Performance of a heat-recirculating combustor for thermophotovoltaic power devices with photonic crystal structure

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ABSTRACT

In the present study, the performance of a heat-recirculating combustor that was designed in the previous study for thermophotovoltaic (TPV) power devices in which thermal energy is directly converted into electrical energy through thermal radiation is investigated for a 10−30 W electrical power-generating TPV device. Performance of various types of emitters is evaluated by measuring temperature distribution on the emitter wall surface and the spectral emissive power density onto a spectrometer. Silicon carbide (SiC) and alumina (Al_2O_3) emitters are first considered, and to apply photonic crystal structure SiC and Al_2O_3 are considered as the emitter substrate. Each emitter substrate is simply wrapped by erbium oxide (Er_2O_3) powder. For the Al_2O_3 emitter, higher maximum and average temperatures on the emitter wall surface are observed compared with the SiC emitter. For the Er_2O_3-wrapped Al_2O_3 emitter the wrapping is well-maintained without any crack at high temperature. Also, higher spectral emissive power density is observed in the wavelength range from 800 to 1100 nm and from 1300 to 1800 nm. For the Er_2O_3-wrapped SiC emitter, however, the wrapping is cracked after several tests and spectral emissive power density is not significantly enhanced at the wavelengths of interest compared with the Er_2O_3-wrapped Al_2O_3 emitter.

Keywords: thermophotovoltaic, TPV, combustor, emitter

1 INTRODUCTION

Recently, advances in portable electronic mobile devices demand light, fast charging and long-durable portable power sources [1]. Combustion-based power generation systems have been considered as one of possible alternatives replacing current lithium-ion batteries since the energy density of hydrocarbon fuel i.e., butane (12,700 Wh/kg), is much larger than that of lithium-ion batteries (100−265 Wh/kg). Therefore, various types of combustion-based power generation systems have been suggested. Although heat engines have been suggested, they have moving parts causing significant heat and friction losses when being scale-downed. Furthermore, they are impractical for the military application due to strong noises in operating. Thermoelectric devices are an example as a combustion-based power generation system without moving parts [2]. However, they have some technical challenges such as structural complexity and maintenance problem. Thermophotovoltaic (TPV) devices are another example of combustion-based power generation systems without moving parts. They have simple structure since thermal energy is directly converted to electricity via photovoltaic cells (PVCs). Thus, TPV devices seem to be more practical than the heat engines and thermoelectric devices with low noise [3].

Important factors in designing TPV power generation systems include stable burning in the combustor, effective and uniform radiation into the PVCs and spectral matching between the thermal radiation wavelength and the PVC's response. In this laboratory, a small and quiet portable TPV power generation device is under development for military applications. A simple cylindrical combustor with multiple injection nozzles and the heat-recirculating concept has been considered for TPV power generation devices in a recent study [4] for satisfying the above key design factors. To further enhance the efficiency of TPV power generation systems, the photonic crystal structure that allows the precise control of electromagnetic wave properties and enlarges the photonic bandgap (PBG) can be applied onto the emitter surface as a selective emitter [5]. While the emitter materials having high emissivity in the near-infrared (NIR) and infrared (IR) region are preferred, the emissivity in this region is determined by the specific photonic crystal structure as well as the emitter materials.

In the present study, using the heat-recirculating combustor that was designed for 10−30 W power-generating TPV devices in the previous study [4], the performance of various types of emitters is evaluated by measuring temperature distribution on the emitter wall surface and the spectral emissive power density onto a spectrometer. Silicon carbide (SiC) and alumina (Al_2O_3) emitters with and without the erbium oxide (Er_2O_3) powder wrapping are considered since ceramics have high melting points and thermal stability and photonic crystal structure is to be applied. Based on the performance evaluation, including the stability of wrapping, proper emitter substrates are suggested for applying photonic crystal structure.

