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Research Paper

Field synergy analysis of the micro-cylindrical combustor with a step

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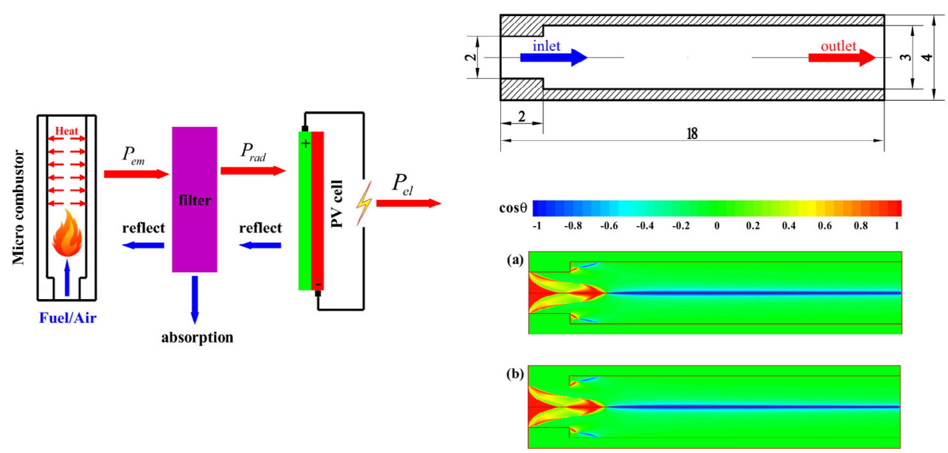
HIGHLIGHTS

- A micro-cylindrical combustor is simulated under various inlet pressures.
- Outer wall temperature and outlet temperature are obtained.
- Field Synergy Principle is employed to investigate the synergy degree.
- Combustion efficiency of two kinds of micro-cylindrical combustors is compared.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to obtain high power density and performance efficiency, it is important for a micro combustor to achieve a high and uniform wall temperature distribution in the micro thermophotovoltaic (TPV) system. In this work, a new method of finding a proper inlet pressure is proposed. Then, Field Synergy Principle is employed to investigate the synergy degree between the velocity vector and temperature gradient in the micro-cylindrical combustor under various inlet pressures. The results indicate that the temperature distribution along the wall of the micro combustor is more uniform, and the mean wall temperature is increased due to the increase of synergy degree at an inlet pressure of 0.08 MPa. Finally, the combustion efficiency and outlet temperature of two kinds of micro-cylindrical combustors with the largest synergy degree and without are compared, showing that the micro-cylindrical combustor with the largest synergy degree is larger than that without it.

1. Introduction

With the development of micro-electromechanical systems (MEMS), great attention has been paid to the study of Micro Power Generation Systems (MPGS) because of its advantages of high energy density, small size and long working time [1–5]. To address this hot topic, various types of MPGS, such as micro turbine engine [6], micro rotary engine [7], micro free piston engine [8], micro thermoelectric system [9], and micro-TPV system [10,11], are being developed. Among the MPGS, the micro-TPV system has a simple structure and is easy to obtain stable energy output. The working principle of MTPV system is shown in Fig. 1 [12]. The chemical energy of fuel is released by combustion and the wall of

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combustor is heated, reaching a high-temperature state and emitting photons. Then, the short-wave radiation will transmit the filter and arrive at the surface of PV cells. Finally, free electron can be generated because of photoelectric effect. As a result, the output power density and energy conversion efficiency of the MTPV system are directly influenced by the micro combustion process and the outer wall temperature.

Because of this, some brilliant researches on the micro-thermal photovoltaic system have been carried out in recent years. S. K. Chou et al. [13], W. M. Yang et al. [14], J. Li et al. [15], and J. F. Pan et al. [16] employed porous media in a micro combustor, indicating that packing the combustor with porous media can significantly enhance the heat transfer between the high temperature combustion products and the emitter wall. Then, another method was proposed; Wenming Yang et al. [12,17] designed and tested a quartz glass recuperator to recirculate the exhaust gas to reheat the outer wall of the combustor and preheat the incoming cold reactant. Results have shown that the mean wall temperature of the combustor with heat recuperation can be increased, and the wall temperature experiences better uniformity due to heat recuperation. In 2012, W. M. Yang et al. [18] studied three micro modular combustors with different fuel supply systems. The results indicated that both the in-line design with two fuel supply tubes and the parallel design could equally deliver the fuel/air mixture to every combustor, and a uniform temperature distribution could be obtained for every combustor.

The above studies present that the wall temperature of micro combustors in MPTV systems has drawn lots of attention and good results were achieved. However, the mechanism of improving the wall temperature of micro combustor and its uniformity is not clearly revealed. In this work, the effects of inlet pressure on wall temperature and outlet temperature of a micro-cylindrical combustor are experimentally and numerically investigated. The Field Synergy Principle is employed to investigate the synergy degree between velocity vector and temperature gradient in this combustor under various inlet pressures, offering a method and explanation for further improvement of the system working performance.

