 9.66 K and 13.53 K, respectively, and the mean nonuniformity of upper and right wall temperature is reduced by about 23.24% and 26.79%, respectively. (b) The improved combustor achieves the largest thermal enhancement at the hydrogen/air equivalence ratio of 0.6, when the hydrogen/air equivalence ratio is ranged from 0.9 to 0.5. Namely, the mean temperature of upper and right wall is improved by about 27.55 K and 29.55 K, respectively, and the mean nonuniformity of upper and right wall temperature is reduced by about 23.24% and 19.51%, respectively. (c) The improved combustor achieves the largest thermal enhancement at the solid material of silicon carbide when the solid material is changed from quartz to silicon carbide. Namely, the mean temperature of upper and right wall is improved by about 16.77 K and 18.38 K, respectively, and the mean nonuniformity of upper and right wall temperature is reduced by about 26.47% and 28.41%, respectively. Finally, some guidelines are proposed for applications of the improved counterflow double-channel micro combustor in the micro-thermophotovoltaic system.

1. Introduction

Micro/meso combustion is an effective solution for offering the high-temperature heat source for the thermophotovoltaic system [1–3]. However, there are some challenges existed in the application of the micro-thermophotovoltaic (MTPV) system such as low energy conversion efficiency [4–6] and combustion instability [7,8]. Therefore, many advanced techniques and methods such as catalytic combustion [9], porous media combustion [10], bluff-body combustion [11], external heating method [12] and electricity field [13] are proposed and employed. Accordingly, the related research results showed that blow-off limit [14,15], thermal performance [16,17], and combustion emissions [18,19] are greatly improved by these methods.

Among the above performance parameters, the thermal performance of the micro combustors must be concentrated on, which has significant effects on the energy conversion efficiency of MTPV systems. For example, heat recirculation is a useful method. The Swiss-roll combustor fabricated by Gupta and its co-authors [16,20,21] showed good thermal performance due to its heat recirculation structure. Yang et al. [22] used a heat recuperator to improve the mean wall temperature and its uniformity of the micro-cylindrical combustor. Tang et al. [23] fabricated a planar combustor with heat recirculation. Experimental results suggested that the radiation efficiencies of heat recirculation combustor were significantly higher than that of straight-channel combustor. Kim et al. [24] designed a heat-recirculating combustor with multiple injectors. Results show that the designed combustor can sustain effective and uniform heat transfer. Alipoor et al. [25] made a U-shaped microtube in a box with a secondary fluid around

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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)

Acronyms

MTPV	micro-thermophotovoltaic
IHR	inner reactor heat recirculation
OHR	outer reactor heat recirculation

the microtube combustor. The results showed that the establishment of secondary flows caused better preheating in the curved tubes. Bagheri et al. [26] compared thermal performance of inner reactor heat recirculation (IHR) and outer reactor heat recirculation (OHR). It was suggested that IHR micro combustor had better thermal performance. Meanwhile, the inserted structure making recirculation region is also helpful for enhancing heat transfer. For instance, Bagheri et al. [27] found that the mean wall temperature of the micro-combustor with wall-blade bluff body was highest among different bluff bodies (circle, ellipse, diamond, semicircular, half ellipse, triangle, crescent, arrow-head and wall-blade). Jiang et al. [28] fabricated a planar combustor with two optimized baffles. It was found that the planar combustor with baffles achieved high wall temperature with superior uniformity. Pan at al. [29] investigated effects of micro-pin-fin arrays on the performance of the micro-combustor. Results indicated that the maximum surface temperature and mean wall temperature of combustor with fins was much higher than that without fins. Ansari et al. [30] investigated a novel planar micro-combustor with combined baffle and bluff configuration. It was shown that the baffle thickness was the most important design parameter controlling the temperature distribution and uniformity. Zuo et al. [31] improved the micro-cylindrical combustor with a rectangular rib for heat recirculation in the back part of the combustor wall. It was observed that the micro-cylindrical combustor with rectangular rib had higher and uniform wall temperature distribution compared with the traditional micro-cylindrical combustor. Moreover, the improvement of the cavity structure is significant and effective. The separated walls make the flame close to the combustor wall for enhancing heat transfer. Yang et al. [32] and Tang et al. [33] separate the flame in the micro planar combustor by inserted walls. Results indicated that the improvement on wall temperature was obvious. Furthermore, Akhtar et al. [34] investigated effects of cross sections on the wall temperature of micro tube combustors. It was shown that trapezoidal and triangular cross-sections had better thermal performance. Then, Akhtar et al. [35] proposed a curved micro-combustor. The results indicated that the outer wall temperature of the curved micro combustor was 110 K higher than that of the straight ones. Zuo et al. [36] developed a micro-cylindrical combustor with gradually reduced wall thickness. It also can be found that the modification in the combustion chamber achieved better thermal performance. Zuo et al. [37] designed a micro elliptical tube combustor. The results indicated the great potentiality in the field of thermal performance compared with the micro circular tube combustor. In the design of multi-cavity combustors, Su et al. [38,39] proposed a double-cavity micro combustor and a multiple-channel micro combustor for a MTPV system. The numerical results indicated that the wall temperature of the micro combustors was much higher than the regular single-cavity combustor. Zuo et al. [40,41] used the counterflow combustion concept to optimize the traditional double-channel micro combustor and double-layer four-channel micro combustor, respectively. It was concluded that the purely counterflow was the best configuration for the best thermal performance. Finally, special combustion modes are also useful. Hosseini et al. [42] found that the wall temperature of micro combustor was moderate and uniform under micro-flameless mode compared with that under conventional micro combustion mode.

Based on the above literature review, it can be concluded that many authors have done some important works to enhance thermal performance of micro combustors. However, there is still some space to improve the thermal performance of micro combustors. In this work, in order to further improve the thermal performance of the counterflow double-channel micro combustor [40], an improved counterflow double-channel micro combustor is designed. Extensive numerical investigations are conducted for thermal performance comparison between the old and improved counterflow double-channel micro combustors. Furthermore, the thermal performance enhancement mechanism is clarified, which offer us significant reference for the design of multi-channel micro combustor.

2. Mathematical and physical model

2.1. Physical model

In this work, based on the geometrical structure of the single-channel micro combustor in our previous work [40] as presented in Fig. 1(a), the combustion chamber of the single-channel combustor is improved and presented in Fig. 1(b). It can be obviously observed in Fig. 1 that the total dimensions of the two different single-channel micro combustors are the same. Namely, the total length (L_1), width (L_3) and height (L_3) of the two single-channel micro combustors are 18 mm, 4 mm, and 4 mm, respectively. It also can be clearly seen in Fig. 1 that the inlet diameter (d_1) and outlet diameter (d_2) of the two