Measured and predicted performance of a micro-thermophotovoltaic device with a heat-recirculating micro-emitter

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ABSTRACT

A new configuration of a 1-10 W micro-thermophotovoltaic (micro-TPV) device is studied experimentally and computationally. In the micro-TPV device thermal energy is directly converted into electrical energy through thermal radiation without any moving parts. For stable burning in a small confinement with uniform wall temperature, the present micro-emitter is a simple cylinder with an annular-type shield to apply for a heat-recirculation concept. The micro-emitter is surrounded with a chamber on the inner wall of which photovoltaic cells (PVCs) are supposed to be installed. The enhanced vacuumity of the PVC-installed chamber does not substantially affect the micro-TPV device performance, while the enhanced gap between the micro-emitter and PVC-installed chamber walls improves the cooling performance. For optimized design conditions, the results show that the present micro-TPV device configuration can be used in practical applications, avoiding frictional losses and clearance problems.

Keywords: micro-thermophotovoltaic device, micro-emitter, micro-combustor, micro-combustion, heat recirculation

1 INTRODUCTION

Recent advances in portable electronic devices such as laptop computers and cellular phones demand light and fast charging portable power sources replacing current lithium-ion batteries. Miniature or micro-scale (that will be called as micro hereafter) power systems using combustion of hydrocarbon fuels are considered one of the alternatives since they can contain more energy per unit mass than the lithium-ion batteries and be fast charged. Thus, various combustion-based micro-power devices have been suggested [1]. Most combustion-based micro-power systems were scaled down from macro-scale heat engines such as gas turbine and rotary engines. However, such micro heat engines involving 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 systems. Considering the technological difficulties of the earlier combustion-based micro-power systems, a novel micro device should be structurally simple and efficient without moving parts. Due to the simple geometry with no moving parts, thermophotovoltaic (TPV) power systems in which photovoltaic cells (PVCs) generate electric energy from thermal radiation (emitted from a micro-emitter) are expected to be easily scaled down for micro-power generation.

An earlier experimental and computational study of micro-emitters in this laboratory showed that a heat-recirculating but still structurally simple micro-emitter (micro-combustor) for micro-TPV power systems using hydrocarbons guarantees stable burning in the small confinement while effectively transferring heat into the micro-emitter wall surface and then uniformly radiating [2]. Thermal characteristics along the micro-emitter wall are improved with increasing ratios of the inner radius of a heat-recirculating shield to the gap between the shield and micro-emitter walls and with decreasing wall thickness of micro-emitter within the thickness allowed for fabrication and structural strength. In the earlier study, however, we focused on demonstrating if the heat recirculation can improve the micro-emitter performance; thus, stainless steel (SUS) was used for the test emitter due to easy fabrication, though better materials for emitters, e.g. silicon carbide (SiC), could be considered.

In the present investigation, a micro-TPV device applying the micro-emitter configuration suggested from the earlier study, using SiC as the materials and including a chamber, on the inner wall of which PVCs are supposed to be installed, surrounding the micro-emitter, is suggested to demonstrate the micro-TPV performance under more practical circumstances, with the following specific objectives. The first is to determine a basic configuration of the micro-TPV device. The second is to observe the effects of the vacuumity of the PVC-installed chamber on the micro-TPV device performance. The third is to observe the effects of geometric variations such as the gap between the micro-emitter and PVC-installed chamber walls on the micro-TPV device performance. The fourth is to identify the optimized design conditions from the observations. We shall also examine the structure of the micro-flame and heat transfer in the small confinement, based on computational fluid dynamics (CFD) simulation with a simplified kinetic mechanism and a radiation model, in order to gain more understanding about some unique characteristics of micro-flames and heat transfer through the walls.

2 EXPERIMENTAL AND COMPUTATIONAL METHOD

A diagram of the present experimental apparatus is given in Fig. 1. The set-up consists of a test micro-TPV device (that is a micro-emitter (SiC) surrounded with a chamber on the inner wall of which PVCs are supposed to be installed), a fuel-air mixture supply system, thermocouples for measuring temperature distribution on the surface of the inner wall of the chamber and a vacuum pump connected into the chamber for controlling chamber pressure. Commercial mass flow controllers (100-4,000 sccm) with an accuracy of ±0.75-1.00% of full-scale deliver the combustible mixture to the micro-emitter. The controllers are managed by a PC-based software that enables independent control of mixture composition (fuel-equivalence ratio ϕ) and micro-emitter inlet velocity V. The temperature distribution on the surface of the inner wall of the chamber is measured using K-type thermocouples (a bead diameter of 250±20 μm) with an accuracy of ±0.05%. Final results are obtained by averaging measurements of 4-5 tests at each condition. Experimental uncertainties (95% confidence) for temperature are less than 2.5%.

