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Effects analysis on combustion and thermal performance enhancement of a nozzle-inlet micro tube fueled by the premixed hydrogen/air

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ABSTRACT

An investigation of premixed H_2/air combustion in a nozzle inlet micro tube has been carried out. The effects of inlet shape on combustion characteristics, flow field, specie distribution and thermal performance are presented and discussed. Also, effects of inlet mass flow rate and equivalence ratio on the entropy generations of combustion in the micro tubes are analyzed. The results show that the mean outer wall temperature and the emitter theoretical radiant efficiency of the nozzle inlet micro tube is higher than that of the straight micro tube. The total entropy generation rate of the nozzle inlet micro tube is lower than the straight micro tube. Moreover, the Inlet 2 and Inlet 3 nozzle inlet micro tube obtain a higher mean outer wall temperature and a lower exergy destruction, which are more appropriate for the application of the micro thermophotovoltaic (TPV) system.

1. Introduction

As a relatively new and miniaturized device [1–3], the urgently need of multi-functionalization, long lifetime, rechargeable power supplies and powerful energy source, has accelerated dramatically the research on micro-power devices (such as micro thermophotovoltaic (TPV) systems) in last decades [4,5]. However, combustion in micro reactors is still a challenging issue, due to the flame instabilities, narrow operational range, non-uniform wall temperature and very low efficiency [6,7]. The large surface-area–to–volume ratio of micro combustor will reduce the time availability for combustion reaction and flame stability and lead to high heat loss through the wall [2,8,9]. To address these issues, Chen et al. [10] constructed a combustion stability diagram, which indicates that gap size, wall thickness [7,11] and combustor length [6,12] have great effects on micro combustion stability. Hua et al. [13] found that micro combustion can be stabilized by increasing the ratio of gas residence time to chemical reaction time [14]. In order to prolong the time availability for the micro combustion reaction to occur, various micro combustor designs have been proposed [15,16], the bluff body [17], backward-facing step [18,19] and cavity-combustor [20,21] are taken into account and they do enhance the flame stability. Besides, the employment of catalytic [22,23] and porous media [24,25] in micro combustor chamber can also dramatic change the combustion reaction characteristic, flame stability and thermal performance. The reduce of heat loss is an useful way to solve the flame instability issue, Hossain and Nakamura [26] found that preheating the incoming fuel contributes to the combustion stabilization, Wang et al. [27] improved the flame stability in micro reactor by providing a warm external surrounding. In addition, reducing heat loss through the wall could be responsible for flame propagation in micro combustors [2,28].

The importance of heat transfer from hot gas to inner wall is a function of energy output in the application of the micro TPV system [29,30]. In particular, the adoption of heat recirculation in

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Nomenclature

A_i	the area of element surface i, m^2
C_{pm}	the specific heat of species m, J/(kg·K)
D_m	the mass diffusion coefficient, m^2/s
$E_{destruction}$	the exergy destruction,W
h_{mo}	the reference enthalphy of species m
k_m	the thermal conductivity of species m, W/(m·K)
m_{H2}	the hydrogen mass flow rate, kg/s
Q_c	the hydrogen higher heating value, MJ/kg
r_m	the chemical reaction rate of species m
R_{gm}	the specific gas constant, J/(kg·K)
S_{mo}	the reference entropy of species m
$S_{conduction}$	the volumetric entropy generation caused by thermal conduction, W/(m^3·K)
$S_{diffusion}$	the volumetric entropy generation caused by mass diffusion, W/(m^3·K)
$S_{reaction}$	the volumetric entropy generation caused by chemical reaction, W/(m^3·K)
S_{total}	the total entropy generation rate, W/K
T	the gas temperature, K
∇T	the gas temperature gradient, K/m
T_0	the dead state temperature, K
$T_{w,i}$	the outer wall temperature of element surface i, K
X_m	the mass fraction of species m
∇X_m	the mass fraction gradient of species m, 1/m
∇Y_m	the mole fraction gradient of species m, 1/m