2 EXPERIMENTAL METHODS

Figure 1 shows a schematic of the experimental apparatus in this study, which consists of an emitter (combustor), a gaseous fuel (butane, C_4H_{10}) and air supply system using mass flow controllers, thermocouples for measuring temperature distribution on the outer wall surface of the emitter, a spectrometer (Aspec 2048L/Nir256-2.5: 300−2500 nm, field of view of 180°) for measuring the spectral emissive power density from the emitter and a digital camera (sony A65) for capturing the images of the outer wall surface of the emitter. Commercial mass flow controllers (MKP: 1,000 and 20,000 sccm for fuel and air, respectively) with accuracy ±0.75−1.00 % of full scale supply fuel and air to the combustor. By using PC-based software (LabVIEW) mass flow rates of fuel and air are controlled to supply appropriate operating test flow rates. Temperature distribution on the outer wall surface of the emitter is measured using K-type thermocouples (a bead diameter of 127±20 µm, the measurement accuracy of 0.4%). Results are obtained by averaging 4−5 tests with each emitter.

A combustor configuration for a 10−30 W power-generating TPV device was designed from the previous study [4] and the operating condition has been obtained from pretests. Figure 2 shows the components of the combustor, which includes an emitter as a combustion chamber, injection nozzles, a quartz shield, a thermal insulator and a heat recuperator (mixing chamber). To achieve stable burning in the combustion chamber and uniform distribution of temperature along the walls, the circularly arrayed multiple injection nozzles (the number of injection nozzles n = 9) and the heat-recirculation concept are applied. High temperature exhausted gas flowing upward collides with the insulator and turns downward to the heat recuperator. Preheated fuel-air mixture enhances uniformity of temperature distribution.

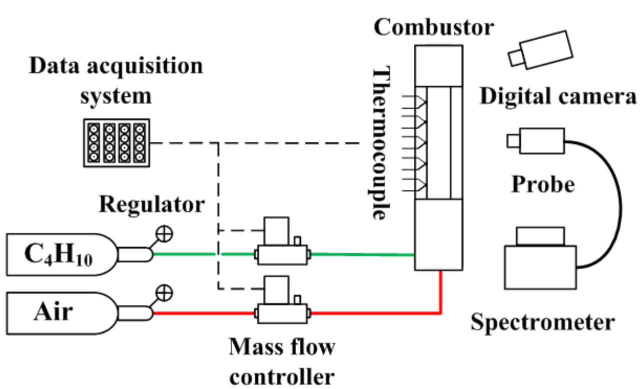

Figure 1: Schematic of experimental apparatus.

Figure 2 also shows the major dimensions; the emitter inner diameter d_i = 25.0 mm, the emitter wall thickness t_w = 1.0 mm, the emitter length l_e = 60.0 mm, the injection nozzle diameter d_n = 4.0 mm, the fuel nozzle diameter d_f = 1.5 mm, the penetration length from the fuel nozzle to the preheating chamber l_f = 40.0 mm and the recuperator length l_r = 98.0 mm.

Flame in the combustion chamber is obtained by establishing a cold injected flow of reactive mixture and then igniting the mixture at the injection nozzle using a spark ignitor. Once the flame is formed, the insulator is covered and then the flame is stabilized in the combustor. Experiments were carried out for a C_4H_{10} (purity>99.5%)-air (21%O_2/79%N_2 in volume) mixture of the fuel-equivalence ratio ϕ = 1.0 and the fuel mass flow rate $\dot{Q}_f$ = 600 sccm at temperature T = 298±3 K and atmospheric pressure (NTP). C_4H_{10} was selected as fuel because it can be easily liquefied at relatively low pressures and be also easily vaporized when mixed with air at NTP. Thus, C_4H_{10} is an appropriate fuel in practical use.

To evaluate the performance of various types of emitters, SiC and Al_2O_3 emitters with and without the Er_2O_3 powder wrapping are considered.

3 RESULTS AND DISCUSSION

Figure 3 shows the temperature distribution along the outer wall surface of the SiC and Al_2O_3 emitters with and without the Er_2O_3 wrapping for the premixed C_4H_{10}-air flames of ϕ = 1.0 and $\dot{Q}_f$ = 600 sccm. The temperature distribution is plotted as a function of the axial location normalized by the emitter length (x/l_e). Higher temperature distribution is observed for the Al_2O_3 emitter compared with the SiC emitter: the maximum and average temperatures are respectively 1463 and 1424 K for the Al_2O_3 emitters, while 1293 and 1257 K for the SiC emitter. In general, the temperature of the Er_2O_3-wrapped Al_2O_3 emitter is slightly lower than the Al_2O_3 emitter, while that of the Er_2O_3-wrapped SiC emitter is higher than the SiC emitter.