2. Construction and verification of a computational model

2.1. Geometric model

In this work, an identical model of micro cylindrical combustor with a step is designed as presented in reference [19]. The dimensions of the micro-combustor are shown in Fig. 2. In Fig. 2, premixed hydrogen–air flow into the micro-combustor through the inlet with the diameter of 2 mm. The exhaust will be expelled out from an outlet with the diameter of 3 mm. Silicon is applied as the material of combustor wall, and the specific heat capacity, thermal conductivity and density of it are 700 J/(kg·K),148W /(m·K) and 2340 kg/m^3, respectively.

2.2. Mathematical model

Considering the chemical energy released from combustion and heat loss to the surrounding, an energy balance is achieved. As a result, a steady-state model is employed. The body force and heat transport caused by concentration gradients can be ignored because of their small magnitude. Based on these, the following assumptions are made: (a) steady-state combustion; (b) no Dufour effects [20]; (c) no work done by pressure and viscous forces; (d) insert wall with no surface reactions; and (e) no gas radiation [21]. The conservation equations of mass, momentum, energy and species are expressed as follows:

Conservation equation of mass

$$\frac{\partial}{\partial x}(\rho u)+\frac{1}{r}\frac{\partial}{\partial r}(\rho v r)=0 \tag{1}$$

where ρ is the density, u is the velocity component in the x direction, and v is the velocity component in the r direction.

Conservation equation of momentum

$$\begin{cases}\frac{\partial}{\partial x}(\rho uu)+\frac{1}{r}\frac{\partial}{\partial r}(\rho uvr)=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\frac{4}{3}\mu\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u}{\partial r}\right) \\ \quad -\frac{\partial}{\partial x}\left(\frac{2\mu}{3r}\frac{\partial}{\partial r}(vr)\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial v}{\partial x}\right) \\ \frac{\partial}{\partial x}(\rho uv)+\frac{1}{r}\frac{\partial}{\partial r}(\rho vvr)=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial r}\right)+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right) \\ \quad -\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{2r\mu}{3}\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{4r\mu}{3}\frac{\partial v}{\partial r}\right)-\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{2}{3}\mu v\right)\end{cases} \tag{2}$$

where p is the pressure, and μ is the dynamic viscosity.

Conservation equation of fluid energy

$$\begin{aligned}\frac{\partial}{\partial x}(\rho hu)+\frac{1}{r}\frac{\partial}{\partial r}(\rho hvr)=&\frac{\partial T}{\partial x}\left(\lambda_f\frac{\partial T}{\partial x}\right)+\frac{1}{r}\frac{\partial}{r}\left(\lambda_f\frac{\partial T}{\partial r}r\right)\\ &-\frac{1}{r}\frac{\partial}{r}\left(\sum_{k=1}^{3}D_k\rho_k r\frac{\partial Y_k}{\partial r}h_k\right)\\ &-\frac{\partial}{\partial x}\left(\sum_{k=1}^{3}D_k\rho_k\frac{\partial Y_k}{\partial x}h_k\right)+q\end{aligned} \tag{3}$$

where h is the enthalpy, λ_f is the thermal conductivity of fluid, T is the temperature, $k=1,2,3$, respectively, represents H_2, O_2, H_2O, D_k

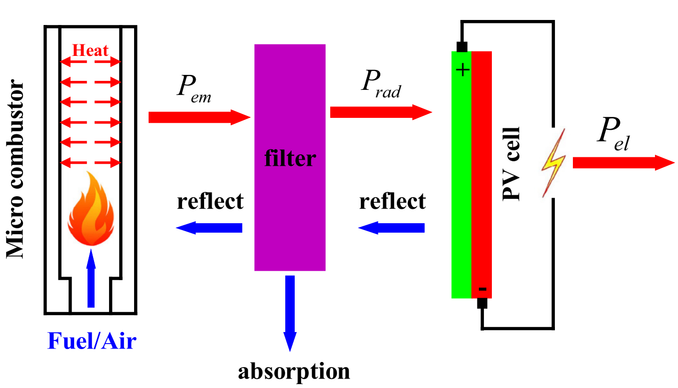

Fig. 1. Schematic diagram of an MTPV system.

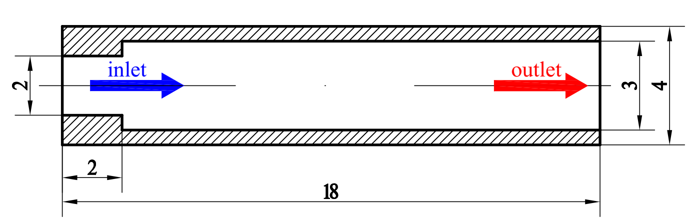

Fig. 2. Schematic diagram of the micro-cylindrical combustor with a step.