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The effect of embedded high thermal conductivity material on combustion performance of catalytic micro combustor

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ABSTRACT

A novel micro combustor embedded with high thermal conductivity material has been proposed for micro-thermophotovoltaic system application. The effect of the materials, which is graphite and nickel with widths 1 mm and 3 mm on the thermal and radiant performance of the new micro combustor, was experimentally and numerically investigated. It was found that high and uniform temperature distribution along the walls of the combustor was obtained by embedding graphite with width of 1 mm because of the enhanced heat transfer, which is desirable for the micro-thermophotovoltaic system. The available radiation energy increased from 4.6 W for the conventional combustor to 5.2 W for the novel combustor when the inlet velocity was 1.0 m/s and the hydrogen/oxygen equivalence ratio was 0.5 under the experimental conditions. The available radiation efficiency increased from 8.9% to 9.8% and the effect of the embedded material could be enhanced by increasing the chemical energy input. Based on the combustor and fuel in this study, the conditions for good thermal performance are graphite with width of 1 mm, inlet velocity of 1.0 m/s and 0.5 equivalence ratio of hydrogen/oxygen by considering the reliability and durability of the combustor.

1. Introduction

Microscale combustion is gradually gaining ground worldwide and is being studied by scholars as a kind of energy supply unit that is stable, lasting and small scaled. Chou et al. [1] summarized the development of micro power generators. Ju et al. [2] summarized the development of microscale combustion. Yang et al. [3] developed a micro-thermophotovoltaic (MTPV) system with heat recuperation and obtained an output power of 1.26 W. Bani et al. [4] studied porous media based MTPV system as an application of micro combustion and obtained an output power of 2.7 W. The chemical energy of fuel is converted to radiant energy by combustion, and the photoelectric materials absorb radiation to generate electrical power [5]. It has the advantages of being stable, no moving parts, low cost and environment friendly. Micro combustor as an important part of MTPV systems, the combustion in the channel and the thermal performance of the wall has a direct impact on the energy conversion efficiency of the MTPV system. Increasing the outer wall temperature is beneficial to improve the power output and energy conversion efficiency [6]. To this end, many scholars have done a lot of research on these two aspects. The combustion stability, the combustion efficiency and the combustion characteristics are widely studied in the field of combustion. Such as the extinction limits of catalytic combustion by Maruta et al. [7], the stability of the methane/air combustion by Karagiannidis et al. [8], the flame dynamics by Bagheri et al. [9] and the catalytic combustion characteristics by Pan et al. [10].

The effect of thermal performance is mainly reflected in the wall average temperature and temperature difference. Therefore, the effects of the structure, materials on the micro combustion have been extensively studied. Park et al. [11] experimentally studied a cylindrical micro combustor with an annular-type shield, which could provide stable combustion and uniform temperature distribution. An output power of 2.4 W and overall efficiency of 2.1% was obtained under optimized operating conditions. Jiang et al. [12] proposed and studied a micro combustor with heat recuperation. The wall temperature had a higher peak value and better uniformity due to the preheating by the exhaust and a system efficiency of 4.1% was obtained. Kim et al. [13] found that the finned recuperator could enhance the average temperature of the outer wall of the emitter, and the estimated thermal efficiency was 59.6%. Tang et al. [14] investigated the combustion characteristics of propane/air in the reheat channel. The result showed that although increasing the inlet velocity resulted in higher wall temperature, the radiation efficiency did not improve. It means that the uniformity of temperature distribution is an important parameter for the radiant efficiency.

The multichannel combustor is another method of improving the

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Nomenclature

A	cross-sectional area of embedded material
$A(i)$	area of each micro cells
c_p	constant pressure thermal capacity
C_R	reference combustor
C_{1Ni}	combustor embedded with 1 mm nickel
C_{1G}	combustor embedded with 1 mm graphite
C_{3Ni}	combustor embedded with 3 mm nickel
C_{3G}	combustor embedded with 3 mm graphite
D_i	mass diffusivity for species i
$E_{b\lambda}(i)$	monochromatic emissive power of micro cells
h	natural convection coefficient
h	enthalpy
h_i^0	enthalpy of formation for species i
HTCM	high thermal conductivity material
MTPV	micro-thermophotovoltaic
M_i	molar weight for species i
P	pressure
P_{in}	chemical energy input of the inlet
P_{tr}	total radiation power of wall
P_{ar}	available radiant power of the outer wall
Q_V	volume flow rate of inlet
Q_{LHV}	lower heating value of hydrogen
R	thermal resistance of embedded material
R_Y	thermal resistance of the wall along the Y-axis
R_Z	thermal resistance of the wall along the Z-axis
t	time
$T(i)$	temperature of each sampling point
T_w	outer wall temperature
T_0	room temperature
$\overline{T}$	inlet velocity
Δt	temperature difference between the adjacent nodes
ΔT	temperature difference
$\boldsymbol{u}$	velocity vector
u_i	velocity composition
v_{in}	inlet velocity
x_i	displacement coordinate
Y_i	mass fraction for species i

