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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 with a heat-recirculating micro-emitter is studied experimentally and computationally. The present micro-emitter is a simple cylinder with an annular-type shield that applies a heat-recirculation concept. The micro-emitter is surrounded by a chamber, the inner wall of which has an installation of photovoltaic cells (PVCs). The micro-emitter materials and the gap between the micro-emitter and the walls of the PVC-installed chamber substantially affect the performance of the micro-TPV device. Under optimized design conditions, a pre-mixed micro-flame stabilizes easily in the micro-emitter, and the heat generated in the micro-emitter is emitted uniformly, providing adequate overall system efficiencies. Thus, the present micro-TPV device configuration can be used in practical applications, avoiding frictional losses and clearance problems without any moving parts.

1. Introduction

Recent advances in portable electronic devices, such as laptop computers and cellular phones, demand light and fast-charging portable power sources to replace current lithium-ion batteries. Miniature or micro-scale (which will be referred to as *micro* hereafter) power systems that use the combustion of hydrocarbon fuels are one possible alternative, since they can charge quickly and store more energy per unit mass than the lithium-ion batteries. Thus, various combustion-based micro-power devices have been suggested [1].

Most combustion-based micro-power systems are scaled down from macro-scale heat engines, such as gas turbines and rotary engines [1]. However, micro heat engines that involve moving parts seem to be impractical since they must overcome heat and friction losses, and the difficulties of fabrication and assembly present technological impediments to the miniaturization of such systems. Micro thermoelectric devices offer an alternative that avoids these technological impediments [2–4]. Although micro thermoelectric power systems could greatly ease fabrication and assembly, they still face technological challenges, such as complicated heat recirculation structures for homogeneous gas-phase combustion, and a maintenance problem due to easily-poisoned catalyst surfaces for catalytic combustion.

Considering the technological difficulties of earlier combustion-based micro-power systems, a novel micro device should be structurally simple and efficient without moving parts. Thermophotovoltaic (TPV) power generators, in which photovoltaic cells (PVCs) generate electric energy from thermal radiation (similar to solar cells, which convert the radiative energy of sunlight into electrical power), have been developed for house heating systems, power suppliers in remote areas, and range extenders in electric cars [5]. Due to their simple geometry and lack of moving parts, TPV power systems are expected to be easily scalable for micro-power generation.

Recently, the effects of major parameters on micro-combustion for TVP energy conversion were investigated, including the configuration, wall thickness, and materials of micro-combustors, and mixture compositions [6]. The investigation was only carried out for hydrogen-air mixtures in a simple cylindrical combustor with a backward facing step. The practical use of hydrogen for micro-combustors is questionable due to the fuel storage problem, though hydrogen is less quenching than hydrocarbon fuels. Radiant micro-burners that apply the heat-recirculation concept and catalytic combustion have been developed [7]; however, they were mainly developed to reform various fuels.

An earlier experimental and computational study of micro-emitters in this laboratory showed a micro-emitter (micro-combustor) that recirculates heat but remains structurally simple for micro-TPV power systems that use hydrocarbons instead of hydrogen to improve volumetric energy density. This micro-emitter

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Nomenclature

d_g	shortest gap between micro-emitter and chamber walls
d_s	inner diameter of shield
d_w	inner diameter of micro-emitter
h	heat transfer coefficient
l	length of main part of micro-emitter
$\dot{m}_f$	fuel mass flow rate
P	pressure
$\dot{q}''$	heat irradiation flux
r	radial coordinate
T	temperature
t_g	gap between shield and micro-emitter walls
t_w	micro-emitter wall thickness
u_r	velocity component in the radial direction
u_x	velocity component in the axial direction
V	average micro-emitter inlet velocity
X_f	mole fraction of fuel
X_i	mole fraction of species i
x	axial coordinate
ϕ	fuel-equivalence ratio

guarantees stable burning in the small confinement with effective heat transfer into the micro-emitter wall surface and uniform radiation [8]. Thermal characteristics along the micro-emitter wall can be improved by increasing the ratio of the inner radius of the heat-recirculating shield to the gap between the shield and micro-emitter walls, and by decreasing the wall thickness of the micro-emitter within the thickness required for fabrication and structural strength. In the earlier study, however, we focused on demonstrating whether heat recirculation can improve the micro-emitter performance. Thus, stainless steel (SUS) was used for the test emitter due to its easy fabrication, although better materials for emitters, e.g., silicon carbide (SiC), could be considered.

