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Hydrogen/oxygen premixed combustion characteristics in micro porous media combustor ☆

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HIGHLIGHTS

- Effect of several parameters on combustion characteristics of micro porous media combustor was investigated.
- Porous media material with low C_p and high thermal conductivity leads to better temperature distribution on the wall.
- The highest emitter efficiency occurs at $\phi = 0.8$, though the highest mean temperature occurs at $\phi = 1.0$.
- The interaction between flow velocity and porosity has strong impact on temperature gradient and pressure drop.

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ABSTRACT

The micro-combustor is a major component of the micro thermophotovoltaic (TPV) system. In order to improve the stability of combustion and efficiency of the micro-TPV conversion device, porous media combustor was designed. Porous media combustion can increase flame stability and gain higher conversion efficiency compared with the free flame combustor. In this work, the influence of several major parameters on micro combustion, namely material of porous media, hydrogen to oxygen equivalence ratio, porosity of porous media and mixture flow rate were investigated using the numerical simulation method. Results indicate that, even though at three different equivalence ratio conditions, SiC is still one of the most suitable porous media materials. Besides, high flow velocity and big porosity both induce high temperature gradient and big pressure drop. The interaction between these two parameters plays an important role in external wall temperature. Analyses in this paper reveal that with the appropriate parameters: $\phi = 0.8$, $v = 6$ m/s, porosity is 0.5 and porous media material is SiC, micro combustor with porous media structure could greatly increase combustion efficiency. Present research will facilitate the optimization and improvement of micro-TPV conversion device.

1. Introduction

In recent years, the energy crisis and environmental issue increasingly attract people's attention. Due to high energy density, compact and portable, micro power generators, such as micro gas turbine [1], micro rotary engine [2,3], and micro free-piston IC engines [4] are being developed. Compared with these kinds of micro power generators with high speed moving parts, direct energy conversion concepts, such as micro thermoelectric device [5] and micro thermophotovotaic (TPV) system [6–9] are attracting more attention.

As a novel energy conversion device, the micro-TPV system [10] mainly consists of a heat source, an emitter, a selective filter and a photovoltaic (PV) cell array. The system uses PV cells to convert thermal radiation energy from combustor into electricity. The conversion efficiency of the PV cell grows with the increase of emitter temperature and the decrease of band-gap energy of PV cell [11]. The most challenging issue in micro combustor design is to keep an optimal balance between heat sustainable capability of combustor material and maximizing radiation heat output per unit volume. As micro-TPV mainly relies on the radiation from external wall of combustor, the high surface to volume ratio in micro combustor can provide higher radiation power output for TPV system than that in macro-scale when at the same unit energy input

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condition. However, high surface to volume ratio leads to excessive heat loss through the wall of combustor, which will suppress ignition and even quench the reaction. Furthermore, with decrease in combustor size, there is less residence time for mixing and combustion process.

From investigation on conventional macro-scale combustor, people found that due to the high conductivity, high heat capacity and high emissivity of the solid matrix, an insert porous media combustor can offer higher burning rates, lower emissions of pollutants, increased power and extension of the lean flammability, compared with free flame combustion [12–14]. In order to solve the aforesaid micro-scale combustion problems, porous media micro-combustor is investigated in microscale. Avdic [15] developed a small scale porous media system for heat production, and analyzed the exhaust gases. The results indicated that developed heat production can reduces the emissions of NO_x and CO from 60 and 50 mg/kW h to 30 and 20 mg/kW h, which is completely fulfilled with the German "Blue Angel" emission limits. Chou et al. [8] are the pioneers on porous media micro-combustor research for micro TPV system. They found that the useful radiation energy from a micro combustor with insert porous media is 81.2% higher than that without porous media under certain operating conduction. Experimental studies have been carried out by Yang et al. [16], results show that the peak wall temperature of micro combustor with porous media increases by 95–120 K than that without porous media, and the overall efficiency of the micro-TPV system is 20% higher.

In this work, micro porous media combustor was designed to topping up the disadvantages of free flame micro combustor without porous media. We use three-dimensional numerical simulation on micro scale combustion in this porous media combustor, effects of major parameters such as porosity, hydrogen to oxygen equivalence ratio ϕ, mixture flow rate v, and porous media materials on micro scale combustion were investigated.