Flames in the micro-emitter were obtained by establishing an injected, cold flow of reactive mixture that was then ignited at the exhaust outlet with a spark. Once the mixture is ignited, flames moved backward and were stabilized in the micro-emitter. Experiments were carried out for a propane (C_3H_8, purity>99.9%)-air ($21\%O_2/79\%N_2$ in volume) mixture of $\phi = 1.0$ and V = 3.9 m/s at a temperature T = 298±3 K and atmospheric pressure (normal temperature and pressure, NTP). To evaluate the effects of the shortest gap between the micro-emitter and chamber walls (d_g) on the micro-TPV device performance, the experiments were carried out for micro-TPV devices with d_g = 6.0 and 12.0 mm.

Computational methods are similar to past work and will be described only briefly (see [2] for more details), though modeling of heat transfer and boundary conditions has been somewhat improved. The micro-combustion in micro-emitters and the thermal radiation in chambers were simulated using a commercially available CFD code FLUENT 6.2 [3], the results from which were analyzed along with those of experimental tests for effectively designing micro-TPV devices. The time-dependent ordinary sets of the continuity equation, the two-dimensional (cylindrical: r-x, where r and x are the radial and axial coordinates, respectively) Navier-Stokes equations, the energy conservation equation and the species conservation equations were solved via the finite volume method. Multi-component diffusion, thermal diffusion, variable thermochemical properties and variable transport properties were considered. The CHEMKIN database was used to find the thermochemical properties [4]. The thermal radiation from the micro-emitter wall surface onto a virtual PVC surface in the chamber was simulated by the surface-to-surface model [5]. Propane and air mixtures were considered with a simplified 4-step reversible C_3H_8/O_2 reaction mechanism involving seven species due to Hautman et al. [6].

The governing equations adapting the above sub-models were discretized and simultaneously solved [3]. The number of grids was determined through the grid-independence test varying the number from 10,000 to 50,000, which showed no changes (within 1%) of the results beyond 45,000 grid points. Applied boundary conditions are as follows: no-slip and zero mole-fraction gradient conditions on the inside wall of the micro-TPV device, pressure outlet conditions at the exhaust outlet, and ambient air of heat transfer coefficient h = 10 W/m^2-K at T = 298 K on the outside wall of the micro-TPV device. Specific heat at constant pressure and thermal conductivity of the walls were provided as a function of T, while a constant emissivity for each material was used. The parallel computation system consisted of 4 personal computers (CPU speed of 2.7 GHz each) allowed for two-dimensional computations with the sub-models. Numerical simulations were conducted for the same conditions as those for the experiments.

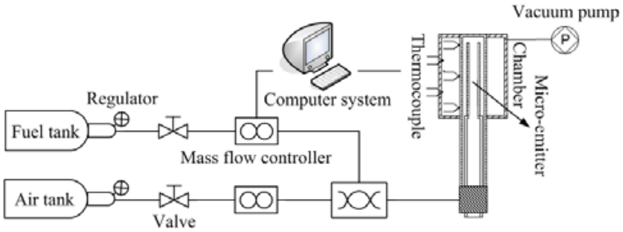

Figure 1: Schematic of experimental apparatus.

3 RESULTS AND DISCUSSION

A basic configuration of a micro-TPV device applying the micro-emitter configuration suggested from the earlier study [2] and the baseline condition obtained from pretests is suggested to demonstrate the TPV performance under more practical circumstances. Figure 2 shows the basic micro-TPV device configuration and major dimensions. The SiC micro-emitter is surrounded with a chamber on the inner wall of which PVCs are supposed to be installed. The chamber is a hexagonal tube for installing slat-type PVCs and welded onto the micro-emitter. For better cooling, the

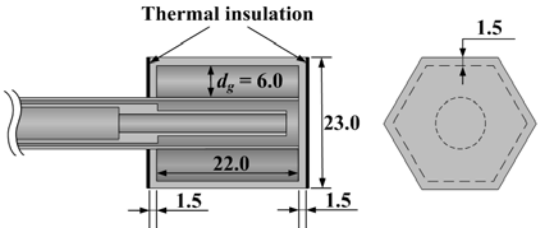

Figure 2: Configuration of micro-TPV device (unit: mm).

chamber is made of copper (Cu). In the present study, however, any special cooling devices such as cooling fins were not used for simplifying measurements and computations. Tow end caps of the chamber are thermally insulated for reducing heat losses. For measuring temperature distribution, thermocouples are installed on the inner wall of the chamber where PVCs are supposed to be installed. Also, a vacuum pump is connected into the chamber in order to control chamber pressure.

