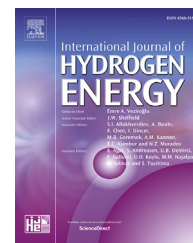


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Power generation performance of hydrogen-fueled micro thermophotovoltaic reactor

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ABSTRACT

A tubular platinum reactor with a perforated annular array enables fuel/air mixtures to exchange sides, thus sustaining flames and preventing heat loss. Consequently, the combustion efficiency and operational range can be enhanced. A hydrogen/air mixture was introduced into inner and outer chambers at different equivalence ratios and flow velocities to chemically and physically investigate the interplay between the chambers. The benefits of hydrogen include a high gravimetric heating value, flame speed, and diffusion capacity and short chemical reaction time. The coexistence of heterogeneous (surface) and homogeneous (gas) reactions in the micro TPV reactor was examined and elucidated in terms of aerodynamics, mass and heat transfer, and chemical reactivity. Furthermore, a TPV reactor with TPV cell arrays was assembled, and the corresponding radiant efficiency of the emitter and the overall efficiency of the proposed micro TPV system were determined in this study.

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Introduction

The proliferation of microelectromechanical systems and their demand for miniature power sources, ranging from 10 to 1000 W/kg [1], have accelerated the development of miniature power. In general, power systems employing hydrogen or hydrocarbon fuels provide much higher energy density according to specific mass compared with traditional systems [2,3]. A series of combustion-based micro power systems have been successfully prototyped, including the micro gas turbine [4], micro-free-piston engine [5], micro thermoelectric device [6] and micro thermophotovoltaic (TPV) system [7–9]. Although their current efficiency is low, these micro systems have exhibited the potential to generate power in the order of

a few watts within a volume of several cubic centimeters. The micro-TPV power generator is a typical direct energy conversion device that uses PV cells to convert heat radiation, from the combustion of fossil fuels, into electricity [10,11]. It does not include any moving parts; therefore, its fabrication and assembly are relatively easy. Unlike solar photovoltaics, TPV cells are illuminated by combustion-driven radiation sources. Because these sources can provide a radiant power density much greater than that of the sun, the electric power density of TPV cells is much higher than that of solar cells. Accordingly, understanding the fundamental characteristics of combustion in the micro scale is the key to improving the system efficiency and optimizing the design.

A reduction in combustor volume results in substantial heat loss and radical destruction on the combustor wall. Some

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research groups have applied combustion-enhancing methods such as external heating to overcome the heat loss problem, whereas others have experimented with catalyzed combustion to minimize the radical quenching effect. A backward-facing step in a millimeter-sized cylindrical tube is employed to control the flame position. This cost-effective configuration has been used as a heat source for micro-TPV systems [12,13]. To maximize the output of the micro-TPV generator, a high wall temperature and uniform distribution are of primary concern. Sui et al. [14] pointed out that the appropriate flow structure design can improve the spatial uniformity of surface temperature. Reducing wall thickness and step height gives rise to a higher wall temperature. For instance, Pan et al. [15] discussed the effects of major micro-combustor parameters on the radiation intensity in micro-TPV system, fuel to oxygen ratio, nozzle to combustor diameter ratio, and wall thickness to combustor diameter ratio. Furthermore, porous media combustion occurs in a three-dimensional solid porous matrix having interconnected pores. This enhances the heat transfer from the burned hot gas to the unburnt mixture through conduction, convection, and radiation. In addition, catalytic micro combustors exhibit wider stability than that of homogeneous micro combustors [16–18]. Using numerical simulation, Li et al. [19,20] investigated heterogeneous and homogeneous mechanisms of hydrocarbon fuels combustion enhancement through catalyst segmentation with cavities in a micro reactor. The catalyst induced an exothermic homogeneous reaction near the following non-catalytic wall or cavity. The cavities in the small-scale reactor effectively reduced flame instability and enhanced flammability. Yang et al. [21] testified the output electrical power of the system with platinum wall increased by 11–23.8% compared with that without platinum. Sui and Mantzaras [22] concluded that blowout limits of fuel-lean hydrogen/air mixture in platinum coated micro-channels could not be reached even for inlet velocities as high as 80 m/s at 1 bar.