Greeks

γ_i	stoichiometric ratio for species i
Φ	equivalence ratio
ω_i	reaction rate for species i
ρ	density
λ	thermal conductivity
λ_g	maximum wavelength that can pass the photocell band gap
δ	Stefan-Boltzmann constant
δ_a	distance between the adjacent nodes
ε	emissivity
μ	viscosity
η_a	radiation efficiency of the combustor

thermal performance. Su et al. [5] found that the wall temperature of the multi-channel micro combustor is more uniform and the average temperature is higher. Sui et al. [15] investigated the combustion and heat transfer characteristics of a micro reactor equipped with six platinum channels. The surface temperature difference of 18.6 K and maximum surface temperatures of 1311 K was obtained in the counterflow configurations. The radiation efficiencies increased to 76%. Zuo et al. [16] found that the mean temperature and the mean uniformity were improved in the counterflow double-channel micro combustor, which is beneficial to the MTPV system. The bluff body or cavity can enhance the turbulence in the channel. Akhtar et al. [17] found that the increased vorticity formed by the cavity could enhance the efficient heat transfer in the recirculation region. Yilmaz et al. [18] numerically investigated the effect of distance of backward facing step and cavity on the combustion and emission behavior because varying the structure is an economical way to improve the performance of the combustor.

The material of the combustor is also an important factor. Vijayan et al. [19] investigated the combustion and heat transfer characteristics of the heat recuperation with different materials. The results showed that lower thermal conductivity of the wall could attain higher flame temperature due to the less heat loss. Wan et al. [20] numerically studied the effect of thermal conductivity of solid wall on the combustion efficiency. The wall with large thermal conductivity can preheat the inlet gas more efficiently. Zhou et al. [21] investigated the combustion process in combustors made by different materials. The copper combustor has lower and uniform surface temperature, and the lower heat loss. It is due to the higher wall thermal conductivity and makes the heterogeneous reaction to dominate. Yan et al. [22] investigated the combustion in heat recuperation micro combustors with different materials. The results showed that the combustor with copper baffles has uniform temperature distribution and best preheating effectiveness. Pan et al. [23] studied the effect of catalyst in the micro combustor. Their results showed that the location of the catalyst segmentation has significant influence on the surface temperature distribution.

In summary, many scholars have done some important works to enhance the performance of micro combustors. However, the performance of micro combustors can be further improved with cost minimization and ease of construction. Since the temperature of the H_2/O_2 premixed flame is usually higher than 2000 K and the maximum working temperature of PV material (GaSb) is 400 K. This is a high requirement for the wall material of the combustor. While meeting high temperature resistance, the high thermal conductivity and emissivity are also required to ensure high average temperature and small temperature difference on the wall, which could make the radiation efficiency higher [24].

In this study, a novel catalytic micro combustor embedded with high thermal conductivity material (HTCM) in the wall was designed. The experimental and numerical investigations were conducted for the comparison of the performance between the conventional and novel micro combustors. The effects of the HTCM on the thermal and radiation performance of the combustor under different operating conditions were obtained by analyzing the wall heat transfer, catalytic reaction and wall radiation. Furthermore, the thermal performance enhancement mechanism obtained from the study can offer significant reference for the design of the novel micro combustor.

2. Experimental apparatus

The experimental apparatus as shown in Fig. 1 consists of a gas supply system, a monitoring system and a catalytic combustor. The gas supply system which consists of gas cylinders and flow meters provided stable source of hydrogen and oxygen with purity of 99.9%. The inlet volumetric flow rate of premixed fuel H_2/O_2 was controlled by calibrated flow meters, with a volume flow range of 0–1000 mm^3/min and the accuracy of flow meters is ± 1% of full scale. The range of inlet velocity was set from 0.75 m/s to 1.5 m/s and the equivalence ratio was set from 0.25 to 0.5. The wall temperature was measured by infrared thermal imager (ThermoVisionTMA40) and it can detect the temperature change between −40 and 2000 °C with measurement accuracy of ± 2%. The camera resolution is 320 × 240, and its minimum focal length is 9 mm. The camera chip records the 12 × 20 mm^2 surface onto