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Thermophotovoltaic power conversion using a superadiabatic radiant burner

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HIGHLIGHTS

- A porous superadiabatic radiant burner (SRB) is used for a TPV device.
- The two-layered SiC SRB includes a preheater and radiation corridors.
- Water-cooled GaSb photovoltaic cells are used for the TPV power conversion.
- Emitter efficiencies up to 32% are observed even for fuel-lean condition.
- The SRB-integrated TPV device demonstrates the practical application of the SRB.

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ABSTRACT

A new configuration of a 5–10 W thermophotovoltaic (TPV) device integrated with a porous superadiabatic radiant burner (SRB) is suggested and experimentally studied. The silicon carbide (SiC) SRB (emitter) consists of a small-pored upstream section (PM1) and a large-pored downstream section (PM2). PM1 is the section where the incoming fuel-air mixture is preheated internally and PM2 is the section where flame is established. Also, a separate preheater is attached on the SRB to externally recover heat from the exiting flue gas and preheat the inlet air for the burner, and radiation rods are embedded at the interface between the PM1 and PM2 to extract heat from the flame and transfer it to radiating disk surfaces. Radiation from the disk surface is used for the TPV power conversion, reaching gallium antimonide photovoltaic cells (PVCs) with proper quantum efficiencies (up to 80%) through a quartz plate for preventing direct convectional heat transfer from the exhaust gas onto the PVCs. Under optimized conditions, uniform radiation provides adequate TPV performance, particularly indicating reasonable emitter efficiencies (up to 32%) with the enhanced disk temperature even for fuel-lean condition. Thus, the present configuration of the SRB-integrated TPV device can be used in practical applications, avoiding high-level noise without any moving parts.

1. Introduction

In the last two decades, small-scale thermophotovoltaic (TPV) devices which use the direct conversion of thermal energy to electricity via photovoltaic cells (PVCs) have been considered as a strong candidate for a portable power source to replace lithium-ion batteries for portable electronic devices because they have no moving parts and even charge fast and last a long time [1]. Thus, various configurations of gas-fired combustors (emitters) for the small-scale TPV devices have been suggested [2–19].

Power output of a micro TPV power system that consists of a cylindrical silicon carbide (SiC) emitter, a nine-layer dielectric filter and a gallium antimonide (GaSb) PVCs [2] could be enhanced by increasing the backward facing step height of the micro combustor [3], and the effects of the mixture composition and the combustor configuration on the combustion characteristics were also experimentally investigated [4]. A micro cylindrical combustor with rectangular ribs for enhancing heat transfer was numerically investigated [5]. A prototype of the TPV system combined with a thermoelectric (TE) device, using a porous SiC emitter, was built and tested [6]; however, flame is established inside the porous foam, which is not effective for the radiative heat absorbed by PVCs. Also, two TPV prototypes using a non-surface combustion radiant burner and a cascaded radiant burner were tested, showing that porous foam structure demonstrates the best performance [7]. A

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computational study of a porous medium combustor for improving the combustion stability in a micro-TPV device shows that flame is established at the front of the combustor due to the increased residence time of the fuel-air mixture, resulting in the nonuniform emitter surface temperature and low thermal efficiency [8]. A computational study on the premixed hydrogen (H_2)-air reacting flow inside various non-circular microchannels shows that the combustor with trapezoidal microchannels demonstrates the best performance among the various configurations [9]. Also, studies for improving combustion efficiency by using a heat-recirculation concept have been continuously conducted. For instance, a high temperature recuperative burner was suggested [10]. In this laboratory, novel micro-emitter configurations for micro-TPV devices, adopting the heat-recirculation concept, have been investigated experimentally and computationally [11–15]. A heat-recirculating cylindrical micro-combustor, extracting heat from exhaust gas for preheating the mixture gas, guarantees the stable burning in the small confinement and effective heat transfer into the micro-emitter wall surface for a micro TPV device [11]; however, stainless steel (SS) was used for the test emitter due to the easy fabrication. When the SS emitter was replaced by a SiC emitter under more practical circumstances, the TPV performance has improved [12] and was directly demonstrated using PVCs [13]. The potential of ammonia (NH_3)-H_2 blends as a carbon-free in a micro-TPV device with the heat-recirculating configuration was experimentally evaluated [14], while the potential of integrating a micro-TPV device with a micro-reformer, using NH_3-H_2 blends, has been studied [15]. Additional heat-recirculating combustors which are similar to those in this laboratory but somewhat different in the specific configurations have been suggested by several research groups: a heat-recirculating configuration that involves a swirl combustor and a reverse tube for a miniature TPV device [16], a TPV system which provides both heat and electric power using a combined TPV furnace generator [17], a recuperator for the exhaust gas to preheat fresh air [18] and the utilization of rare earth for selective emitters to enhance the TPV efficiency further [19].

