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Combustion process and entropy generation in a novel microcombustor with a block insert

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HIGHLIGHTS

- A novel micro combustor with block insert is presented in this work.
- The block can significantly increase the mean wall temperature.
- The block can improve the uniformity of the wall temperature distribution.
- The entropy generation due to various processes has been presented.

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ABSTRACT

A novel micro combustor with block insert has been introduced in this work. The effect of block insert on wall temperature distribution and entropy generation of the micro combustor is investigated. The results indicate that the employment of a block insert can significantly increase the mean wall temperature and improve the uniformity of temperature distribution along the wall. When the gap length is 4.2 mm, the micro combustor can produce the highest mean wall temperature with the lowest entropy generation.

1. Introduction

Micro-Electro-Mechanical Systems (MEMS) technology has been the subject of escalating research interest as miniaturized electrical and mechanical products are continuously being developed for wide range of applications in the field of industrial, medical, domestic and military. However, a key bottleneck for these MEMS gadgets often lies in their heavy and bulky power generating devices. Hence there is a vital need to create a higher energy density microscale power source. Various micro power generators that make use of the high specific energy from combustion of hydrocarbon/hydrogen fuel such as micro thermoelectric devices [1,2], micro free piston engine [3,4], micro rotary engines [5,6] micro gas turbine engine [7,8] and micro thermophotovoltaic (TPV) power generator [9–11] are therefore being developed.

Of the various micro power generators, micro-TPV power generator is recognized as one of the most promising technologies due to the fact that it does not include any moving parts. Fig. 1 shows the schematic of a typical micro-TPV system, it mainly consists of: (1) a heat source, (2) an emitter (for micro TPV system application, to minimize the overall size of the system, the combustor wall usually acts as the emitter), (3) a filter and (4) a PV cells. The basic operating principle is: liquid hydrocarbon fuel or hydrogen is burnt in the micro combustor and release heat, when the wall of the micro combustor is heated to a high temperature, it emits a lot of photons, when those photons with energy higher than the bandgap of the PV cells impinge on the surface of the PV cells, it will evoke free electrons. Electrical current is produced with the movement of the free electrons under the function of the PN junction formed in the PV cells. A filter is often employed between the emitter and the PV cells to reflect those photons with energy lower than the bandgap of the PV cells back to the emitter, thereby improving the overall efficiency of the system.

As the micro-TPV system depends on the heat radiation from the surface of the micro combustor (i.e., emitter) to produce electricity, the high surface-to-volume ratio of micro combustor is favorable for the system to achieve a high power density.

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Nomenclature

g	volumetric entropy generation rate, W/(m^{3}K)	s	specific entropy, J/(kgK)
K_i	the rate of formation of the i th species per unit volume per unit time	S_{gen}	entropy generation rate, W/K
		t	time
n_i	number density of species i, particle number per volume	T	temperature, K
$\mathbf{P}$	pressure tensor	$\mathbf{v}$	velocity tensor
$\mathbf{q}$	energy flux, W/m^2	$\mathbf{V}_i$	diffusion velocity of species i
$\mathbf{r}$	radial coordinate, m	μ_i	chemical potential, J/kg

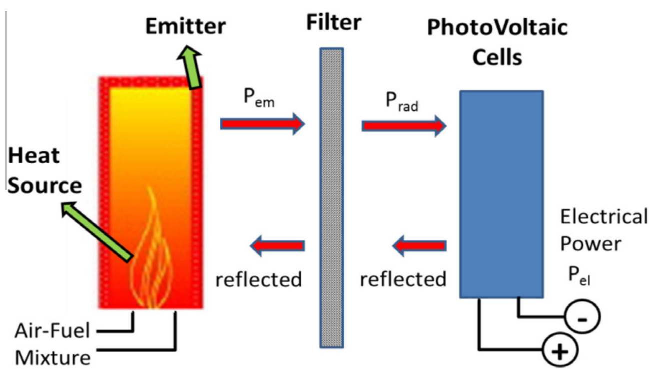

Fig. 1. Schematic of micro-TPV system.

