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Development of a Mesoscale Thermophotovoltaic Power Generating System Using Porous Media Combustion

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Abstract

A mesoscale thermophotovoltaic (TPV) power generating system has been developed and described in this work. The system consists of a flow system for introducing fuel/air mixtures, a parallel-plate silicon combustor with porous media inserted and a gallium antimonide (GaSb) TPV circuit. Using the porous media effectively enhanced the combustion, increased the combustor surface temperature and extended the operational limits. Owing to the partially-transmissive property of the silicon wafer in the PV cell convertible band, the porous media at a high temperature also serves as a secondary emitter. Experimental results show that incorporation of the porous media leads to a significantly higher open circuit voltage and short circuit current at the same inlet mass flow rate, when compared to the combustor configuration without the porous media inserted.

Introduction

In the past two decades, combustion in narrow channels has received considerable research impetus, owing to its significantly higher specific energy per unit mass compared to the traditional electrochemical batteries (45 vs 0.6 MJ/kg) [3]. This small-scale combustion is termed microscale (dimension < 1 mm) or mesoscale (dimension close to flame thickness) combustion [10, 5]. Past fundamental works observed a range of interesting flame phenomena such as flames with repetitive extinction and ignition (FREI) [2] and various flame patterns [1], suppressed flame instabilities [6], as well as enhanced combustor operational regimes [14, 7].

Apart from the fundamental studies, in order to harvest the combustion heat and convert it into electrical power, various types of micro/mesoscale combustion-driven energy conversion prototypes have been developed, which can be found in recent review articles [10, 5]. The micro/mesoscale thermophotovoltaic (TPV) system, has been extensively studied among those energy conversion devices, owing to its simple structure, easy assembly and the absence of frictional loss (without any high-speed moving-part) [16, 8, 11]. In a combustion-based TPV system, the combustor walls are heated to a high temperature, emitting photons to the surroundings. Photons with energy higher than the bandgap of the TPV cells can be used to evoke free electron and hole pairs to produce electricity. In the operation of such systems, it is important to attain a high wall temperature, since it can not only enhance the radiation intensity, but also increase the portion of useful photons with the energy higher than the TPV cells' bandgap.

This work aims to develop and study the performance of a small-scale TPV power generating system driven by a mesoscale silicon combustor. Although silicon is one of the most prevalent materials in micro electromechanical systems (MEMS), there is limited publication using this material for fabricating micro/mesoscale combustor in TPV systems. The use of porous media combustion is also proposed, as it has been proved to be an effective method to stabilise the flame and increase the combustor outer surface temperature [15, 9].

Experiment Setup

Figure 1 shows the schematic diagram of the experimental setup. Gas mixtures of methane and air are introduced into the system via two Sierra SmartTrak-C100 mass flow controllers with an accuracy of $\pm 1\%$ of full scale (0-1000 sccm for methane and 0-10000 sccm for air). A stainless steel gas mixer (filled with steel wool) together with a stainless steel plenum are used to provide sufficient mixing before the gases enter the combustion chamber. The combustor itself consists of two rectangular silicon wafers sitting above the plenum, with the wafer-dimension of 80 mm $\times$ 60 mm $\times$ 1 mm (in length $\times$ width $\times$ thickness), and wafer-spacing of 3.5 mm. Two ceramic pieces clamp the combustor wafers from the side and provide thermal insulation. The silicon wafers were purchased from Knight Optical Ltd., having a high thermal conductivity of 163 W/m·K (evaluated at 0 °C) and a high melting point of 1420 °C. Importantly, silicon can offer an emissivity of 0.6 - 0.7 at elevated temperatures in the convertible band of the PV cells [12]. Therefore, it is considered as a reasonable emitter material serving for the purpose of TPV power generation.