In the present investigation, we suggest a micro-TPV device that applies the micro-emitter configuration suggested from the earlier study, uses SiC as the material, and includes a chamber, the inner wall of which has an installation of PVCs, surrounding the micro-emitter to demonstrate TPV performance under more practical circumstances. Identifying the structure of micro-flames in the micro-emitter and heat transfer in the surrounding chamber helps explain the mechanisms of micro-combustion and heat transfer in the micro-TPV device. Predicting the micro-flame structure and heat transfer requires simulations in either two or three dimensions.

In view of the above considerations, in the present investigation we aim to design a novel micro-TPV power device configuration with the following specific objectives. The first objective is to observe the effects of micro-emitter materials on micro-emitter performance using the heat-recirculating configuration from the earlier study that can sustain stable burning for a 1–10 W micro-TPV device. We determine the proper range of mass flow rates of the supplied hydrocarbon-air pre-mixtures for stable burning and heat transfer. The second objective is to determine a basic configuration of the micro-TPV device. The third objective is to observe the effects of the vacuity of the PVC-installed chamber on the performance of the micro-TPV device. The fourth objective is to observe the effects of geometric variations (such as the gap between the micro-emitter and PVC-installed chamber walls) on the performance of the micro-TPV device. The fifth objective is to identify the optimal design conditions from our observations. We also examine the structure of the micro-flame and heat transfer in the confined micro-TPV device (based on a computational fluid dynamics (CFD) simulation with a simplified kinetic mechanism and a radiation model) to gain further understanding about some unique characteristics of micro-flames and heat transfer through the walls.

The effects of varying the micro-emitter materials on the performance of the micro-emitter, the basic configuration of the micro-TPV device, the effects of the vacuity and geometric variation of the PVC-installed chamber on the performance of the micro-TPV device, and the optimal design conditions will be subsequently presented, following the specifications of the experimental and computational methods used during this investigation.

2. Experimental and computational methods

A diagram of the experimental apparatus used in this study is given in Fig. 1. The set-up consists of a test micro-TPV device (a micro-emitter (SiC) surrounded by a chamber, the inner wall of which has an installation of PVCs), a fuel-air mixture supply system, thermocouples for measuring temperature distribution on the walls, a vacuum pump connected to the chamber for controlling chamber pressure, and a digital camera (Canon S5) for recording the radiating micro-emitter images. Commercial mass flow controllers (Teledyne Hasting Instruments: 100 and 1000 sccm; Alicat Scientific: 2000 and 4000 sccm) with an accuracy of ±0.75–1.00% of full-scale delivered the combustible mixture to the micro-emitter. The controllers were managed by PC-based software (LabVIEW) that enables independent control of mixture composition (fuel-equivalence ratio ϕ) and volume flow rate (micro-emitter inlet velocity V). The mixture was delivered into the annulus through beads to obtain uniform flow at the micro-emitter inlet. The temperature distributions on the surfaces of the outer wall of the micro-emitter and the inner wall of the chamber were measured using K-type thermocouples (a bead diameter of $250 \pm 20\ \mu\text{m}$) with an accuracy of ±0.05%. Final results were obtained by averaging measurements of 4–5 tests at each condition. Experimental uncertainties (95% confidence) for temperature were less than 2.5%. Configurations of designed micro-TPV devices are discussed later.

Flames in the micro-emitter were obtained by establishing an injected, cold flow of reactive mixture that was then ignited at the exhaust outlet by a spark. Once the mixture was ignited, flames moved backward and stabilized in the micro-emitter. Experiments were carried out for propane (C_3H_8, purity >99.9%)–air (21%O_2/79%N_2 in volume) mixtures of $\phi = 1.0$ and $V = 2.7$–3.9 m/s (laminar flow condition) at a temperature $T = 298 \pm 3$ K and atmospheric pressure (normal temperature and pressure, NTP). Propane was chosen as fuel since it can be liquefied at relatively low pressures and easily vaporized when mixed with air at NTP. Thus, propane can potentially be used in practical applications. To evaluate the effects of the shortest gap between the micro-emitter and chamber walls (d_g) on the performance of the micro-TPV device, the experiments were carried out for micro-TPV devices with $d_g = 6.0$ and 12.0 mm.

The computational methods used are similar to those used in past work, and are described only briefly (see [8] for more details), though the modeling of heat transfer and boundary conditions has been somewhat improved. The micro-combustion in the micro-emitters and the thermal radiation in the chambers were simulated using a commercially available CFD code FLUENT 6.2 [9], the results from which were analyzed along with those of experimental tests regarding the effective design of micro-TPV devices. The time-dependent ordinary sets of the