Design of a heat-recirculating combustor for a thermophotovoltaic system

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ABSTRACT

In the present study, a new combustor configuration for a thermophotovoltaic (TPV) system in which thermal energy is directly converted into electrical energy through thermal radiation is investigated experimentally. The combustor as a thermal heat source is designed for a 10-30 W power-generating TPV system. The combustor consists of an emitter (combustion chamber), injection nozzles, a mixing chamber and a quartz shield. To satisfy the primary requirements for designing the combustor (i.e., stable burning in the combustor chamber, maximized heat transfer through the emitting walls, but uniform distribution of temperature along the walls), the multiple injection configuration with annularly arranged nozzles and the cylindrical emitter with the quartz shield to apply a heat recirculation concept are adopted to the present combustor. Results show that the heat recirculation substantially improves the performance of the combustor. Compared with conventional combustors with no heat-recirculation, the efficiency of the combustor has been enhanced and the observed thermal radiation from the emitter walls indicates that heat generated in the emitter is uniformly emitted. Thus, the present combustor configuration can be applied to the practical TPV systems without any moving parts (i.e., without frictional losses and clearance problems). The fuel nozzle length substantially affects flame behaviors.

Keywords: thermophotovoltaic, TPV, heat recirculation, combustor, emitter

1 INTRODUCTION

Recently, the demand for light, fast-charging and long-lasting portable power sources to replace current lithium-ion batteries has been increased because of development of portable electronic devices such as laptop computers, cellular phones and signal equipment. Power systems using combustion of hydrocarbon fuel are considered one of the alternatives since the specific energy of hydrocarbon fuel, i.e., 12,700 Wh/kg for butane, is much larger than that of lithium-ion batteries (100-265 Wh/kg) and the fast-charging is possible when hydrocarbon fuel is used. Thus, various combustion-based power devices have been suggested [1]. However, such heat engines with moving parts seem to be impractical since overcoming heat and friction losses and the difficulties of fabrication and assembly are considered technological challenges for miniaturizing the system. In order to avoid such the technological difficulties for developing power systems involving moving parts, a thermoelectric device that consists of a combustor connected with a heat-recirculating fuel-air mixture inlet and exhaust outlet assembly for reducing heat losses and thermoelectric elements was suggested [2]. Another type of thermoelectric device using catalytic combustion for stable burning in a relatively simple configuration of combustor was developed [3]. Although the thermoelectric power systems could much improve the difficulties of fabrication and assembly, there are still technological challenges: complicated structure for homogeneous gas-phase combustion and maintenance problem due to easily poisoned catalyst surface for catalytic combustion.

Considering the technological difficulties of the aforementioned combustion-based power system, a novel device should be structurally simple and efficient without moving parts. Thermophotovoltaic (TPV) power generation in which TPV cells generate electric energy from thermal radiation, similar to solar cells converting the radiative energy of sun light into electrical power, have been developed for house heating systems and power suppliers in remote areas [4]. Due to the simple geometry with no moving parts, the TPV power systems are expected to be easily scaled down for power generation. Thus, in this laboratory a small and quiet portable TPV power generation system is under development for military applications. It adopts a heat-recirculating concept [5].

In the present investigation, a heat-recirculating TPV power system using hydrocarbon fuel for improving energy density is suggested to guarantee stable burning in the emitter (combustor) while effectively transferring heat into the emitter surface and then uniformly radiating into the TPV cells. We aim to design a novel combustor configuration without catalysts for a TPV power system, with the following specific objectives. The first is to determine a basic configuration of the combustor that can sustain stable burning for a 10-30 W power-generating TPV system. The second is to observe the effects of heat recirculation on the temperature distribution of the emitter surface. The third is to provide the optimized design condition for stable burning in the combustor from the observation.

