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An all-metallic microburner for a millimeter-scale thermophotovoltaic generator

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Abstract.
Thermophotovoltaics (TPVs) is the conversion of heat to electricity via the thermal emission of photons and their subsequent absorption and conversion to electricity by infrared photovoltaic cells. One of the key challenges is designing a robust microburner with an integrated selective emitter—and having the system operate at 1000°C for thousands of hours. Previous attempts at TPV system demonstrations tend to be large, inefficient, and have limited lifetimes. Here we present a novel all metallic microburner design and experimental results in the context of a proposed small, robust, and efficient TPV generator. Fabricated entirely by machining and welding, the microburner is comprised of a serpentine channel in a 20 × 20 mm slab of Inconel with inlet and outlet capillaries that double as mechanical supports. The microburner has a thermal power input of 50 to 100 W and reaches temperatures of 700 to 1100°C. The metallic microburner is robust under high temperature operation and a 2D tantalum photonic crystal can be attached by welding for high fuel-to-electricity conversion efficiency. We characterized the microburner’s exhaust composition and temperature distribution which matched well with CFD simulations. We operated the microburner at 60 W of input power (reaching about 1000°C) for 135 hours before it failed.

1. Introduction
The ongoing proliferation of power-intensive mobile devices has driven the development of increasingly compact, energy-dense power sources. Batteries represent a mature technology capable of providing energy densities of up to 1 MJ/kg, whereas hydrocarbon fuels have energy densities approaching 45 MJ/kg while promising rapid refueling. To this end, researchers have explored several possible energy conversion routes for providing next-generation portable power including mechanical heat engines, fuel cells, thermoelectrics, and thermophotovoltaics [1].

Thermophotovoltaics (TPVs) is the conversion of heat to electricity via the thermal emission of photons and their subsequent absorption and conversion to electricity by infrared photovoltaic (PV) cells. TPVs present an extremely appealing approach for small-scale power sources due to the combination of high power density limited ultimately by Planck blackbody emission, multifuel operation due to the ease of generating heat, and a fully static conversion process. Small-scale TPVs have yet to be demonstrated and are particularly challenging because of the need to develop strong synergistic interactions between chemical, thermal, optical, and...
Figure 1: Schematics of the silicon and metal microburners.

### Table 1: Parameters of the silicon and metallic microburners.

|                       | Silicon Microburner                  | Metallic Microburner                  |
|-----------------------|--------------------------------------|---------------------------------------|
| **Active area**       | $10 \times 10 \times 1.4$ mm thick   | $20 \times 20 \times 3.2$ mm thick    |
| **Channels**          | $0.4 \times 0.4$ mm by KOH etching   | $2.3 \times 2.7$ mm deep by machining |
| **Tubes**             | Single premixed inlet/single exhaust, $0.55$ OD $\times 0.4$ mm ID borosilicate glass tubes attached with solder glass | Single unmixed tube-in-tube inlet/dual exhaust, $1.6$ OD $\times 1.1$ mm ID Inconel tubes attached by welding. |
| **Emitter**           | Five layer Si/SiO$_2$ stack deposited by chemical vapor deposition directly on the microburner | Bare Inconel (this work), 2D tantalum photonic crystal attached by welding (in progress) |
| **Typical operation** | $<1$ hour at $13$ W and $800^\circ$C with catalytic combustion | $135$ hours at $60$ W and $1000^\circ$C with homogeneous combustion |
| **Fuel to electricity** | $2.7\%$ (measured)                  | $5\%$ (simulated)                     |

In this work we propose an all metallic, robust, high temperature microburner which overcomes limitations associated with previous silicon-based microburner designs [5–8]. A comparison of the presently reported metallic microburner with our previously reported silicon microburner is presented in Fig. 1 and Table 1. The metallic microburner addresses the three primary shortcomings of the silicon microburner: (i) cracking due to a thermal expansion mismatch between the solder glass and silicon, (ii) the inherent difficulties of integrating a metallic photonic crystal (described in Ref. [9]) with silicon for improved fuel-to-electricity conversion efficiency and (iii) the high costs and long lead times associated with silicon micromachining.  