3.1 Effects of vacuumity of PVC-installed chamber

Figure 3 gives the temperature distribution along the inner wall surface of the chamber shown in Fig. 2 (T as a function of x normalized by the micro-emitter length l) for C_3H_8-air mixture of $\phi = 1.0$ at V = 3.9 m/s at pressure P = 1.00 and 0.05 atm ($d_g = 6.0$ mm). Predicted distributions of the temperature and the mole fraction of fuel in the micro-TPV device for the atmospheric condition are presented in Fig. 4. Temperature along the inner wall surface of the chamber for both conditions is high, compared with the operating limit temperature of 400-500 K for typical PVCs, e.g. gallium antimonide (GaSb) cells. This high temperature will degrade the PVC performance. The measured temperature tendency and gradient are well predicted computationally, except for the ends where temperature is significantly overestimated. Disagreement between the measured and predicted temperature distributions near the ends can be attributed to the difference between experimental and computational boundary conditions. Tow end caps of the chamber are not perfectly adiabatic, though they were tried to be thermally insulated for reducing heat losses, and heat is partially conducted along the Cu walls, while they are ideally adiabatic for computations. Overall, however, this observation justifies the present micro-emitter design combining measurements with computations. Considering the temperature distribution for the present test conditions, a cooling device should be installed or a gap between the micro-emitter outer wall and the chamber inner wall should increase. This issue will be discussed in the subsection 3.2.

Temperature in the chamber is enhanced with the reduced pressure, compared with that for the baseline atmospheric pressure condition, but the increase is not significant (less than 50 K). The temperature uniformity is somewhat enhanced: the temperature gradient along the wall ≈ 60 K (cf. 98 K for the atmospheric pressure condition). Considering the efforts to vacuumize the chamber, however, the improvement is not significant. For the configuration and condition in Figs. 3 and 4, the amount of delivered energy and the final output power can be estimated from the results of thermal radiation from the micro-emitter wall surface into the virtual PVC surface in the chamber. Assuming the PVC efficiency of 10% [2], the predicted output power and overall efficiency of the micro-TPV device for the atmospheric chamber condition are 2.1 W and 1.6%, respectively. The corresponding power and efficiency for the low pressure condition are 2.4 W and 1.8%, respectively. The performance for the reduced pressure is somewhat improved; as expected from the results in Fig. 3, however, the enhanced vacuumity of the PVC-installed chamber does not substantially affect the micro-TPV device performance. Thus, the experiments and computations hereafter were conducted only for atmospheric chamber condition.

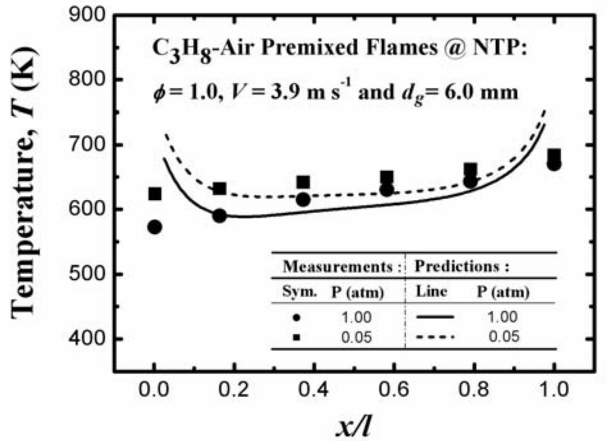

Figure 3: Measured and predicted temperature distribution along inner wall surface of chamber at atmospheric and low pressures ($d_g = 6.0$ mm).

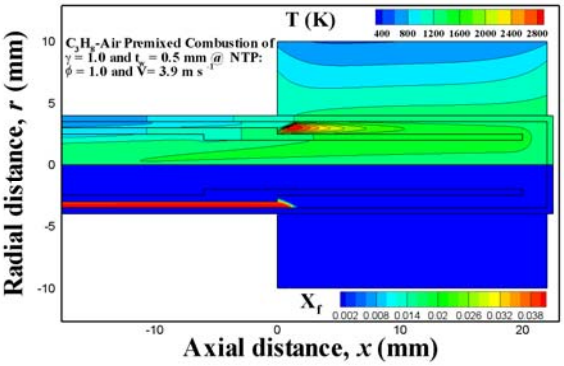

Figure 4: Predicted distributions of temperature and mole fraction of fuel in micro-TPV device at atmospheric pressure ($d_g = 6.0$ mm).