Greek letters

ε	the emissivity of the wall
η	the emitter theoretical radiant efficiency
μ_m	the chemical potential, J/k
ρ	the gas density, kg/m^3
σ	the Stephan-Boltzman constant, σ=5.67 × 10^{-8} W m^2 K^{-4}
Φ	the equivalence ratio

micro reactors can enhance flame stability, which can also improve the combustor's wall temperature and efficiency of the micro TPV system [31,32]. This can be explained by the fact that heat recirculation and flow recirculation affect the flame blow-off limit [33], and the recirculation zone improves the combustion stability and the outer wall temperature [34]. Bagheri and Hosseini [35] observed that flammability and blow-off limits are significantly extended by preheating the reactive mixture. Tang et al. [36] indicated that the radiation efficiency of combustor's external wall is improved in a micro combustor with heat recirculation. Furthermore, both inner reactor and outer reactor heat recirculation in combustor are effective [35,37], and added porous media into combustors is a direct method to enhance heat recirculation [24,25]. However, the thermal performance and chemical structure formed in micro combustors are affected by excess heat recirculation [26] and remarkable efforts are still needed.

Interactions between molecular diffusion and thermal diffusion play a key role in flame propagation of micro combustion [28], as the fuel of micro combustion, hydrogen has original high heating value, fast diffusion velocity, short combustion reaction time and high flame speed [1]. Furthermore, the hydrogen blended hydrocarbon fuel can also contribute to overcome the shortcomings of micro flame instability [38–40], Yilmaz et al. [41] revealed that the quality of fuel-air mixing process, gas and wall temperature distributions, and the ratio of fuel energy to utilizable heat can improve micro combustion performance. A high and uniform outer wall temperature profile of micro combustor is especially important for the application [11,42,43]. The change of flow field in micro combustor can optimize the temperature distribution and uniformity [44,45], such as the micro combustor with multi-tube [46,47] enhancing the heat transfer of gas to inner wall and improving the outer wall temperature. Pan et al. [48] proposed a combustor with fins obtaining a higher value of maximum surface temperature, and the block insert can also enhance the heat transfer and reduce entropy generation of micro combustor [49].

Furthermore, the high heat loss from outer wall and outlet of combustor also imply that the micro combustor has great potential to improve the efficiency of the integrated system [29]. In order to extend the limit of micro combustion flame stability, improve the wall temperature and energy conversion efficiency of the micro TPV system and expend its application, a nozzle-inlet micro tube is proposed. The effects of inlet shape on combustion characteristics of premixed H2/air in micro tubes, that is, flow field, species distribution and thermal performance are investigated. The entropy generation analysis [50–53] of premixed H2/air combustion in the micro tube is also adopted, to identify the causes of inefficiency and conceive the possibility of globally more effective systems.

2. Mathematical-physical model of combustion

2.1. Physical model of micro tube

A three-dimensional micro tube with nozzle inlet is modeled and investigated in this study. Fig. 1 depicts the geometric construction and parameters of the micro tube with a schematic diagram of heat transfer. δ ($\delta = 0.5$ mm) is introduced to illustrate the micro tube dimensions, both the wall thickness and the largest gap of backward-facing step are δ, while inner diameters of the inlet and the outlet are 4δ, and the overall length of micro tube is 18 mm. As for the nozzle inlet section, which has a gradual change inner diameter and the length of it is L_{in}, and the minimum inner diameter before the backward-facing step is 2δ, the extreme length of L_{in} is 6δ.

2.2. Boundary conditions and grid division

The three-dimensional physical model of micro tubes are calculated and modeled in the software ANASYS-FLUENT 14.0, which coupling the pressure and velocity by the SIMPLE method [24]. Due to the nozzle inlet section and the step can sharply change the flow field in the combustion chamber, the standard k-ε model and the steady state model are adopted [5,29]. Furthermore, the interface of fluid and inner wall takes the coupled thermal condition, the micro combustion reaction employs a detailed H_2/air

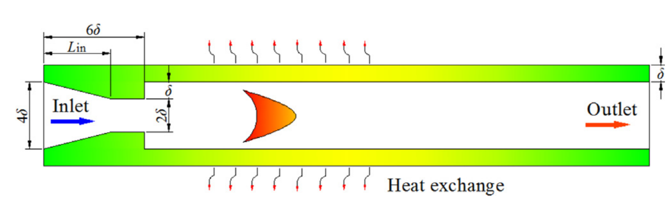

Fig. 1. Geometries of the micro tube.