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Experimental demonstration of a novel approach to increase power conversion potential of a hydrocarbon fuelled, portable, thermophotovoltaic system

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ABSTRACT

A novel, compact mesoscale thermophotovoltaic (TPV) power generating system using a combination of porous media combustion and a simple band-pass filtering method has been proposed and experimentally studied. The novelty in this work is the idea of harvesting the heat produced in the microcombustor via the silicon carbide (SiC) porous media which becomes an effective radiator owing to its high emissivity. This is then combined with wafers that have a high optical transmissivity in the part of the spectrum that is useful for power conversion using the TPV system. In this work, we utilised two combustor wafers (silicon and quartz) with suitable thermal and optical properties. Quartz having a high transmissivity of 0.9 compared to silicon (<0.6) proved to be superior in performance when combined with the porous media combustion for TPV power generation. To further illustrate the combination of effects, we also performed experiments in which porous media was not inserted in the combustor and the radiation was effectively from the hot combustor walls. In this case, silicon which has a higher emissivity than the quartz performs better. Overall the TPV power generation was SiC + quartz > SiC + Si > pure Si walls > pure quartz walls.

1. Introduction

Micro/mesoscale combustion which can be viewed as combustion in narrow passages or ducts on the order of the flame thickness (dimension < 1 mm for microscale and >1 mm for mesoscale), has drawn wide research interest in the past two decades [1–13]. Compared to traditional lithium-ion or alkaline batteries, micro/mesoscale combustion using hydrogen or hydrocarbons as energy sources could offer considerably higher (tens of times) energy densities per unit mass and instant rechargeability, thereby leading to fewer logistical issues [14,15]. Various combustion-based small scale devices that adopted conventional thermal cycles to harvest the heat from combustion have been developed, such as micro-gas turbine engine [16], micro-rotary engine [17], micro-free-piston engine [18] and micro-internal swing engine [19]. However, the existence of high-speed moving parts (such as blades, rotors or pistons) usually lead to significant frictional losses, consequently reducing the system efficiency to a large extent [14].

The direct conversion systems which do not involve those complex moving parts, are thus able to overcome the issue of frictional losses. One example is the small-scale coupled combustor/reformer system that enables a hydrogen economy [20,21]. In this kind of system, the hydrogen carrier such as ammonia is converted to hydrogen via the endothermic reforming reaction, which is driven by the heat generated in a coupled micro-combustion process. For the purpose of power generation, micro/mesoscale thermoelectric (TE) generators [22–24] can offer an alternative to convert thermal energy into electrical energy directly. Our previous study using orthotropic wall materials [25] demonstrated a uniform and moderate temperature distribution on a mesoscale combustor outer surface, which was favourable for continuous working of the TE system (avoid hot spot that could damage TE elements). However, special attention on cooling the combustor chamber should be taken since overheated wall temperature (upper limit of 300 °C for the most commercial Bi_2Te_3 modules) could potentially damage the TE device [23].

Thermophotovoltaic (TPV) system, as an alternative structurally simple direct energy conversion device, has also been extensively studied for its application in both conventional [26–33] and small scale systems [13,34–45]. In a micro-combustion based TPV system, the combustor walls are heated to a high temperature and

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consequently act as an emitter to radiate photons to the surroundings. Photons with energy higher than the bandgap energy of the PV cells can be utilised to evoke free electron and hole pairs to generate electricity. Therefore, it is critical to achieve a high operating temperature on the combustor outer surface, which can not only intensify the radiative energy, but also improve the radiation spectrum (increase the portion of useful photons with the energy higher than the bandgap) [38].

Using porous media inserts in micro-combustion was found to be an effective method to increase the TPV power output in past studies [13,38,39]. This is because the gas phase combustion was enhanced by the porous media inserts, thereby leading to an increased combustor wall temperature.

Another typical method for improving the TPV power output is to use spectral-control techniques [46] for tailoring the radiation spectrum emitted onto the TPV system. This includes having a selective emitter (suppressing the emission of sub-bandgap photons) and a selective filter (transmitting convertible photons while reflecting low energy photons back to the emitter). However, the fabrication processes of most of the selective emitters and filters are complex and relatively expensive, which currently inhibits this technology from being practically viable. Quartz, a thermally robust material, was extensively used in past micro/mesoscale combustion studies [43,44,47–50]. Moreover, quartz is able to provide optical transmission from near-ultraviolet to mid-infrared while filtering the radiation in the far-infrared region [51], and therefore, draws the authors' interests to use it as a simple band-pass filter to improve the TPV system performance. Li et al. [43,44] utilised the visually transparent property of the quartz material to allow the combination of both the visible radiation from high luminosity flames and the near-infrared radiation from the heated emitter inside a quartz-tube combustor to be emitted. The emphasis in their work was on introducing carbon monoxide (CO) and other additives that can increase emission from the gaseous flame. This is an interesting concept, however, it will limit applications to a more industrial scope where CO and other additives are readily available and is less practical for portable power systems.