2. Numerical models and simulation approach

The geometry of the cylindrical micro porous media combustor is shown in Fig. 1. The combustion chamber is 20 mm long with an inner diameter of 2.4 mm, and the combustor wall is about 0.3 mm thick, which is made by SiC material. A kind of micro-combustor with a backward facing step designed by Yang et al. [17] is capable of enhancing mixing process and prolonging residence time. Hence, the premixed hydrogen–oxygen mixture is injected into the combustor from the nozzle which is 0.8 mm in diameter.

Based on the volume average theory on porous media, we simplify the inner flow field. Regarding the momentum and energy during fluid molecules collision as viscosity fluid flowing [18,19], the parameters we research are the average parameters of control volume.

The Reynolds number for flow in porous media is defined as

$$Re = \frac{\rho_{\text{mix}} \cdot \overline{v_p} \cdot l}{\mu_{\text{mix}}} \tag{1}$$

where l is the average characteristic length scale for the pore space, $\overline{v_p}$ is the average pore velocity which is defined as $v_p = v/\varepsilon$, ε is the porosity of porous media. ρ_{mix} and μ_{mix} are the density and viscosity of mixture fluid.

$$\rho_{\text{mix}} = \frac{\sum_{i=1}^{n} \rho_i \cdot X_i}{\sum_{i=1}^{n} X_i} \tag{2}$$

$$\mu_{\text{mix}} = \frac{\sum_{i=1}^{n} X_i \cdot \mu_i \cdot M_i^{1/2}}{\sum_{i=1}^{n} X_i \cdot M_i^{1/2}} \tag{3}$$

M_i and X_i are the molar mass and molar fraction of species i.

In porous media, Reynolds number divides flow regimes into three-parts: (a) Darcy or laminar flow regime: $Re = 1$–10; (b) unsteady transition flow regime: $10 < Re < 100$; (c) turbulent flow regime: $Re > 100$. Kuwahara et al. [20] also point out that turbulence characteristics in porous media is different from those in clear fluid flow, that is high turbulence intensity usually occurs in porous media, so they suggest to consider the turbulence effect when Re is larger than 80. In our study, Reynolds number ranges from 95 to 286, so we use RNG k–ε turbulence model. Besides, EDC model is used to simulate the turbulence flow with complex chemical reaction mechanism. DO radiation model is used to deal with the radiation of inner porous media.

At the micro combustor wall, mixed thermo boundary conditions are applied. Velocity boundary conditions are specified at the inlet of the micro combustor, where the flow rate and mass fractions are set. The inlet temperature of mixture is considered to be uniform at 300 K. At the exit, an outflow boundary condition is set up. Porous zone boundary condition is specified in fluid area. Permeability α and inertial resistance coefficients C_2 are calculated by semi-empirical formula Ergun equation [21].

$$\alpha = \frac{D_p^2}{150} \frac{\varepsilon^3}{(1-\varepsilon)^2} \tag{4}$$

$$C_2 = \frac{3.5}{D_p} \frac{(1-\varepsilon)}{\varepsilon^3} \tag{5}$$

where D_p is the average diameter of particles, ε is the porosity of porous media.

To verify the accuracy of the numerical solution, we contrast the numerical simulation result with experiment data from Ref. [22]. Fig. 2 is the temperature distributions along combustor wall obtained from simulation and experiment when the fuel–air equivalence ratio is 0.8 and 1.0; flow velocity is 6 m/s. It shows that temperature distributions under two conditions are basically identical, except for the inlet temperature. This is due to higher heat conduction loss by a connector made of steel 316 in the experiment which connects to the micro combustor inlet.

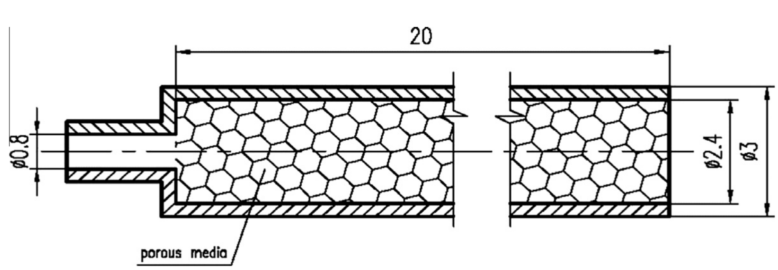

Fig. 1. Schematic diagram of the cylindrical micro porous media combustor.