Due to the limited PVC efficiency [15], the aforementioned small-scale TPV devices generally exhibit low overall efficiencies in the range of 0.05–0.95%, though some systems demonstrate relatively higher efficiencies in the range of 2.1–2.3% [7,13,14]. Thus, they seem to be useful for the specific applications such as the military application where the design requirements of fast charging and low-level noise rather than high efficiencies are more important. Nevertheless, enhancing the overall efficiency via improving the combustor efficiency is still meaningful to reduce operating costs. To increase the combustor efficiency the porous ceramic combustors instead of conventional combustors are often adopted due to the concept of their excess enthalpy burning [20]. For the porous ceramic combustors, however, flames are generally established inside the porous medium to maximize the excess enthalpy burning. Thus, if they are adopted for the TPV devices, the radiative heat generated from the flame cannot be effectively absorbed by the PVCs unless there are special radiation corridors between the flame and the PVCs.

A novel porous superadiabatic radiant burner (SRB) with augmented preheating (i.e., internal and external heat-recirculation) and radiation rods (corridors) was recently suggested [21], and its superadiabatic performance has been experimentally demonstrated in this laboratory [22]. The alumina SRB with a square cross-section consists of a fine-pored upstream section to internally preheat the incoming fuel-air mixture and a coarse-pored downstream section to establish flame. A separate preheater is also installed to externally reproduce the heat using the flue gas and warm the inlet air previously for the burner. Finned radiation rods are put at the interface between the two porous media to absorb heat from the flame and the heat is distributed to radiating disk surfaces by the rods. The radiation disk is placed at the downstream end of the radiation rod. Thus, the SRB has the potential of utilization for the TPV power conversion, showing a significant improvement in the performance compared with the conventional porous burners [22]. However, the practical application of the novel SRB has not been demonstrated yet.

Based on these reasons, this experimental study focuses on the design and performance evaluation of a SRB-integrated TPV device as the real application of the SRB. We will first construct the PVC-installed TPV power device applying the SRB referring to the previous research in this laboratory [22]. For this purpose, the detailed dimensions of the SRB have been modified to be integrated with the TPV device as well as to improve the SRB's own performance. As aforementioned, the SRB has a very novel configuration and the unique features [22]. Thus, the present study itself can be considered as the unique study demonstrating the practical application. Then, we will determine the distance between the water-cooled PVCs and the radiation disk surface for avoiding damage to the PVCs due to high operating temperature and maximizing heat irradiation onto the PVCs. Finally, the effects of mixture flow rates and fuel-equivalence ratios on the TPV performance will be observed. Through the experiment, the optimal operating conditions are determined.

2. Experimental methods

A diagram of the experimental apparatus used in this study is given in Fig. 1. It consists of a test TPV device including PVCs and a SRB with two-layer porous media, radiation rods placed in the porous media and a preheater, a fuel-air mixture supply system for the SRB, a water cooling system for the PVCs, a ventilation system, K-type thermocouples for measuring temperature distribution in the SRB and on the PVC surface, a digital camera (Sony A65) for recording the emitter (i.e., the radiation disk) surface and flame images, a spectrometer (Aspec 2048L/Nir256-2.5: 300–2500 nm) for measuring the spectral distribution of the radiating disk surface and a multimeter (Hioki 3803: 0.4000–40.00 V with accuracy of ± 0.6% and 0.4000–10.00 A with accuracy of ± 1.5%) for measuring the electrical output characteristics of the PVCs.

Propane (C_3H_8, purity $> 99.9999\%$) and air (21% O_2/79% nitrogen (N_2) in volume, purity $> 99.9\%$) are supplied respectively to a mixing chamber and to a preheater using commercial mass flow controllers (Area and MKS: 0–200 slm) with accuracy of ± 1.0% of full scale. Calibration for the mass flow controllers was done using a bubble meter and managed by PC-based software (Lab-VIEW) which is able to control fuel-equivalence ratio (ϕ) and the mixture inlet velocity (V) defined as the total volume flow rate of the mixture divided by the cross-sectional area of the SRB, independently. The fuel-equivalence ratio is defined as the fuel-to-air mass ratio of a reacting mixture normalized by the stoichiometric fuel-to-air mass ratio of the corresponding mixture. Thus, $\phi < 1$, $=1$ and > 1 indicate fuel-lean, stoichiometric and fuel-rich conditions, respectively. The preheater using a 10.2 mm (stainless steel, SUS316L) spiral fin tube is located between the downstream end of the porous medium of the SRB and the radiation disks of the radiation rods. It is designed to warm the fresh air using the exhaust gas before the air enters the burner. The preheated air and fuel are mixed in the mixing chamber and are issued from the bottom of a distributor ($68 \times 68 \times 60$ mm^3) that is filled with stainless steel beads with an average bead diameter of 1.5 mm for obtaining uniform flow. The distributor is also windowed to detect flashback using quartz. The preheated air-fuel mixture is fed into the porous medium of the SRB with uniform flow.

The SRB consists of a porous medium with fine SiC foam (PM1: 65 ppi (pores per inch), porosity of 0.835, $68 \times 68 \times 40$ mm^3, Ultramet Inc.) upstream and the other porous medium with coarse SiC foam (PM2: 20 ppi, porosity of 0.870, $68 \times 68 \times 40$ mm^3, Ultramet Inc.) downstream. The heat-insulated case with thickness of 5.0 mm (SUS316 L, $78 \times 78 \times 140$ mm^3) surrounds the four sides of porous media. At the exhaust outlet of the burner the preheated air-fuel mixture of near stoichiometric condition is ignited by a torch-igniter. Once the mixture is ignited and a flame is successfully generated, V and ϕ