However, it should be noted that at micro-scale, the small confinement for combustion also brings about challenges uniquely different from conventional combustors. First, at micro-scale, the residence time of the reactants for combustion is greatly reduced and limited. Second, flame stability and sustainability is also a major challenge. With the high surface-to-volume ratio of micro combustor, thermal and radical quenching could occur causing the combustion to extinguish [12]. Thermal quenching occurs when the heat loss in the flame zone exceeds that of the heat generated [13]. Due to the higher heat loss, the temperature in the combustion region would drop, when it falls below the ignition temperature, thermal quenching of the flame will happen. Radical quenching occurs when active species generated during combustion undergoes adsorption and depletion at the walls of the high surface-to-volume micro combustor [12,13]. Third, at micro-scale, micro combustor may pose difficulty in terms of fabrication, assembling and sealing due to very small tolerances required.

To achieve a stable combustion in micro combustors, various methods have been adopted to enhance the combustion process. Yang et al. investigated the effect of backward facing step on the combustion process in a micro cylindrical combustor and found that the employment of a backward facing step could significantly extend the range of H_2/air equivalence ratio and flow speeds for the micro combustor to obtain a stable combustion [14]. In a following research, they further investigated the effect of the backward facing step height and the diameter of the cylindrical combustor on temperature distribution along the wall of the micro combustor [15]. Bhupendra et al. also found that the backward step modified the flow velocity profile, helped in stabilizing the flame within the micro combustor and enhanced the flame stability limits significantly [16].

Heat recuperation is another effective method to enhance combustion in micro combustor, which recirculates the waste heat from the exhaust gas either to preheat the fresh charge or reheat the wall near the exit, thereby improving the efficiency of the micro combustor. Lee and Kwon studied the effect of heat recirculation on the performance of micro-TPV system [17], both the numerical simulation and experimental results indicated that heat recirculation substantially improved the performance of the micro emitter, a higher and more uniform temperature was obtained on the emitter. Li et al. designed and investigated a mesoscale liquid fuel-film combustor with heat recuperator [18], found that a stable combustion could be obtained even with liquid fuel and the employment of a heat recuperator could significantly increase the wall temperature and improve the temperature distribution. Yang et al. also investigated the effect of heat recirculation on the performance of micro modular combustor and found that a more uniform temperature could be obtained on the wall of the micro modular combustor [19].

The use of porous media packed in micro combustor emerged in recent years [20–22]. It is believed that the inclusion of porous media enhances the heat transfer between the hot combustion products and the combustor walls. In addition, the porous media also acts to preheat the incoming fresh charges, resulting in an increased wall temperature and radiation energy from the micro combustor.

In this work, we are presenting a new micro combustor with block insert, the effect of the gap length (distance from the inlet to the insert block) on the wall temperature distribution of the micro combustor are investigated. The entropy generation in the micro combustor under various operating conditions is also studied.

2. Design of micro combustors with and without block insert

It can be seen from the operating principle of the micro-TPV system that micro combustor is one of key components. As we know, the power of the micro-TPV system depends on the radiation energy which is proportional to the temperature of the emitter, so, in order to maximize the output power, a high and uniform temperature distribution on the emitter, i.e., the combustor wall, is desirable. In this work, a novel micro combustor with block insert is designed, fabricated and tested. Fig. 2 shows the schematic of the micro combustor with block insert. The concept for including the block insert is to utilize the barrier within the combustion chamber to channel the flame and high temperature combustion products towards the side wall as depicted in Fig. 2b, thereby enhancing the heat transfer from the combustion products to the wall aiming to get a higher and more uniform temperature distribution along the wall of the combustor.

The micro combustor excluding the block has an inner dimension of 10 mm (width) × 1.6 mm (height) × 16 mm (length). The distance from inlet to the block is defined as gap length (L). The effect of the gap length on wall temperature distribution has been numerically investigated in this work. The distance from the inner surface of the combustor to the block, i.e., t, is fixed at 0.4 mm in this study. A prototype micro combustor (B1) with a gap length of 2 mm and a gap height of 0.4 mm has also been fabricated and