2. Experiment

The metallic microburner was assembled of machined components as shown in Fig. 1b by electron beam welding and mounted in a vacuum chamber to prevent convective heat loss. A $5\%$ platinum on porous alumina catalyst was loaded into the microburner by washcoating [5–8]. To ignite
the microburner, it was heated to approximately 400°C with a halogen lamp. Above that temperature, the propane kinetics over the catalyst were sufficient for autothermal operation, and the halogen lamp was shut off.

Instrumentation consisted of four thermocouples, a thermal imager, and a mass spectrometer (MS). The K-type thermocouples were spot welded to the body of the microburner and are visible in Fig. 2(a). The FLIR SC660 thermal imager looked through a NaCl window at the microburner. The thermal images were calibrated from thermocouple readings. The Pfeiffer GSD 301 MS sniffed the exhaust gases after they passed through a condenser chilled to 0°C to remove water vapor. Exhaust composition was found using a least squares method to fit a combination of NIST mass spectra and our own calibrations to the raw data.

Steady state temperature versus total propane flow was measured by increasing propane flow in increments from 30 to 60 standard cubic centimeters per minute (sccm), corresponding to a total latent heat input of \( Q = 60–91 \) W, while maintaining an oxygen flow of 7.5 times that of propane (an equivalence ratio of \( \phi = 1.5 \)). Surface temperatures were allowed to stabilize at each set of flow conditions, typically 5 to 10 minutes. Flowrates were then decreased to 30 sccm propane to investigate possible hysteresis. Experimental data is presented in Figure 3a.

At a constant propane feed of 40 sccm, the equivalence ratio was varied between 1 and 2 by a similar process. For all equivalence ratios \( \phi \geq 1.25 \), only carbon dioxide and unreacted oxygen were present in the exhaust, indicating complete combustion.

Once the above data was obtained, we conducted a longterm study summarized in Fig. 3b. The microburner was ignited at \( Q = 60 \) W and \( \phi = 1.5 \) (point a). The periodic dips in temperature and MS data (points b and c) are caused by the periodic removal and de-watering of the condenser. The occasional changes in steady state temperature (point d and e) are due to a transition between homogeneous and catalytic combustion. The MS data begins to indicate incomplete combustion around 135 hours (point f), evidenced by reduction in CO\(_2\) signal and increased O\(_2\) and propane signals. Work is currently underway to ascertain the cause of device failure.

3. Model
Initially, a first order analytical model was used to predict microburner temperature. Assuming complete combustion and a uniform temperature, the heat of combustion was equated to heat loss by radiation, conduction down the tubes, and heat carried out in the exhaust. The analytical model accurately captures the trend versus propane flow in Fig. 3a but obviously cannot predict
Figure 3: Experimental and modeling results. (a) summarizes the steady state temperature as a function of propane flow with $\phi = 1.5$. Individual CFD simulations do not fall exactly on a smooth curve because of the mesh size used. (b) is a long term study of the microburner running at $Q = 60$ W and $\phi = 1.5$. 

the observed 200°C temperature distribution. A uniform temperature is important for efficient operation of the PV cells and reactor robustness. 

In order to model the temperature distribution, we conducted a computational fluid dynamics (CFD) simulation of the microburner in COMSOL using the Chemical Engineering Module and a combination of weakly compressible flow, convection and conduction and Maxwell-Stefan multicomponent diffusion physics packages. The homogeneous combustion of propane was described using a single-expression kinetic model [10]. Gas-phase dynamic viscosity, thermal conductivity, heat capacity, and diffusivity were calculated according to the methods in Ref. [11–13] from literature data. Inlet flow was assumed to have a uniform velocity across the channel cross-section, have a uniform temperature of ambient, and consist of uniformly premixed propane and oxygen with no tube-in-tube segregated feed to facilitate convergence. Outlet boundary conditions assumed constant pressure of 1 bar and were open to convective heat and mass transport. A combination of no-slip, no mass flux (impermeable wall) and continuity of heat flux boundary conditions were used to describe fluid-wall interfaces. Radiative heat losses from all external surfaces of the solid-phase were described using a simple Stefan-Boltzman expression assuming an emissivity of 0.5 for all surfaces. Finite-element meshes consisted of approximately $10^5$ individual elements, corresponding to $10^6$ degrees of freedom. Typical solution times were an hour.