Figure 4 shows the spectral emissive power density onto an optical probe as a function of wavelengths for the premixed C_4H_{10}-air flames of ϕ = 1.0 and $\dot{Q}_f$ = 600 sccm at NTP. For the Er_2O_3-wrapped Al_2O_3 emitter, the Er_2O_3 wrapping is well-maintained without any crack at high temperature. Also, higher spectral emissive power density is obtained in the wavelength range from 800 to 1100 nm and from 1300 to 1800 nm which correspond to the response of gallium antimonide (GaSb) cells (from 700 to 1800 nm) which will be used as PVCs for the TPV power generation device under development in this laboratory. For the Er_2O_3-wrapped SiC emitter, however, the Er_2O_3 wrapping is cracked and peeled off from the SiC substrate surface after several tests. The spectral emissive power density is not significantly enhanced at the wavelengths of interest compared with the Er_2O_3-wrapped Al_2O_3 emitter. Thus, the cut-off effect of photonic crystal structure due to the Er_2O_3 wrapping is clearly observed only for the Er_2O_3-wrapped Al_2O_3 emitter (in the wavelength range from 1100 to 1300 nm and from 1800 to 2000 nm).

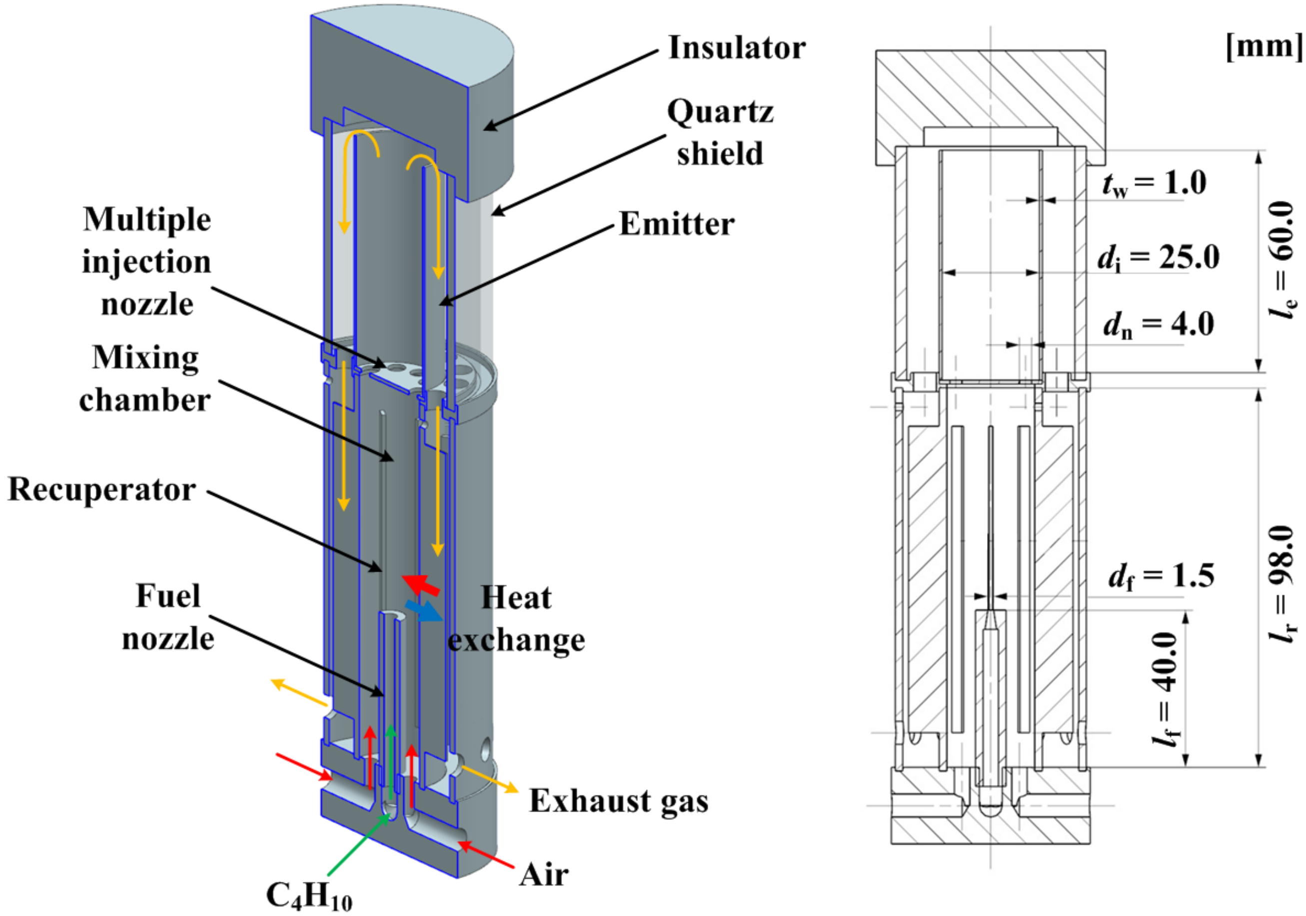

Figure 2: Configuration of heat-recirculating combustor for thermophotovoltaic power generation device.

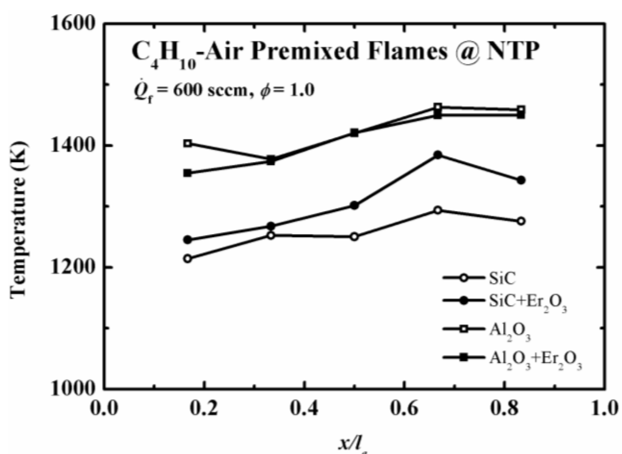

Figure 3: Temperature distribution along outer wall surface of various emitters for C_4H_{10}-air premixed flames of $\dot{Q}_f$ = 600 sccm and ϕ = 1.0 at NTP.

