Prototype of radioisotope thermophotovoltaic system using photonic crystal spectral control

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Abstract. This work describes a prototype of a small-size radioisotope thermophotovoltaic (RTPV) system with the two-dimensional metallic photonic crystal emitter and the low bandgap TPV cell. The project demonstrates the simulation and measurement of a system powered by an electrical heat source that mimics the radioisotope fuel pellet. The photonic crystal and the polished Ta3%W substrate are both used as the emitting surfaces to demonstrate the benefits of spectral control. The rest of the system is thermally insulated to increase the overall system efficiency. The photonic crystal emitter demonstrates four times more output power over a flat metal emitter from the 1 cm^2 TPV cell. With more cell areas, better TPV cells and improved insulation design, the system is expected to reach an efficiency of 7.8%.

1. Introduction

Nuclear power systems are the most promising way to provide long term electrical power for long duration when providing additional energy input, fuel or maintenance is impossible. The most common way to use the nuclear energy is to use the heat released during the radioactive decay. Plutonia, which is an alpha emitter with high decay heat, is fabricated into fuel pellets and packaged into the rectangular General Purpose Heat Source (GPHS) containing four pellets [1]. Thermal-based radioisotope powered systems have been developed and utilized since the 1960s and have demonstrated numerous safe and reliable usages in space and land missions such as Apollo, Cassini-Huygens, etc. [2].

Over the past 50 years, various kinds of radioisotope powered thermal-to-electric conversion mechanisms have been investigated: the thermal-electric generators (RTG) [3], Stirling engines [4], alkali-metal thermal-to-electric converter (AMTEC) [5] and radioisotope thermophotovoltaic systems (RTPV) [6] [7]. RTGs are most widely used and have provided reliable sources for spacecrafts and remote sensors for decades, but the efficiency is limited by the thermoelectric material to ~6.6%. Stirling engines can achieve an efficiency over 30%, but the moving piston creates reliability concerns. AMTEC systems are chemical heat engines with a sodium or potassium working fluid that have demonstrated an efficiency of 20%, but the specific power of the systems is limited to ~6 W/kg. In an RTPV system, radioisotope decay heats an emitter to incandescence, and the resulting thermal radiation is converted to electricity by a low bandgap TPV cell as shown in figure 1. The energy conversion elements are solid-