2 EXPERIMENTAL METHOD

A diagram of the present experimental apparatus appears in Fig. 1, which consists of a combustor (stainless steel, SUS304), a fuel and air supply system, thermocouples for measuring temperature distribution on the outer wall surface of the emitter, and a digital camera (sony A65) for recording the radiating emitter images. In the present study, we focus on demonstrating if heat recirculation can improve the emitter performance; thus, stainless steel was used for the test emitter due to easy fabrication, though better materials for emitters could be considered, i.e., silicon carbide (SiC). Commercial mass flow controllers (MKP: 1,000 and 20,000 sccm) with accuracy ±0.75-1.00% of full scale deliver fuel and air to the combustor: they are commanded by a PC-based software (LabVIEW) that enables independent control of mixture composition (or fuel-equivalence ratio ϕ) and the emitter inlet velocity V (or volume flow rate Q). Temperature distribution on the outer wall surface of the emitter is measured using K-type thermocouples (a bead diameter of 127±20 μm) with the measurement accuracy of ±0.4%. To prevent sagging when thermocouples are contacted on the emitter, tension is added to the bead. Configurations of designed combustors will be discussed in Section 3.

Flames in the emitter are obtained by establishing a cold injected flow of reactive mixture and then igniting the mixture on the injection nozzle outlet with a spark. Once the mixture is ignited, the insulator is covered and then flames are attached on the injection nozzle and stabilized in the emitter. Experiments were carried out for butane (C_4H_{10}, purity>99.5%)-air (21%O_2/79%N_2 in volume) mixtures of $\phi = 1.0$ and $V = 3.0$ m/s at temperature $T = 298 \pm 3$ K and atmospheric pressure (NTP). Butane has been chosen as fuel since it can be liquefied at relatively low pressures and be easily vaporized when mixed with air at NTP; thus, C_4H_{10} has a potential in practical use. To evaluate effects of heat recirculation and the fuel nozzle length (l_f) on the combustor performance, the experiments were carried out for combustors with l_f = 1.0-4.0 mm.

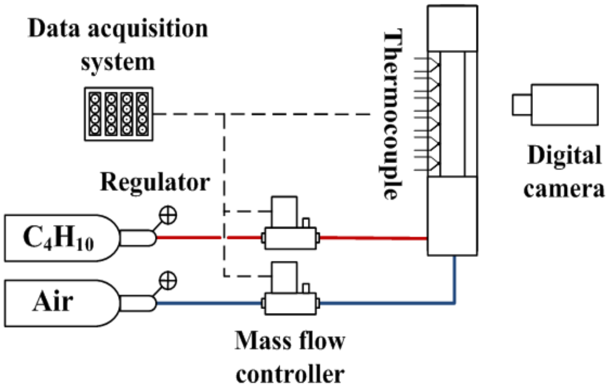

Figure 1: Schematic of experimental apparatus.

3 RESULTS AND DISCUSSION

A combustor configuration for a 10-30 W power-generating TPV has been designed based on the previous study [5] in this laboratory, and baseline dimensions were obtained from pretests. Figure 2 shows the heat-recirculating combustor configuration and major dimensions (the emitter thickness t_w = 1.0 mm, the inner diameter of the emitter d_i = 25.0 mm, the diameter of injection nozzles d_n = 4.0 mm, the emitter length l = 48.0 mm, the diameter of the fuel nozzle d_f = 1.5 mm and the length of the fuel nozzle l_f = 20.0 mm). The combustor consists of an emitter (combustion chamber), injection nozzles, a mixing chamber, a quartz shield and an insulator. In order to use a simple structure but uniformly radiating emitter, a cylindrical configuration was chosen as a basic geometry of the emitter. To satisfy the primary requirements for designing the combustor (i.e., stable burning in the combustor chamber, maximized heat transfer through the emitting walls, but uniform distribution of temperature along the walls), the multiple injection configuration with annularly arranged nozzles (the number of injection nozzles n = 9) and the cylindrical emitter with the quartz shield to apply a heat recirculation concept are adopted to the combustor: exhaust gas burned in the emitter turns around the insulator at the upper end of the emitter, and then heat transfers through the wall of the mixing chamber as the fuel-air mixture flows in one direction and the exhaust gas flows in the opposite direction. When the preheated fuel-air mixture is burned, enhanced uniformity of temperature distribution is expected.

