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A heat-recirculating combustor with multiple injectors for thermophotovoltaic power conversion

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HIGHLIGHTS

- A novel heat-recirculating combustor for TPV power conversion is suggested.
- The combustor consists of multi injectors, an emitter a shield and a recuperator.
- The combustor with closer injectors shows an extended stable-burning regime.
- The SiC emitter shows higher spectral emissive power density than the SUS emitter.
- The suggested combustor is acceptable for practical TPV applications.

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ABSTRACT

A novel configuration of a heat-recirculating combustor with multiple injectors for 10–30 W power-generating thermophotovoltaic (TPV) systems is suggested. For the combustor as a heat source the combustion stability limits of premixed butane-air flames, the temperature distribution on the outer wall surface and the spectral emissive power density onto photovoltaic cells are measured to evaluate the combustion and radiation performance. Results show that the combustor can sustain stable burning and effective and uniform heat transfer for a wide operating range, due to the heat-recirculation using a cylindrical emitter with a quartz shield and a recuperator. Two distinct combustion stability limits, i.e., flashback and blowout limits, are observed, and a somewhat extended stable-burning regime is found for the combustor with a finned recuperator and closer injectors. The recuperator and injector geometry also affects the temperature distribution on the emitter wall surface. A silicon carbide (SiC) emitter shows higher spectral emissive power density than the stainless steel emitter, due to higher surface temperature and emissivity, and the emissive power density is further enhanced by applying the photonic crystal structure on the SiC emitter surface, due to the optical resonance effects. Thus, the present combustor configuration can be used in practical TPV power systems.

1. Introduction

Recently, combustion-based portable power systems, particularly using hydrocarbon fuel, have been considered as one of the possible alternatives to replace current lithium-ion batteries since they can satisfy the demand for fast-charging, light and long-lasting portable power sources [1]. Although heat engines could be commonly proposed, they have significant heat and friction losses due to moving parts when being scaled down and seem to be impractical for the specific applications such as military application because of strong noise. As a combustion-driven power system with no moving parts, thermoelectric devices can be considered [2,3], but they still face other technological challenges such as the limited figure of merit (*ZT*), the complicated and large structure due to a cooling system and the resulting maintenance problem [4]. Combustion-driven thermophotovoltaic (TPV) devices are structurally simple since they use the direct conversion of thermal energy into electricity via photovoltaic cells (PVCs), and also have no moving parts. Thus, overcoming the aforementioned problems of heat engines and thermoelectric devices, they are expected to be easily adopted for portable power generation devices. Particularly, TPV devices seem to be more practical for military applications due to the simple structure and low noise, while they have been developed for power and heating systems in remote areas [5].

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Key factors in designing TPV power systems include stable burning in the combustor, effective and uniform radiating into the PVCs via the emitter and spectral matching between the emitter's thermal radiation and the PVC's response. In this laboratory, a small (meso-scale) and quiet portable TPV power generation system is under development for military applications. It will adopt a heat-recirculating cylindrical combustor with multiple injectors [6] for satisfying the above key design factors, though various configurations of micro-scale and small combustors have been suggested for miniature TPV devices, e.g. backward-facing step combustors [7], liquid fuel-film combustors [8], percolated platinum emitters [9], combustors with a rectangular rib [10], combustors with various non-circular microchannels [11], porous media combustors [12] and TPV-integrated boilers [13]. Also, to increase the efficiency of TPV systems, the photonic crystal structure that allows the precise control of electromagnetic wave properties and enlarges the photonic bandgap (PBG), applying to the emitter surface, can be considered [14]. Actually, spectrally selective emitters which can control the emitter's spectral features by applying photonic crystals on the emitter surface have recently been studied [15]. While the emitter materials having a 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 and the emitter materials. As the emitter materials to apply the photonic crystal structure on the surface both metals and ceramics have been studied [16,17]. Metals are easy to fabricate and have high toughness compared with ceramics, while ceramics have high melting points and thermal stability compared with metals. Thus, proper emitter materials should be considered to apply the photonic crystal structure.

