Towards a portable mesoscale thermophotovoltaic generator

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Abstract. Thermophotovoltaics (TPV) is the conversion of fuel to electricity with heat and light as intermediaries, and is a promising source of high energy density power at the mesoscale. This work describes our transition from our bench-top experiments to a fully-integrated portable generator. Specifically, we redesigned the microcombustor for propane-air combustion from the previous propane-oxygen design. Next, we validated vacuum package of the microcombustor, necessary to preserve the photonic crystal, in a 50+ day experiment in which there was no degradation of vacuum level. Finally, we vacuum packaged a microcombustor with integrated photonic crystals in a housing with two infrared-transparent windows to transmit the thermal radiation to external PV cells. Although considerable challenges remain, this work demonstrates the feasibility of a mesoscale TPV system.

1. Introduction

Thermophotovoltaics (TPV) is a promising technology that can generate watts of electricity from a heat input similar to that of a lighter, in a volume that is only a fraction of a cubic inch. In our system, a propane-fueled microcombustor heats a photonic crystal emitter to incandescence and the resulting tailored thermal radiation drives low-bandgap photovoltaic (PV) cells to generate electricity. Previously, we achieved unprecedented efficiencies of above 4% in a mesoscale form factor by employing new high-temperature material systems, processing, and fabrication techniques, and showed computationally that 12% efficiency should be achievable with engineering optimization [1]—exceeding the 2–3% was previously thought to be the practical limit [2]. (For comparison, an efficiency of 1.5% is equivalent to lithium batteries.) This work describes our transition from our bench-top experiments to a fully-integrated portable generator. Specifically, we redesigned the microcombustor for propane-air combustion from the previous propane-oxygen design. Next, we validated vacuum packaging of the microcombustor, which is necessary to suppress convective heat loss and prevent degradation of the photonic crystal. Finally, we vacuum packaged the microcombustor with integrated photonic crystals.
2. Propane-Air Microcombustor

The microcombustor catalytically reacts propane with air to bring the photonic crystal emitter to incandescence. It is a $20 \times 20$ mm Inconel slab with two internal layers of catalyst-loaded channels, as shown in Fig. 1. Propane and air react in the channel and the resulting heat is conducted through the channel walls to the photonic crystal emitters on the top and bottom surfaces. The device was fabricated by diffusion brazing stacked layers. A two layer design was required in order to attain sufficiently long residence time and sufficiently short diffusion time to react 100 W of propane flow with air. We modified the propane-oxygen microcombustor used in the bench-top experiment for propane-air operation [1], using the design and fabrication methodology detailed in Ref. [4].

Two simulations were used. First, we used a simple analytical heat balance model, which assumed a uniform temperature across the burner surface. Second, we developed a reduced-order modeling tool that enables the evaluation of different reactant compositions and geometry modifications on system thermal efficiency and surface temperature uniformity. These results are shown in Fig. 1, where the shaded region represents the range of surface temperatures predicted by the second model.

The microcombustor was tested in the vacuum chamber described in the next section. A thermocouple was spot welded to the surface to measure temperature and another thermocouple was inserted into the exhaust tube during some experiments to measure exhaust gas temperature. The microcombustor was ignited by bubbling the air through methanol, which reacted at room temperature over platinum, until heated to around 300°C, at which point propane-air operation was possible and the methanol bubbler was bypassed. Exhaust and surface temperatures for a range of propane flows are shown in Fig. 1.

3. Vacuum Packaging

In order to prevent degradation of the photonic crystal emitter and to suppress convective losses, vacuum packaging is required. To test the feasibility of vacuum packaging we assembled...
Figure 2. Temperature and vacuum during a 50+ day experiment, with time measured relative to pinch-off \( (t = 0) \). Inset: the experimental setup was composed of a microcombustor (a), ion gauge (b), and copper pinch-off (c).

a microcombustor and hot filament ion gauge in a Conflat (CF) tee, as shown in the inset of Fig. 2. A zirconium based getter (Saes) was also placed in the chamber. A soft copper tube connected the test chamber to a turbomolecular pump and residual gas analyzer. With the turbomolecular pump running, the chamber was heated to 350°C to degas and to activate the getter. In addition, the burner was ignited and the ion gauge was electrically heated. At the beginning of the bakeout, water vapor dominated; at the end, hydrogen and carbon monoxide dominated. The hydrogen was determined to be permeating through the walls of the microcombustor by injecting pulses of deuterium into the combustion reaction and observing the isotope ratio in the vacuum chamber. At the end of the bakeout, the copper tube was pinched off with a hydraulic crimper, isolating the vacuum chamber from the pump. Temperature and vacuum near pinch-off are shown in Fig. 2.

After pinch-off the microcombustor was run for six days without degradation of the vacuum. In fact, an improvement in vacuum was observed because the getter continued to act as an internal pump. The apparatus was left for nearly 40 days, during which the vacuum level was \( \sim 10^{-8} \) Torr. The microcombustor was successfully reignited and run without vacuum degradation, and stepped through several fuel flows.

4. System integration
After validating the microcombustor and vacuum packaging strategy, we designed and fabricated an integrated unit with a photonic crystal emitter and sapphire windows to transmit the infrared radiation to PV cells. The package, shown in Fig. 3, was fabricated from commercial sapphire viewports and custom components by welding and brazing. Although vacuum level could not be directly measured, no discoloration of the microcombustor or photonic crystal (an indication of oxidation) was observed.
5. Conclusion

This work advances our bench-top TPV experiment towards a portable system by design and fabrication of a propane-air microcombustor and of a vacuum packaged microcombustor with integrated photonic crystal and infrared transparent windows to allow for PV cells. Although considerable engineering efforts are required in the area of fuel and air delivery, cell cooling, and packaging, this initial effort demonstrates that mesoscale thermophotovoltaic power generation is practical. This technology would have applications reducing the weight of batteries carried by soldiers, extending the range of drones, and enabling new applications by untethering portable electronics from bulky power sources.

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References

[1] Chan W R, Stelmakh V, Ghebrebrhan M, Soljačić M, Joannopoulos J D and Čelanović I 2017 Energy Environ. Sci. 10 1367–1371
[2] Chan W R, Bermel P, Pilawa-Podgurski R C N, Marton C H, Jensen K F, Senkevich J J, Joannopoulos J D, Soljacic M and Čelanovic I 2013 Proceedings of the National Academy of Sciences of the United States of America 110 5309–14
[3] Stelmakh V, Rinnerbauer V, Geil R D, Aimone P R, Senkevich J J, Joannopoulos J D, Soljacic M, Čelanovic I, Soljačić M and Čelanovic I 2013 Applied Physics Letters 103 0–4
[4] Chan W R, Stelmakh V, Allmon W R, Waits C M, Soljacic M, Joannopoulos J D and Čelanovic I 2016 Journal of Physics: Conference Series vol 773 p 012108 p 012108