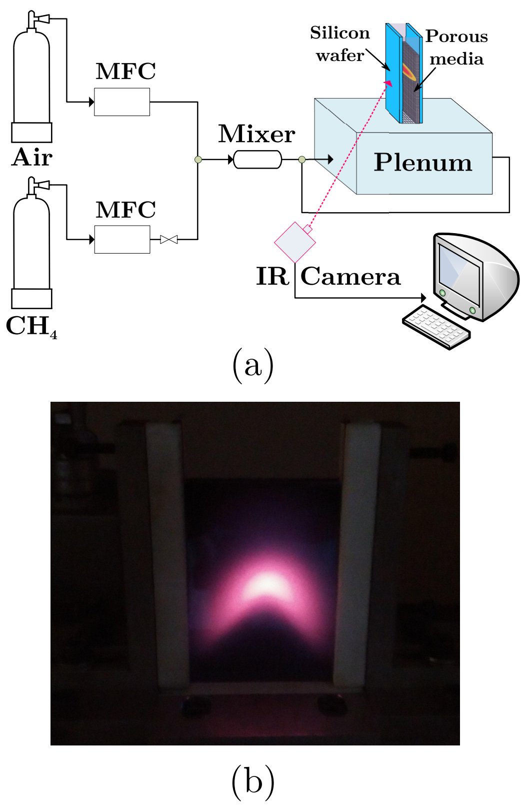

Figure 1: Schematic side-view of the experimental setup (a) and photograph of silicon combustor under operation (b).

The silicon carbide (SiC) porous foam from ERG Aerospace

Inc. (dimension of 50 mm × 50 mm × 1.7 mm in length × width × thickness) with the porosity of 100 PPI (pores per inch) and relative density of 4-6%, is inserted into the combustor, in order to enhance the combustion.

The TPV circuit consisting of 25 gallium antimonide (GaSb) PV cells (dimension of 11.94 mm × 16.51 mm for each cell) from JX Crystals Inc. was placed approximately 15 mm in front of the combustor to convert the radiation into electricity. A photo of the TPV panel is shown in Figure 2. Five cells are first vertically connected in parallel, by adhesively bonding (both electrically and thermally conductive) themselves to a copper plate to form a block. Then such five blocks are wired in series to each other in the horizontal direction to compose a complete TPV circuit. For cooling purpose, the whole circuit is mounted on a cooling fan-attached aluminium heat sink.

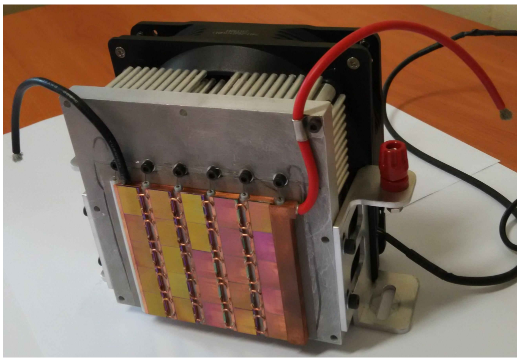

Figure 2: Photograph of the GaSb PV panel with cooling components.

During experiment, 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. A FLUKE 77 multimeter with the DC voltage accuracy of ±0.3% and DC current accuracy of ±1.5% was used to measure the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of the TPV panel under operation. The multimeter was calibrated by a FLUKE 5522A Multi-Product calibrator.

Experiments for stoichiometric methane/air combustion, with and without the SiC porous media were performed. To start the experiment, the volume flow rate (Q_{in}) was first set to a relatively low value (∼5.0 litres/min) to allow the flame stabilised within the channel in a short time. When changing the volume flow rate from one condition to another, the interval of Q_{in} was taken to be ∼0.34 litres/min. Also, a certain period of time (∼20 minutes) was needed prior to each measurement (IR image and TPV output measurement), in order to ascertain that the combustor had reached its equilibrium state. Measurements of the TPV system performance (V_{oc} and I_{sc}) were performed at least three times, with good repeatable results obtained.

Results and Discussions

Flame Stability Limits

As discussed in our previous work [7], for a given equivalence ratio, the flame could only be stabilised within the combustor for a range of mixture flow rates between two limits Q_{low} and Q_{high}.

For a flow rate value below the Q_{low}, the drastically reduced amount of chemical heat release owing to the low input energy could not compensate for the significant wall heat losses. Consequently, the flame first showed instabilities of spatial oscillations, and was eventually extinguished. The use of the porous foam is found to lower this limit, compared to the case without the porous foam (4.37 vs 5.05 litres/min). This is because the porous media can store the heat from the flame and, in turn, enhance and sustain the combustion at lower input energy conditions. This combustion enhancement can be indicated from the infrared images of the combustor outer surface shown in Figure 3. At the common flow rate of Q_{in} = 5.05 litres/min (lower flame stability limit for the case without the porous foam), the combustor outer surface temperature is considerably higher for the case using the porous media.