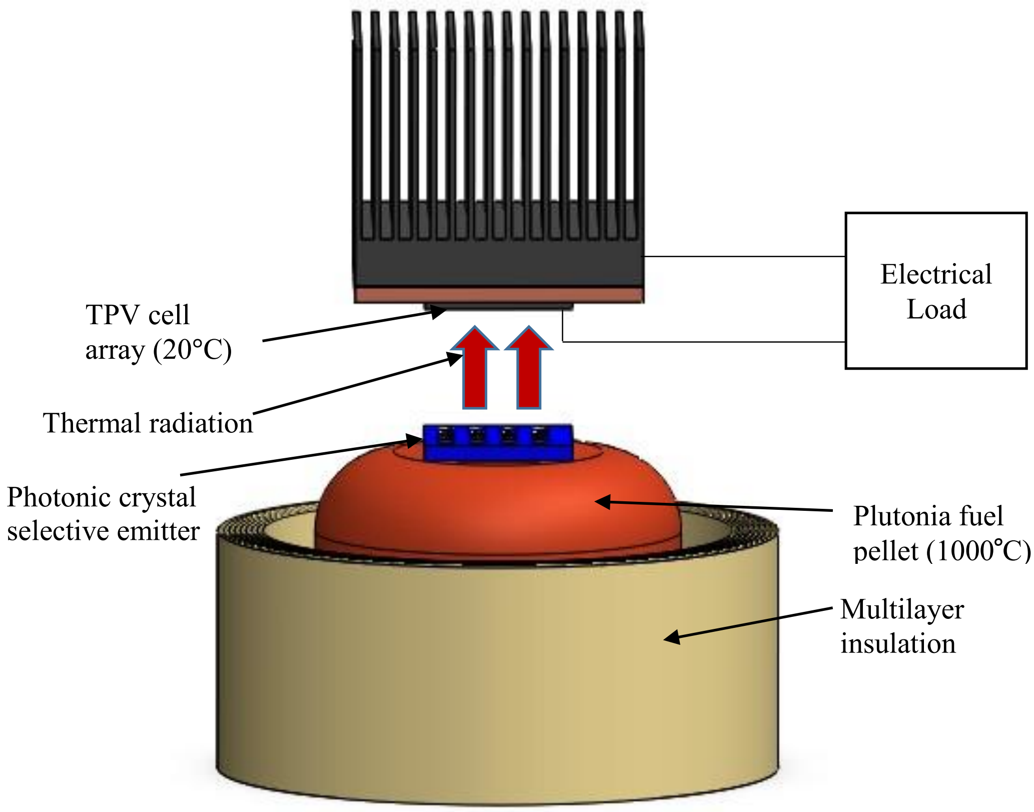

Figure 1. Radioisotope thermophotovoltaic system using photonic crystal spectral control.

state, light-weight components that make RTPV the most promising technology to achieve high efficiency, high energy density, and high reliability.

In an RTPV system, spectral control is needed to modify the thermal emission spectrum to match the TPV cell. Ideally, the emitter has high emission for the photons above the cell bandgap to generate more electricity and low emission for the low energy photons in far infrared to reduce waste heat. With recent advances in photonic crystals, a micro-fabricated metallic photonic crystal patterned with periodic holes can shape the spectrum of the hot emitter to approach the ideal emitter [8] [9] [10]. Spectral control using photonic crystals has demonstrated many successful results in other TPV systems, such as the propane powered micro-reactor [11], solar TPV system [12], etc.

2. System construction and characterization

In the current prototype, the heat source was an electrical button heater enclosed in a cylindrical Inconel case to mimic the plutonia fuel pellet. The heater was supported through a hollow Inconel tube, which was back supported by a stainless steel plate fixed on the vacuum flange. The selective emitter was brazed on top of an extruded stand.

The emitter was a 1×1 cm^2 Ta3%W photonic crystal comprised of a square array of cylindrical cavities fabricated by semiconductor process. The geometry (cavity radius, depth and lattice period) of the photonic crystal determines the resonant modes which correspond to the cutoff wavelength of the emission spectrum. For photons above the bandgap, the deep holes on the photonic crystal make it a good emitter. For photons below the bandgap, the emitter appears to be a polished reflective metal. The photonic crystal gives the emission approaching a blackbody emitter in the useful region, but does not

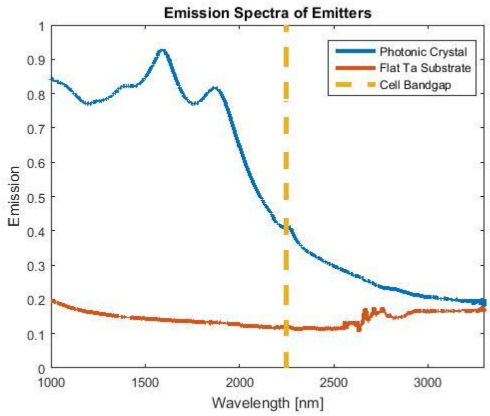

Figure 2. Measured spectra of photonic crystal and flat metal emitter at room temperature.

emit much waste heat produced by long wavelength photons. The measured spectra of the photonic crystal and the flat metal substrate at room temperature is shown in figure 2.

