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Effects of inlet pressure on wall temperature and exergy efficiency of the micro-cylindrical combustor with a step

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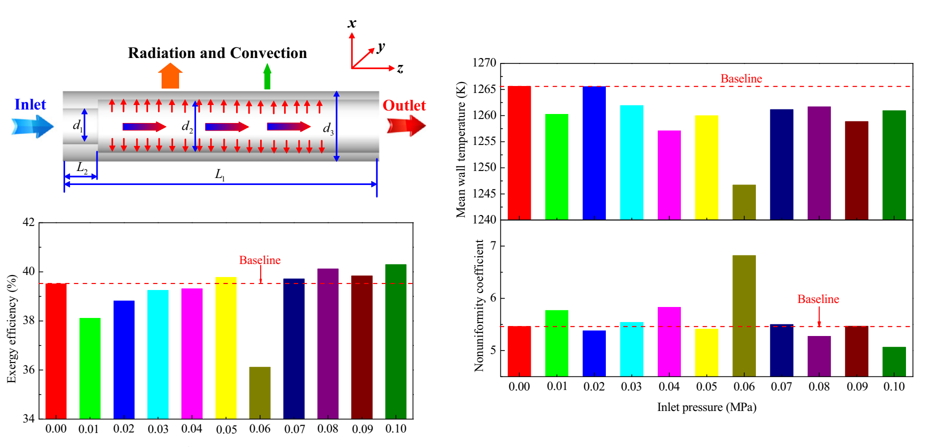
HIGHLIGHTS

- Variation of velocity, temperature and specific entropy field is obtained.
- Effects of inlet pressure on wall temperature and exergy efficiency are investigated.
- A variable $R_{T,w}$ is adopted to characterize the uniformity of wall temperature.
- The best performance for energy usage is obtained at $p_{in} = 0.1$ MPa.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy conversion efficiency of a micro thermophotovoltaic (TPV) system strongly depends on wall temperature of micro combustors and its uniformity. In this work, a 3D numerical model is built to investigate effects of inlet pressure on premixed H_2/air combustion in a micro-cylindrical combustor with a step. The variation of velocity, temperature and specific entropy field are analyzed. Moreover, in order to characterize the uniformity of wall temperature, a nonuniformity coefficient $R_{T,w}$ is introduced. Results suggest that the variation of velocity, temperature and specific entropy field is mainly existed at the reaction and outlet regions. And the highest mean wall temperature (1265.59 K) is arrived at $p_{in} = 0$ MPa, while the lowest nonuniformity coefficient $R_{T,w}$ (5.06) and the highest exergy efficiency (40.29%) is approached at $p_{in} = 0.1$ MPa. In the viewpoint of energy usage, the micro combustion system has the best performance at $p_{in} = 0.1$ MPa due to that it has the potentiality to obtain better energy conversion efficiency and higher exergy efficiency. This work provides us a direction to improve the performance of the micro combustor without changing the structure of the micro combustor, and can combine with other optimization methods.

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Nomenclature

A_i	surface area of grid cell i (m^2)
E_f	total fluid energy (J/kg)
E_{des}	exergy destructive (W)
E_{loss}	energy brought away by the exhaust gas (W)
h_0	natural convection heat transfer coefficient, 10 W/(m^2 K)
h_j	enthalpy of species j (J/kg)
I	unit tensor
$\vec{J}_j$	diffusion flux of species j (kg/(m^2 s))
k_{eff}	effective conductivity (W/(m K))
k_w	thermal conductivity of wall (W/(m K))
L	length of the micro combustor (mm)
$\dot{m}$	flow rate of gas (kg/s)
$\dot{m}_{H_2}$	flow rate of hydrogen (kg/s)
n_j	number density of species j
p	gas absolute pressure (Pa)
p_{in}	gauge pressure of inlet (Pa)
Q_{LHV}	lower heating value of hydrogen, 119.96 MJ/kg
R_j	net production rate of species j by chemical reaction (kg/(m^3 s))
$R_{T,w}$	nonuniformity coefficient of the wall temperature
S_f^h	fluid enthalpy source term (W/m^3)
s	specific entropy (J/(kg K))
S_{gen}	total entropy generation (W/K)
T	temperature (K)
T_0	ambient temperature (K)
$T_{w,i}$	temperature of grid cell i at the wall (K)
$\bar{T}_w$	mean wall temperature (K)
u	specific internal energy (J/kg)
$\vec{u}$	velocity vector (m/s)
x, y	radial coordinate (mm)
Y_j	mass fraction of species j
z	axial coordinate (mm)