The Q_{high} is the higher flame stability limit above which the flame propagation speed could not catch up with the flow velocity. As a result, the flame would be pushed downstream and blown out of the channel. This critical flow rate was found to be 7.10 litres/min for the case without the porous media. As shown in Figure 3, at this flow rate value, the flame is located close to the combustor exit. Further increase of Q_{in} would lead to the flame blown out. On the other hand, incorporating the porous media enabled the further increase of this value. The flame was able to stabilise within the channel at much higher flow rates. For up to the highest flow rate reported here (9.15 litres/min), the flame was still attached to the porous media. This can be mainly attributed to the enhanced heat conduction via the porous foam from the post-flame to pre-flame region, leading to a significantly enhanced flame propagation speed. Experiments at even higher Q_{in} were not conducted, since the highest tested value of 9.15 litres/min was already close to the full scale of the mass flow controllers.

TPV Power Output

Figure 4 shows the measured open circuit voltages (V_{oc}) and short circuit currents (I_{sc}) of the PV circuit versus the mixture flow rate, for the experiments with/without the porous media. The estimated power output P_{max} ($P_{max} = FF \cdot V_{oc} \cdot I_{sc}$) at the PV's maximum power point (MPP) using a known fill factor (FF) value of 0.7 [4] is also computed.

For the experiment without the porous foam inserted, the V_{oc}, I_{sc} and P_{max} first increase as the flow rate increases, reaching the maximum value of 1.20 V, 51.69 mA and 43.55 mW respectively, at Q_{in} = 6.76 litre/min. The output then decreases with further increase of the Q_{in}, since the flame is close to the channel exit, having a smaller radiating surface area.

With the assistance of the SiC porous media, the TPV output is found to increase dramatically. For example, at the same flow rate of Q_{in} = 6.76 litre/min, the P_{max} is increased by 52.5% (66.39 vs 43.55 mW), compared to the case without the porous media. Two main mechanisms can explain the improved power output: First, as mentioned earlier, the porous foam serves as a media to conduct the combustion heat from the post-flame region to the pre-flame region. The feedback heat, in turn, is used to preheat the incoming mixture so that the combustion is effectively enhanced. With the help of the porous media, the temperature of the emitter (combustor outer surface) is considerably increased. Second, since the silicon wafer is partially transmissive in the PV convertible band (∼0.4 - 1.8 μm) [13], radiation from the high-temperature porous media inside the combustor is used as a secondary emitter for the TPV power generation.

More importantly, since the flame stability limit is dramatically extended for the use of porous media combustion, the system can thereby operate at a much higher inflow rate associated with much higher input energy, which maximises the TPV power output.