Although the aforementioned various combustor configurations from the previous studies [7–13] have their own unique features, the combustor (emitter) and overall TPV efficiencies are somewhat limited. The backward-facing step combustor with a silicon carbide (SiC) emitter exhibits the maximum electrical output powers of 1.02 W and the overall TPV (i.e., fuel-to-power) efficiency of 0.68% when it is integrated with a TPV device [7]. This low efficiency seems to be observed since no heat recovery is considered, though the backward-facing step configuration allows for the local flow-recirculation that results in somewhat extended mixture residence time. A miniature TPV device using the liquid fuel-film combustor with a central porous inlet can deliver a promising electrical power output of 8.3 W but the overall efficiency of 1.47% [8]. Although the heat-recirculation concept is applied by using a reverse tube, a recuperator (i.e., a heat exchanger) is not used, which does not maximize the heat-recirculation effects. The percolated platinum emitters were proposed as a novel configuration, but they indicate lower output power due to the relatively low emissivity than the corresponding conventional SiC emitters [9]. A micro cylindrical combustor with the rectangular rib for enhancing heat transfer has been numerically investigated [10]. Although the rectangular rib has a positive effect on heat transfer, this concept should be experimentally demonstrated. A computational study on the premixed hydrogen (H_2)-air reacting flow inside various non-circular microchannels shows that the combustor with a trapezoidal microchannel exhibits the best performance among the various configurations [11]. The maximum thermal efficiency of the combustor and the overall TPV device efficiency were numerically estimated to be 34.6% and 5.33%, respectively. This somewhat enhanced performance was supposed to be observed because of the enhanced uniformity of the emitter surface temperature distribution due to the increased vorticity of flow in the combustor chamber. However, the numerically estimated performance should be experimentally validated. In order to improve the stability of combustion and efficiencies of a micro-TPV device, the porous media combustor was designed [12]. The maximum thermal efficiency of the porous SiC emitter is 18.2%. For this configuration, the flame is established at the front of the porous media combustor since the use of porous media enhances the residence time of the mixture. This results in the nonuniform emitter surface temperature and low thermal efficiency. The TPV-integrated boiler has been designed, built and investigated for the combined heat and power application in residential buildings [13]. The total output power, the thermal efficiency of the boiler and the overall system efficiency were reported to be 246.4 W, 22.1% and 2.0%, respectively.

In the present investigation, a heat-recirculating combustor for TPV power conversion using hydrocarbon fuel for fast-charging and improving energy density is suggested to guarantee stable burning in the combustor while effectively transferring heat into the emitter surface and then uniformly radiating into the PVCs with low noise. We aim to design a novel meso-scale combustor configuration with multiple injectors for the TPV power system, including the emitter to apply the photonic crystal structure, with the following specific objectives. The first objective is to determine a basic configuration of the heat-recirculating combustor that can sustain stable burning for a 10–30 W power-generating TPV system. Since the aforementioned earlier configurations have been suggested mainly for the micro-scale combustors (emitters) [7–12], they are not appropriate to directly apply for meso-scale combustors targeting such the power range, particularly in terms of combustion stability. Thus, a novel configuration is needed to guarantee stable burning, effective heat transfer and uniform radiation with low noise for the meso-scale combustor. Also, the present combustor should provide the emitter configuration to apply the photonic crystal structure, which was not considered in the previous studies [7–13]. Furthermore, the multi-injection configuration that cannot be adopted for the micro-combustors will be considered for improving the combustion stability. The second objective is to measure the combustion stability limits of butane (C_4H_{10})-air flames in the combustor, including the blowout (i.e., high-stretch) limits and the flashback (i.e., low-stretch) limits in order to provide the fundamental database of operating limits of the combustor. The third objective is to observe the effects of geometric variations, including the distance between injectors and the surface area to volume ratio of a recuperator, on the combustor and emitter performance. Finally, the effects of emitter materials (metal vs. ceramic) on the emitter performance, including the temperature distribution on the emitter surface and the emissive power density onto the PVCs, are evaluated.

The basic configuration of the heat-recirculating combustor with multiple injectors, the combustion stability limits for flames in the combustor, the effects of geometric variations and emitter materials on the combustion and heat transfer characteristics, and the optimal design and operating conditions will be subsequently presented, following the descriptions of the experimental methods used during this investigation.

2. Experimental methods

Fig. 1 shows a diagram of the experimental apparatus used in this study, which consists of a test combustor for TPV power conversion, a gaseous fuel-air mixture supply system, thermocouples for measuring temperature distribution on the outer wall surface of emitters, a spectrometer (Aspec 2048L/Nir256-2.5: 300–2500 nm, field of view (FOV) of 180°) for measuring the spectral distribution of the emitter walls and a digital camera (sony A65) for recording the radiating emitter images.

In the present study, stainless steel (SUS304) and SiC are used for emitters since both the materials can be considered to apply the photonic crystal structure on the surface, as discussed in