Greek letters

ε	wall emissivity
$\eta_{\prod}$	exergy efficiency
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)

1. Introduction

Micro Power Generation Systems (MPGS) are the promising power generation systems for solving the problem of driving micro machine systems [1–3]. As the micro combustor is one of the most important components of the MPGS [4,5], it has drawn lots of attention and many authors have made great contributions to it, especially in increasing mean wall temperature and its uniformity, improving the fuel conversion efficiency and extending the blow-off limit [6–11].

In order to improve the energy conversion efficiency, lots of methods have been investigated and tested. Heat recirculating is taken to be an efficient method. The Swiss-roll combustor as the recirculated combustor was investigated by Vijayan, Gupta, Shirsat and Wierzbicki et al. [12–15]. It was shown that the flow recirculation in the combustion zone transferred the reaction heat to the incoming unburned and cold reactants through the combustor wall, serving as an ignition source. However, Yang, Chou and Taywade et al. [16–18] employed the recuperator for improving the combustor wall temperature. The principle was that the hot exhaust flowed out the micro combustor, then flowed into the region between the recuperator and the micro combustor, reheating the outer wall of the combustor. Moreover, porous media [19–23] was employed in a micro combustor to enhance the heat transfer between the high temperature combustion products and the emitter wall. Finally, catalyst assisted combustion [24–28] was an advanced technique to strengthen chemical reaction and increase fuel energy conversion efficiency.

However, the irreversible energy loss in fuel combustion cannot be ignored. Jejurkar and Mishra [29] investigated the relationship between wall thermal conductivity and micro-combustor performance. Results suggested that wall heat losses at higher thermal conductivities adversely affected the exergetic performance of micro-combustor, and wall thermal conductivity in the range 0.1–1.75 W/m K was suitable for obtaining uniform wall temperature and high exergetic efficiency. Datta [30] investigated diffusion flames in a confined geometry at various gravity levels for finding the effects of gravity on entropy generation rate and second law efficiency. Results showed that the entropy generation rate due to heat transfer increased considerably at normal gravity compared to that at zero gravity, while the entropy generation rate due to chemical reaction and mass transfer remained almost unaltered at all gravity levels. The lowering of the total entropy generation rate and the corresponding exergy destruction increased the second law efficiency of a confined diffusion flame at reduced gravity compared to that at normal gravity. Briones et al. [31] conducted a theoretical-numerical analysis to examine the propagation of laminar H_2-enriched CH_4–air flames. Results showed that with the increase of H_2 addition to methane fuel, the integrated entropy generation increased primarily due to enhanced heat conduction and chemical reactivity. Chen et al. [32–34] applied the lattice Boltzmann model to solve the governing equations for the combustion process and entropy generation in premixed and non-premixed hydrogen/air combustion. Moreover, Emadi and Emami [35] investigated the local entropy generation and the exergy loss in a turbulent nonpremixed H_2-enriched CH_4–air bluff-body flame. It was found that entropy generation and exergy loss decreased by H_2 addition. Jiang et al. [36] investigated the H_2/air premixed flame under different inlet velocities and H_2/air equivalence ratios, showing a higher flow velocity and higher H_2/air equivalence ratio increased entropy generation rate and the usage of heat recuperator decreased the rate of entropy generation. Then, the entropy generation distribution of H_2/air premixed flame in micro-combustors with baffles was investigated, finding that a higher baffle leads to more entropy generation and larger destruction of available energy [37]. Finally, the volumetric entropy generation rate distributions and exergy losses of fuel lean premixed CO/H_2/air flames in a micro-scale cylindrical channel was investigated. It was indicated that the entropy generation rate induced by chemical reaction was suppressed by adding more CO to the mixture [38]. Yang et al. [39] proposed a novel micro combustor with block insert. Results suggested that the micro combustor obtained the highest mean wall temperature with the lowest entropy generation at the gap length of 4.2 mm.

Although the wall temperature and the entropy generation of premixed H_2/air combustion has been widely investigated, to the best of authors' knowledge, no study has so far been carried out to investigate the effects of inlet pressure on the exergy efficiency of premixed H_2/air combustion in the micro combustor. Be different from our previous work [40], a 3D model is built to investigate