Simulation predictions of burner surface temperature at $Q = 60$ W and $\phi = 1.5$ are presented alongside thermal images obtained experimentally in Fig. 2. A summary of measured and simulated thermocouple temperatures over the span of propane flow rates studied is presented in Fig 3, alongside the analytical model. Simulations predict a more symmetric and focused hot-spot than experimentally observed; this is attributed to a combination of (i) assumption of pre-mixed fuel and oxidant leading to a pre-mixed flame shape, as opposed to a diffusion-flame shape expected with segregated feed, and (ii) known limitations of the single-expression kinetic model for accurately predicting flame location [14]. Even with these assumptions, we obtained a good overall temperature agreement.

As noted above, two distinct operating regimes were observed within the microburner, corresponding to homogeneous and catalytic combustion. In the homogeneous regime (shown
in Fig. 2), a stable flame is present near the reactor inlet, as evidenced by the presence of an intense hot-spot located at the reactor inlet. In contrast, the catalytic regime is characterized by a cooler and more distributed hot-spot along the entire central channel length. The microburner would oftentimes begin in the catalytic regime but would transition the the homogeneous regime. Once in the homogeneous regime, it would not transition back to the catalytic regime without some external disturbance, such as a brief decrease in fuel flow. Given that homogeneous combustion was predominant in the present study, simulations reported herein neglected catalytic combustion. In future work, the combustion regime can be controlled using thermal and radical quenching by altering the channel geometry [15].

4. Conclusion
In this work, we presented a metallic microburner that will serve as a platform for a portable TPV system. The metallic microburner is more robust than the previous silicon one, allowing for higher temperature operation. Furthermore, the 2D tantalum photonic crystal (described in Ref. [9]) can be welded to the metallic microburner for a twofold increase fuel-to-electricity conversion efficiency as compared to previous silicon-based devices. Experimental and simulation results confirmed stable operation at flow rates corresponding to $Q = 45–90$ W with homogeneous flame corresponding to a hot-spot temperature of up to $1100^\circ C$.

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References
[1] Mitsos A 2009 Microfabricated power generation devices : design and technology (Weinheim: Wiley-VCH) ISBN 978-3527320813
[2] Doyle E, Shukla K and Metcalfe C 2001 Development and demonstration of a 25 watt thermophotovoltaic power source for a hybrid power system Tech. Rep. TR04-2001 National Aeronautics and Space Administration
[3] Fraas L M, Avery J E and Huang H X 2003 Semiconductor Science and Technology 18 S247
[4] Wenning Y, Siawkiang C, Chang S, Hong X and Zhiwang L 2005 Journal of Micromechanics and Microengineering 15 S239
[5] 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 Celanovic I 2013 Proceedings of the National Academy of Sciences 110 5309–5314
[6] Blackwell B S 2008 Design, fabrication, and characterization of a micro fuel processor Ph.D. thesis Massachusetts Institute of Technology
[7] Arana L, Schaevitz S, Franz A, Schmidt M and Jensen K 2003 Microelectromechanical Systems, Journal of 12 600–612
[8] Nielsen O M, Arana L R, Baertsch C D, Jensen K F and Schmidt M A 2003 Transducers, Solid-State Sensors, Actuators and Microsystems, 12th International Conference on, 2003 vol 1 pp 714–717
[9] Rinnerbauer V, Ndao S, Xiang Yeng Y, Senkevich J J, Jensen K F, Joannopoulos J D, Soljacic M, Celanovic I and Geil R D 2013 Journal of Vacuum Science Technology B: Microelectronics and Nanometer Structures 31 011802–011802–7
[10] Westbrook C K and Dryer F L 1981 Combustion Science and Technology 27 31–43
[11] Wilke C R 1950 The Journal of Chemical Physics 18 517–519
[12] Bird R 2007 Transport phenomena (New York: J. Wiley)
[13] Fuller E N, Sachtler P D and Giddings J C 1966 Industrial & Engineering Chemistry 58 18–27
[14] Vlachos D, Schmidt I. and Aris R 1993 Combustion and Flame 95 313 – 335
[15] Miesse C M, Masel R I, Jensen C D, Shannon M A and Short M 2004 AIChE Journal 50 3206–3214 ISSN 1547-5905