In recent years, many scholars have focused on applying TPV power systems as portable devices. Li et al. [23] and Yang et al. [24] proposed a hydrogen-fueled micro TPV combustor and used a backward-facing step as a flame stabilization mechanism to control the flame position. Li et al. [25] studied TPV power extensively, converting flame radiation into electrical output by using PV cells. Jiang et al. [26] corroborated a micro-combustor with baffles to apparently extend the blowout limit and enhance the combustion and radiant efficiency. Park et al. [27] proposed a heat-recirculating micro-emitter and its power ranges from 1 to 10 W. Lei et al. [28] designed a micro-combustor with heat recirculation and achieved the extension of flammability. Qiu and Hayden [10] demonstrated a novel cascading TPV and TE power generation system. Yang et al. [29] discussed the factors affecting the combustor of a TPV power system, which include the fuel ratio, flow velocity, and dimensions of the burner exit.

Regarding to the improvement of TPV power output, the use of spectral-control technique for tailoring the radiation spectrum emitted onto the TPV system is prevailing. A selective emitter capitalizes on suppressing the emission of sub-bandgap photons. Similarly, a selective filter benefits from transmitting convertible photons while reflecting low energy

photons back to the emitter. Owing to complex fabrication processes and expensive cost of selective emitters and filters, the emitter material in a typical TPV power system is usually silicon carbide (SiC). It emits blackbody radiation (emissivity ≈ 0.9) and is resistant to high temperature. However, the radiation spectrum of SiC is broadband. According to the Stefan–Boltzmann law, a higher emitter surface temperature leads to higher power output. Therefore, a means for increasing the temperature of the reactor is required. Yang et al. [30] tested different emitting materials for enhancing radiation efficiency. In addition, quartz enables to provide optical transmission from near-ultraviolet to mid-infrared wavelength, and it is effective filter to block low-energy photons [31]. Accordingly, quartz tube acts like a band-pass filter to trap thermal radiation inside the chamber and enhance the chamber temperature. Li et al. [32] proposed a metal-oxide-deposited quartz emitter. This emitter pertains a semi-transparent chamber to allow the portion of radiation emitting outward the chamber and low-energy radiation reflecting back inward the chamber.

In previous papers [23,25], a platinum tube with a perforated ring and fuel/air mixture deployment conditions was testified to overcome the problems of combustion instability and radical termination in a small space. Compared to a plain platinum tube, a perforated platinum tube with a backward-facing step apparently enhances flame stabilization and extends stable flammability. In this study, a micro TPV reactor was fueled with hydrogen due to inherent advantages of high gravimetric heating value, flame speed, and diffusion capacity. The interaction between the inner and outer chambers was experimentally and numerically investigated with regards to the effect of fuel concentration and flow velocity. The coexistence of heterogeneous (surface) and homogeneous (gas) reactions in the micro TPV reactor was examined in terms of aerodynamics, mass and heat transfer, and chemical reactivity. Finally, a TPV reactor with PV cell arrays was assembled, and the corresponding radiant efficiency of the emitter and the overall efficiency of the proposed micro TPV system are determined.

Experimental apparatus

Fig. 1 shows a schematic diagram of the micro TPV reactor, which consists of a platinum tube with dimensions of 5.3 mm (ID) \times 6 mm (OD) \times 30 mm (L) and a quartz tube with dimensions of 8 mm (ID) \times 10 mm (OD) \times 160 mm (L). The quartz tube is mounted outside the platinum tube. Eight perforation holes (1 mm in diameter) are equidistantly placed around the platinum tube at a distance of 5 mm from the bottom. The platinum tube is mounted on the flange of a stainless steel tube, which measures 4 mm in ID and 5.3 mm in OD. It features a backward-facing step, the length of which is 1 mm, in the connection section. The experiment involved introducing fuel at different equivalence ratios and compositions into the inner and outer chambers to investigate the flame behavior in the micro combustor. The flame behavior was recorded using the Nikon D80 with the aperture and exposure time fixed at F5.6 and 1/100, respectively, for all photographs. The wall temperature of the micro TPV reactor was measured using an

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