3.2 Effects of geometric variations

Experiments and computations were conducted to investigate the effects of geometric variations of the PVC-installed chamber on the micro-TPV device performance. Compared with the results for the baseline configuration of the chamber that was presented in the subsection 3.1, those for a micro-TPV device with a radially expanded chamber were obtained, since the narrow gap between the micro-emitter and the chamber walls yielded inappropriate operation temperature.

Figure 5 gives the temperature distribution along the inner wall surface of the radially expanded chamber (d_g = 12.0 mm) for the same atmospheric test condition as provided in Figs. 3 and 4. The predicted heat irradiation fluxes onto the inner wall of the chamber ($\dot{q}''$) are presented in Fig. 6. Temperature on the inner wall surface of the expanded chamber is significantly reduced (the maximum temperature ≈ 560 K), compared with that for the baseline configuration. However, the temperature distribution shows the inner wall is not cool enough for PVCs to endure without any special cooling device (> 500 K). Thus, a special cooling device such as cooling fins should be installed but it is not necessary to use a large device due to the small gap between the limit and maximum temperatures. The temperature gradient (≈ 100 K) is almost the same as that for the baseline atmospheric pressure condition in Fig. 3. The predicted heat irradiation fluxes onto the inner wall of the chamber are much reduced but the uniformity is much enhanced, compared with those for the baseline configuration (not shown here), which was expected.

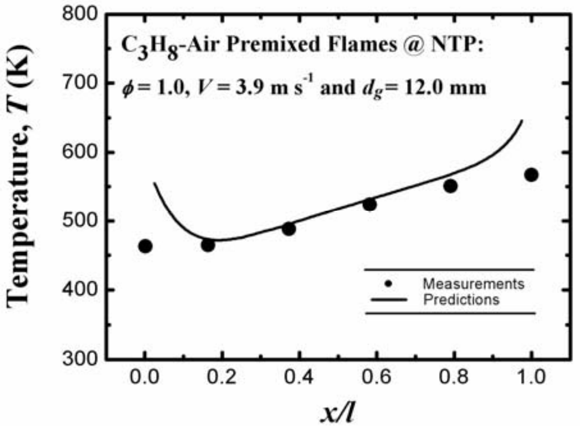

Figure 5: Measured and predicted temperature distribution along inner wall surface of chamber at atmospheric pressure (d_g = 12.0 mm).

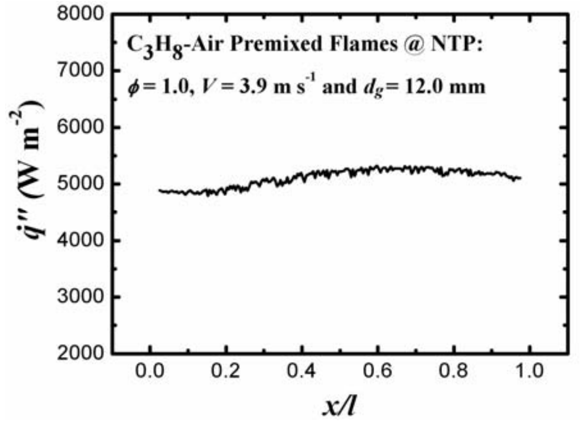

Figure 6: Predicted heat irradiation fluxes onto inner wall of chamber at atmospheric pressure (d_g = 12.0 mm).

The predicted output power and overall efficiency of the micro-TPV device are 2.1 W and 1.6%, respectively, again assuming the PVC efficiency of 10%. Comparing with the previous results for the baseline configuration, the performance for the micro-TPV device with the radially expanded chamber is almost the same. Thus, the inner wall surface of the chamber (hence installed PVCs) can be appropriately cooled down by changing the chamber size for a given micro-emitter and (probably) installing small cooling fins without substantially degrading the micro-TPV device performance.

4 CONCLUTIONS

A new configuration of a 1-10 W micro-thermophotovoltaic device with a heat-recirculating micro-emitter has been studied experimentally and computationally. The major conclusions of the study are as follows:

1. The enhanced vacuumity of the PVC-installed chamber does not substantially affect the micro-TPV device performance.
2. The inner wall surface of the chamber (hence installed PVCs) can be appropriately cooled down by changing the chamber size for a given micro-emitter and (probably) installing small cooling fins without substantially degrading the micro-TPV device performance.
3. For the optimized design condition (in terms of both the power/efficiency and cooling performance), among the present test conditions and configurations of the micro-TPV devices, the predicted output power and overall efficiency of the micro-TPV device for the atmospheric chamber condition are 2.1 W and 1.6%, respectively, assuming the PVC efficiency of 10%.

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