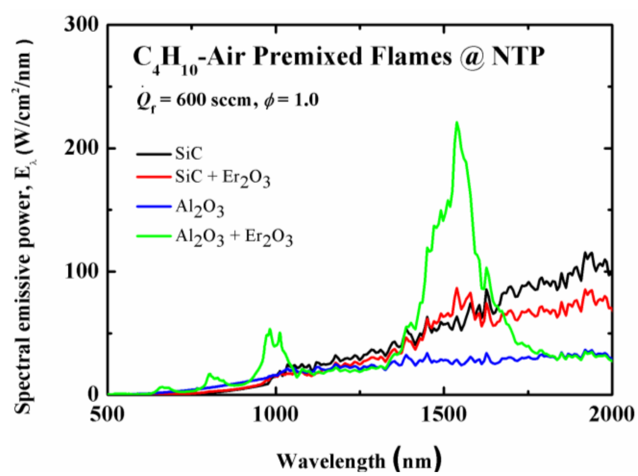

Figure 4: Spectral emissive power density onto optical probe at x/l_e = 0.5 and 100 mm apart from emitter outer surface as function of wavelengths for C_4H_{10}-air premixed flames of $\dot{Q}_f$ = 600 sccm and ϕ = 1.0 at NTP.

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4 CONCLUDING REMARKS

Performance of various types of heat-recirculating combustors for TPV power generation using SiC, Al_2O_3 and Er_2O_3 was investigated experimentally. For the Al_2O_3 emitter, higher average and maximum temperature on the emitter wall surface is observed compared with the SiC emitter. Er_2O_3 wrapping is well-maintained at high temperature without any crack for the Al_2O_3 emitter substrate, while it is cracked after several tests for the SiC emitter substrate. Higher spectral emissive power density is obtained in the wavelength range from 800 to 1100 nm and from 1300 to 1800 nm for the Er_2O_3-wrapped Al_2O_3 emitter. For the Er_2O_3-wrapped SiC emitter, however, spectral emissive power density is not significantly enhanced at the wavelengths of interest compared with the Er_2O_3-wrapped Al_2O_3 emitter. The cut-off effect of photonic crystal structure due to the Er_2O_3 wrapping is clearly observed only for the Er_2O_3-wrapped Al_2O_3 emitter (in the wavelength range from 1100 to 1300 nm and from 1800 to 2000 nm).

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