3.1 Effects of heat recirculation

Figure 3 shows the temperature distribution along the outer wall surface of the emitter without heat recirculation and a radiating image. For no heat recirculation, the insulator has been removed. The maximum temperature of the emitter wall surface that would be surrounded by the TPV cells (x/l = 0-1 for the present coordinate system in Fig. 2) is 985 K and the average temperature is 877 K. It shows relatively low temperature and nonuniform radiation compared with the heat-recirculating combustor (Fig. 4). Thus, as expected, the direct burning without heat recirculation is not suitable for the combustor application.

Figure 4 shows the temperature distribution along the outer wall surface of the heat-recirculating combustor and a radiating image. The maximum temperature of the emitter wall surface is 1225 K and the average temperature is 1165 K. It shows remarkably enhanced temperature compared with the combustor without heat recirculation (Fig. 3). Also, compared with the temperature distribution without the recirculation of the exhaust (Fig. 3), the temperature distribution with the recirculation shows a reduced temperature gradient along the emitter wall. As shown in the radiating image, the temperature uniformity seems to be high enough for the best performance of a TPV system.

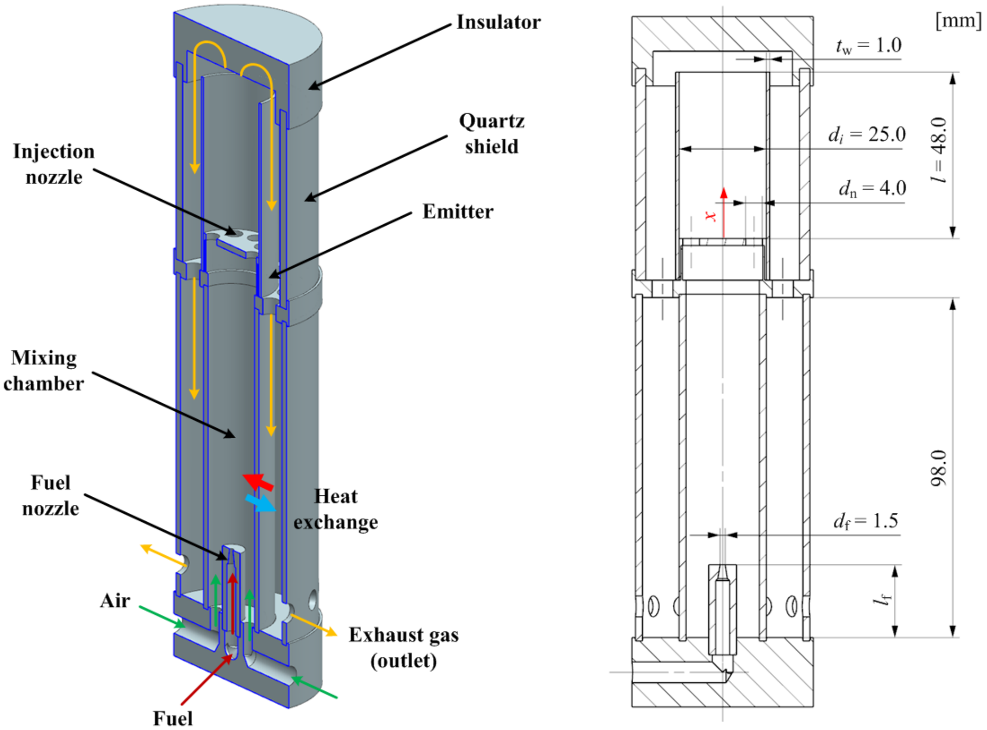

Figure 2: Configuration of combustor.

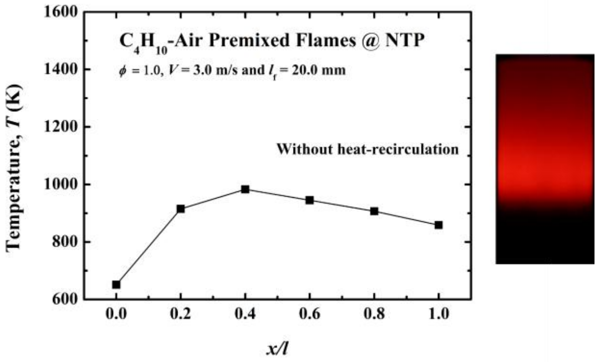

Figure 3: Measured temperature distribution along outer wall surface of emitter without heat-recirculation and radiating image.