Thermal radiation from the emitter illuminates the TPV cells. We used an array of two InGaAsSb cells with a bandgap of 0.55 eV (2250 nm) with a total area of 1 cm^2 [13]. The distance between the emitter and the cell was adjusted to be ~1.2 mm,

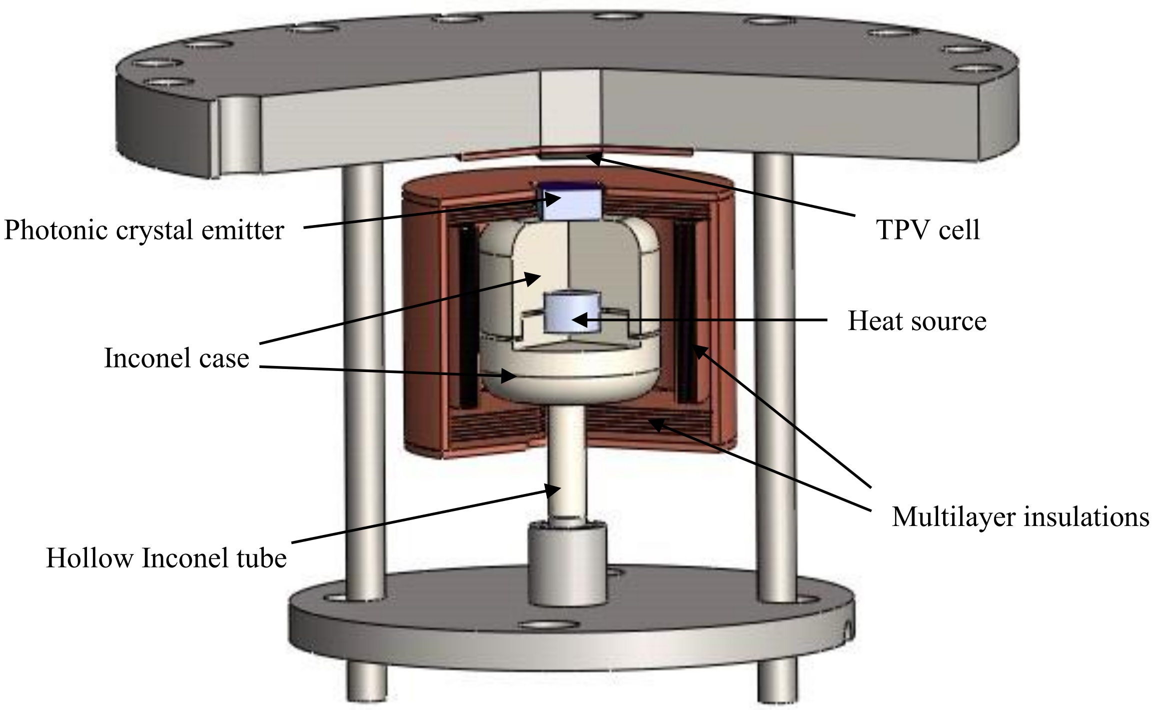

Figure 3. Illustration of RTPV system prototype.

The system configuration is shown in figure 3. In order to improve the system efficiency, all surfaces of the heater except the emitter were insulated by multilayer insulation layers (MLI) made with copper foil and zirconia powder. MLI layers were spirally wound around the heater side. Patterned MLI layers with cutouts for the emitter and support tube were placed on the front and back surfaces of the heater.

