Energy Conversion and Management 160 (2018) 1–13

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Numerical investigations on different configurations of a four-channel meso-scale planar combustor fueled by hydrogen/air mixture

Wei Zuo[a,b,d], Jiaqiang E[a,b,d,*], Rongming Lin[c], Yu Jin[a,b], Dandan Han[a,b]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
[b] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China
[c] School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University, Singapore 639798, Singapore
[d] Institute of New Energy and Energy-saving & Emission-reduction Technology, Hunan University, Changsha 410082, China

ARTICLE INFO

Keywords:
Meso-scale combustion
Four-channel meso-scale planar combustor
Coflow
Counterflow
Wall temperature

ABSTRACT

Multiple single-channel meso-scale combustors assembling into a multi-channel meso-scale planar combustor is a good solution for elevating the output power of the micro-thermophotovoltaic system. Consequently, how to assembly a multi-channel meso-scale planar combustor for achieving higher output power comes to be an interesting issue. In this work, four representative four-channel meso-scale planar combustors, namely, combustor A, combustor B, combustor C and combustor D are designed. Extensive numerical investigations are conducted to compare the wall temperature of the four combustors under various hydrogen mass flow rates, hydrogen/air equivalence ratios and solid materials. Two variables, namely, mean wall temperature and nonuniformity coefficient of wall temperature are defined for comparing the wall temperature of the four meso-scale combustors. It is found that the purely counterflow four-channel meso-scale planar combustor D has more uniform and higher wall temperature compared with other combustors. Furthermore, the detailed heat transfer mechanisms of four different four-channel meso-scale planar combustors are analyzed and presented. In addition, some critical values are proposed for keeping high and uniform wall temperature on the purely counterflow four-channel meso-scale planar combustor. This work offers us great reference value for the design of multi-channel meso-scale planar combustor.

1. Introduction

With the development of advanced combustion techniques [1], micro/meso-scale combustion has been an effective and promising method to convert chemical energy into electricity for supporting micro/meso-scale mechanical systems [2]. It is attributed to that micro/meso-scale power generation systems driven by combustion of hydrocarbon fuels own higher energy densities than chemical batteries [3]. However, the energy conversion and output power of the micro thermophotovoltaic system is still low for practical application. As shown in Fig. 1, it can be concluded that the micro combustor is one of the most important components in the micro thermophotovoltaic system [4]. This is due to that the combustion chemical reactions occur here, and it is the most significant energy conversion process for electricity generation [5]. Consequently, lots of experts and authors have done some important and interesting works on micro/meso combustors for elevating the energy conversion and output power of the micro thermophotovoltaic system.

Concentrated on single-channel micro/meso combustors, some effective methods are proposed and applied. Firstly, Ran et al. [6] used catalyst in the micro-channel with convex wall cavity. It was observed that the heat transfer was enhanced and more uniform temperature distribution was achieved. Pan et al. [7] compared the premixed methane-air flames in catalytic and non-catalytic rectangular micro channel. Results showed that the addition of catalyst in the channel made the outer wall temperature more uniform. Then, Yang et al. [8] used the SiC porous medium foam to enhance heat transfer between the hot gas and the wall for increasing the wall temperature of a micro modular combustor. Pan et al. [9] compared effects of SiC, Si_3N_4 and Al_2O_3 porous media material on heat transfer of micro combustor. It was found that SiC had the best effects. Kang and Veeraragavan [10] investigated silicon carbide porous media micro combustor with different walls for mesoscale thermophotovoltaic system. It was found that the combination of silicon carbide porous media and quartz walls had the largest power generation. Aravind et al. [11] integrated micro combustor with three backward facing steps and porous media into a micro power generator. Experimental results indicated that a power density of 0.12 mW/mm^3 was achieved. Finally, E et al. [12] increased

* Corresponding author at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China.
E-mail address: ejiaqiang@hnu.edu.cn (J. E).

https://doi.org/10.1016/j.enconman.2018.01.033
Received 30 October 2017; Received in revised form 26 December 2017; Accepted 14 January 2018