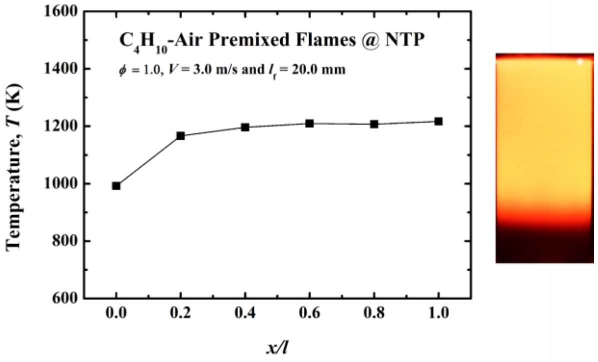

Figure 4: Measured temperature distribution along outer wall surface of heat-recirculating emitter and radiating image.

3.2 Effects of geometric variations

Figure 5 shows radiating images of the heat-recirculating emitters with various l_f: l_f = 10.0 (a), 20.0 (b) and 40.0 mm (c). For l_f = 10.0 mm, the flame location is observed in the mixing chamber since the residence time of the fuel-air mixture gas increases in the mixing chamber and the burning intensity (velocity) is enhanced due to the heat-recirculation. This configuration reaches a condition in which the burning velocity is greater than the mixture gas velocity. Thus, as observed, the flame propagates down into the injection nozzle and the flashback occurs. For l_f = 20.0 mm, stable burning in the combustor chamber is observed, which has been discussed for the measured temperature distribution and image in Fig. 4. For l_f = 40.0 mm, the flame is located at the upper end of the emitter since the residence time for mixing with fuel and air is not sufficient. Thus, the lift flame is observed and the flame is not stabilized on the injection nozzles.

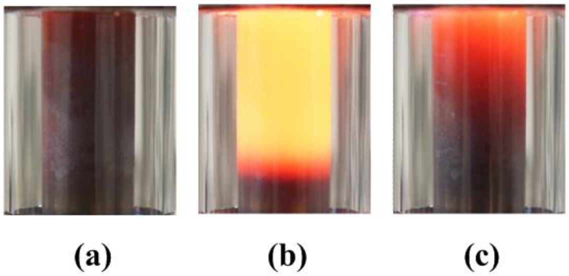
(a) (b) (c)

Figure 5: Radiating images of heat-recirculating emitters (l_f = 10.0 (a), 20.0 (b) and 40.0 mm (c)).

4 CONCLUDING REMARKS

A new combustor configuration for a TPV system in which thermal energy is directly converted into electrical energy through thermal radiation was investigated experimentally. The combustor as a thermal heat source was designed for a 10-30 W power-generating TPV system. The present preliminary results can be used as baseline data for the further develpment of the emitter and the TPV system. The major conclusions of the study through the preliminary tests are as follows:

1. In order to satisfy the primary requirements for designing the combustor, i.e., stable burning in the combustor chamber, and maximized heat transfer through the emitting walls but uniform distribution of temperature along the walls, the present combustor consists of the multiple injection configuration with annularly arranged nozzles and the cylindrical emitter with the quartz shield to adopt a heat-recirculation concept.
2. For the optimized design condition, the heat recirculation substantially improves the performance of the combustor: the observed thermal radiation from the emitter wall indicates that heat generated in the emitter is uniformly emitted.
3. Three distinct flame stability behaviors are observed: flashback, stable flame and lift flame. The flashback is observed for a short fuel nozzle due to the intensified burning with the long residence time of the fuel-air mixture, while lift flame is observed for a long fuel nozzle due to the limited residence time of the mixture.

This work was supported by the Civil-Military Technology Cooperation Program, Korea under Grant No. 15-CM-EN-08.

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