In this paper, we proposed and experimentally studied a novel, compact mesoscale TPV system using a combination of porous media combustion and a simple band-pass filtering method, in which the porous media is used for both stabilising the flame and emitting photons, and the quartz wafers serve as the combustor walls to confine the flame and a band-pass filter to re-shape the radiation spectrum from the emitter. Through this method, the porous media would be able to achieve a considerably higher temperature to emit high-energy photons, owing to a strong thermal interaction with the flame. According to Kirchhoff's Law (the sum of the transmission, reflection, and absorption of an incident flux is equal to unity), photons in the optical band region (>4 μm) where the quartz is not transmissive, will be either thermally absorbed by the quartz to increase the combustor surface temperature or reflected back inside the combustor to reduce the system heat losses, hence helping to enhance the combustion. Therefore, the TPV power output is expected to be effectively increased. In this work, we report experimental results of this novel combination of porous media enhanced combustion/radiation and optical filtering using a conventionally available window (quartz) on the TPV system performance.

2. Experiment setup

The schematic diagram of the experimental setup is shown in Fig. 1(a). It consists of two mass flow controllers, a gas mixer, a plenum and a mesoscale combustor. Different parts of the system are connected together using Swagelok stainless steel tubing and fittings. Gas mixtures of methane and air are supplied to the system via two SmartTrak-C100 mass flow controllers (from Sierra Instruments) with an accuracy of ±1% of full scale (0–1000 sccm for methane and 0–10,000 sccm for air). These are used to control the mixture mass flow rate and equivalence ratio. A gas mixer consisting of a 1¼ inch diameter stainless steel tube filled with steel wool, and a stainless steel plenum are used to sufficiently mix the gas. Below the combustor chamber, a stainless steel screen is employed to flatten the velocity profile of the inlet flow and also used as a flashback arrestor.

The assembly drawings of the parallel plate mesoscale combustor are shown in Fig. 1(b). The combustor consists of two rectangular wafers attached to adjustable supporting plates above the plenum. Two ceramic pieces clamp the combustor wafers from the side and provide thermal insulation. As mentioned earlier, quartz wafers were used as both the combustor walls and a simple band-pass filter to study the TPV system performance in this paper. The wafers were purchased from Knight Optical Ltd., with the dimensions of $80\,\mathrm{mm} \times 60\,\mathrm{mm} \times 1\,\mathrm{mm}$ (in length × width × thickness). As a comparison, experiments with silicon wafers (from Knight Optical Ltd.) at the same dimensions were also performed. As one of the most prevalent materials for micro electromechanical systems (MEMS), silicon was widely used for manufacturing prototypes of micro-power generating devices and micro-propulsion systems owing to its favourable mechanical and thermal properties [16,17,52]. Moreover, silicon can offer an emissivity of 0.6–0.7 at elevated temperatures in the convertible band of the PV cells [53], and is therefore considered a reasonable emitter material serving for the purpose of TPV power generation. Table 1 has summarised the typical thermal properties of quartz and silicon wafers used in this study.

Two pieces of silicon carbide (SiC) porous foams (shown in Fig. 2) from ERG Aerospace Inc. with each dimension of $50\,\mathrm{mm} \times 25\,\mathrm{mm} \times 1.7\,\mathrm{mm}$ (in length × width × thickness) were assembled into a whole piece ($50\,\mathrm{mm} \times 50\,\mathrm{mm} \times 1.7\,\mathrm{mm}$) and inserted into the combustor, attaching to one of the combustor wafers via a small stainless steel groove (Fig. 2(b)). Some of important properties of the SiC porous foams are listed in Table 2. During the experiment, the gap between the two combustor wafers was maintained at 3.5 mm. It was the minimum gap value that was able to render the flame attached to the porous foam.

A high-performance FLIR Systems A655 infrared camera with the resolution of 640 × 480 pixels and accuracy of ±2% of reading was used to measure the combustor outer surface temperature distribution. The camera detects the radiation over the wavelength range of 7.5–13 μm. For obtaining the temperature contour, the emissivity ε of the combustor surface (over the detection band) is needed as an input. In this work, a high-emissivity black paint (with a known emissivity of 0.95 [56] and heat resistant up to 1108 K) from the Flood Company Australia Pty. Ltd. was used to determine the spectrally-averaged emissivity of the combustor wafers over the camera detection band. The black paint's emissivity has been found to show only limited variation with the temperature in this wavelength range [57]. Fig. 3 shows an example of calibrating the emissivity of a quartz wafer heated by the flame. During the emissivity calibration process, the paint was coated on a small spot of the wafer surface. The emissivity ε_{quartz} over the whole wafer was first set equal to the paint value of $\varepsilon_{paint} = 0.95$. Then the temperature profile along a short slicing line across the paint spot was obtained. However, only the peak temperature over a few pixels (within the blue rectangle in the right plot of Fig. 3) could be considered as the "real" values while the temperature for the other pixels was underestimated (as the actual $\varepsilon_{quartz} < \varepsilon_{paint}$). Since the temperature near the spot can be assumed to be the same as the value within the spot area, the averaged peak