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 meso-scale combustor (mm)
L_2	step length of the single-channel meso-scale combustor (mm)
L_3	width and height of the single-channel meso-scale 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))
$R_{T,w}$	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)

the wall temperature and its uniformity by adjusting the inlet pressure of the micro-cylindrical combustor. Apart from the above methods, the advances in the cavity structure of micro combustors should be paid much attention. Swiss-roll combustor has good heat recirculation performance [13]. Shirsat and Gupta [14] demonstrated that methanol and kerosene both achieved above 90% thermal efficiency in the meso-scale heat-recirculating combustors. Yang et al. [15] fabricated a micro-cylindrical combustor with a heat recuperator and used it in a micro-thermophotovoltaic system. It was indicated that the electrical power of the micro-thermophotovoltaic system with a heat recuperator was significantly increased. Kim et al. [16] developed a heat-recirculating combustor with multiple injectors. It was suggested that the uniform heat transfer was achieved for a wide operating range due to the usage of a recuperator. Jiang et al. [17] used two baffles to form a heat recirculation chamber in a micro planar combustor and employed it in a micro thermophotovoltaic system. It was shown that the system efficiency was twice higher than before. Tang et al. [18] experimentally investigated a micro-planar combustor with heat recirculation. Results showed that the radiation efficiencies of micro-planar combustor with heat recirculation are obviously higher than that without heat recirculation. Bagheri and Hosseini [19] numerically investigated and compared inner reactor heat recirculation and outer reactor heat recirculation. It was found that outer reactor heat recirculation had a higher range of emitter efficiency. Zuo et al. [20] inserted a rectangular rib in a micro-cylindrical combustor with. It was found that the heat recirculation zone formed at back of the rectangular rib greatly promoted the mean wall temperature and its uniformity. Expect the effects of heat recirculation brought by combustor structure, other improvements on combustion chamber also play significant effects. Akhtar et al. [21] investigated the effect of reactor cross sections on the wall temperature. It was found that trapezoidal and triangular cross-sections had better performance. Zuo et al. [22] gradually varied the wall thickness of the micro-cyclindrical combustor with a step. It was also indicated that the modified micro tube combustor owned better thermal performance. Then, Zuo et al. [23] developed a micro elliptical tube combustor to enhance 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. [24] 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. Su et al. [25] designed a novel double-cavity micro combustor for a micro thermophotovoltaic system. It was found that the new combustor obtained higher and more uniform temperature. Yang et al. [26] separated the flame in a micro-planar combustor by an inserted block, which pushed the flame close to the combustor wall, while Tang et al. [27] separated the micro planar combustor into multiple channels. Their results suggested that the wall temperature and its uniformity of the micro planar combustor were obviously improved.

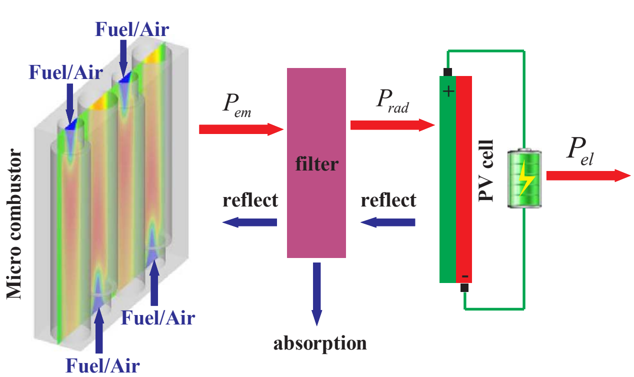

Fig. 1. Schematic diagram of a MTPV system.

However, the potentiality of the output power of the thermophotovoltaic system based on a single-channel micro/meso combustor is limited. Therefore, multiple individual single-channel micro combustors assembling into a multiple-channel micro combustor is a good solution. Su et al. [28] proposed a multiple-channel micro combustor based on the single-channel micro combustor. Results suggested that the multiple-channel micro combustor had more uniform and higher wall temperature compared with that of the single-channel micro combustor. Zuo et al. [29] developed a counterflow double-channel micro combustor. It was found that the wall temperature of the counterflow double-channel micro combustor were more uniform than that of the coflow double-channel micro combustor. Then, Zuo et al. [30] extended this counterflow combustion concept in a micro-cubic combustor. Results suggested that the thermal performance of the purely counterflow micro-cubic combustor was much better than that of the counterflow double-channel micro combustor.

As a result, based on the above research on micro/meso combustors, it can be found that no researches have been done to assembly multiple single-channel meso-scale combustors into a multi-channel meso-scale planar combustor for improving the energy conversion efficiency and