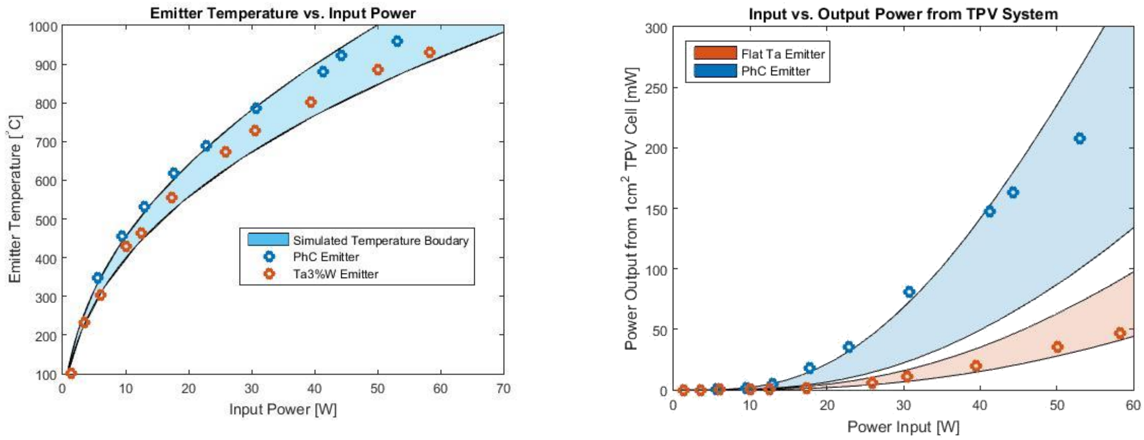

Figure 4(a). Measured emitter temperature as function of input power.

Figure 4(b). Input power vs. output power from 1 cm^2 TPV cell.

The heater and MLIs were placed inside a polished copper case only leaving the emitter area to be exposed.

The system was fired inside a vacuum chamber with a pressure in the range of 10^{-5} Torr. The TPV cell was maintained at 20°C by a chiller outside of the chamber. The generated electrical power and the required heat input were measured up to 950°C for both the photonic crystal and flat metal emitters. The reflection spectra of the emitters were measured before and after the firing to verify that there was no degradation.

The temperature of the heater as a function of the input power with both emitters did not show much difference as shown in figure 4(a). The only difference in the two system was the 1 cm^2 emitter area that was very small comparing to the whole heater. The system with the photonic crystal emitter showed four times more output power in comparison to the flat metal emitter as shown in figure 4(b) because of the increased in-band emissivity compared to unstructured metal.

3. System modelling and improvements

The overall simulation was done by COMSOL and Matlab Livelink. The heat transfer through the complex geometry was simulated using COMSOL Heat Transfer Module. The heat flux through the multilayer insulation layers (MLI), the photocurrent and the maximum power output from the TPV cell were computed using Matlab nonlinear solver and optimization functions. Since many material parameters are temperature dependent, the simulation was performed based on the best and worst case material parameters.

One major limitation of the current system is the TPV cell performance. The current TPV cell only has 0.6 internal quantum efficiency above the cell bandgap, where a quantum efficiency of 0.9 can normally be achieved [13]. In addition, the thermal insulation of the system can also be further improved. Copper foils are used in the current setup to shield the radiation loss. The system performance can be much more improved by utilizing gold foils which are more reflective in infrared regime.

A realistic RTPV system with 8 cm^2 TPV cell insulated with gold foil was estimated in figure 5. The system based on one fuel pellet can potentially output 5.5W power with 70W of thermal input power, reaching an efficiency of 7.8%. Due to the cylindrical shape of the fuel pellet, the curved side surfaces of the heater is not utilized efficiently. In the RTPV system powered by the General Purpose Heat Source (GPHS), all surfaces can potentially be used efficiently as the emitters to reach a higher efficiency. The weight for the RTPV system will be estimated in future work.

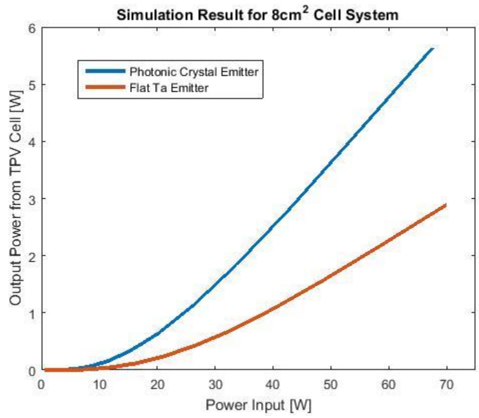

Figure 5. Simulation result for an 8 cm^2 cell system insulated with gold foil.

4. Conclusions

The project demonstrated the simulation and measurement results of an RTPV prototype system using photonic crystal spectral control to realize high efficiency. Comparing to other types of thermal-based radioisotope power sources, RTPV system has the advantages of reaching higher efficiency than the thermal-electric generators. The absence of moving parts or working fluids also makes it an ideal power source in unattended regions for several decades of battery lifetime.

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