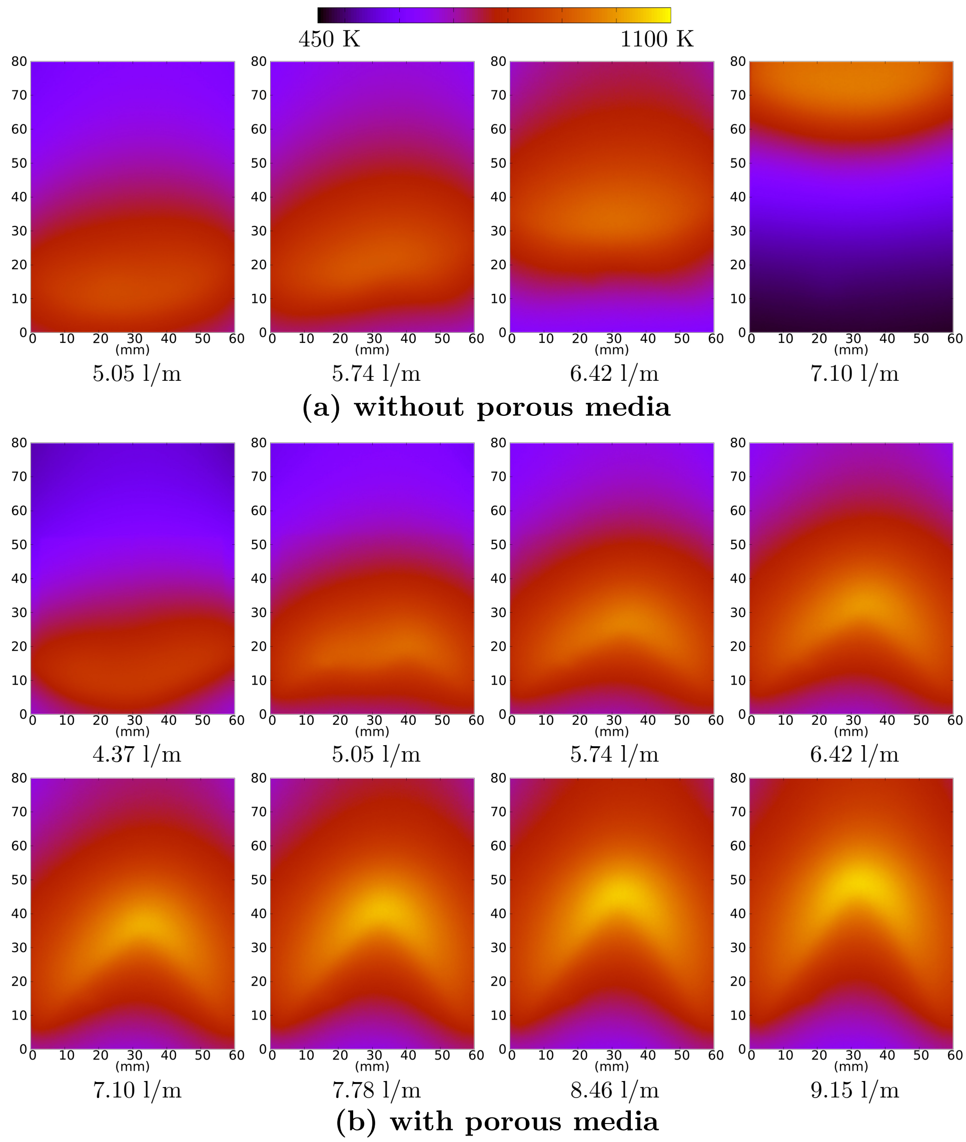

Figure 3: Infrared images of the combustor outer surface across the flame stability limits, for the experiments without (a) and with (b) the porous media.

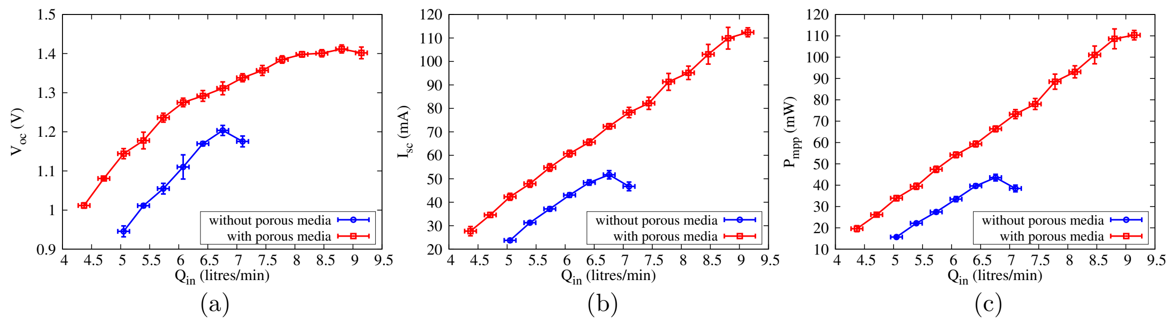

Figure 4: Measured open circuit voltages (V_{oc}), short circuit currents (I_{sc}) and estimated power output (P_{max}) for the experiments with/without the porous media, within their respective operational flow rate range.

Conclusions

This paper experimentally studied a mesoscale thermophotovoltaic (TPV) power generating system driven by a parallel-plate silicon combustor. A gallium antimonide (GaSb) TPV circuit was installed for the electrical power generation. Experiments with/without the porous foam inserted inside the combustor were performed. When incorporating the porous media, TPV system performance in terms of the measured open circuit voltage and short circuit current was found to be dramatically improved, compared to the case without the porous media. This is because that the porous media is able to effectively enhance the combustion, increase the combustor wall temperature and extend the combustor operational limits. Moreover, owing to the partially-transmissive property of the silicon wafer, the high-temperature porous media also serves as a secondary emitter, making contributions to the system power output.

Acknowledgements

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