



Experimental studies of thermoelectric power generation in dynamic temperature environments



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ABSTRACT

We show that thermoelectrics can generate power from environments experiencing temporal temperature fluctuations; this source of power is useful for low-power devices in remote locations. We design and characterize devices that employ a thermoelectric module sandwiched between two heat exchangers with significantly different thermal masses and examine the effects of heat exchanger size and material selection, period of oscillation of the environmental temperature fluctuations, and radiative heat transfer on the thermoelectric power output. We report maximum experimental power generation on the order of milliwatts using standard bismuth telluride thermoelectric modules in devices with a size of about 10 cm³.

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1. Introduction

Thermoelectric devices are capable of generating electric power given a temperature difference (ΔT) across the device. TPG (Thermoelectric power generation) is governed by the relation $P = (\alpha \Delta T)^2 / R_{\text{total}}$, where α is the Seebeck coefficient and R_{total} is the sum of the internal and load resistances. A TPG device consists of a thermoelectric module between two heat exchangers. In the simplest case, the heat exchangers are thin ceramic plates that physically support the thermoelectric elements and aid in heat distribution. Some novel, high-performing thermoelectrics include doped semiconductors [1], semiconductors with buried epitaxial nanoparticles [2], and silicon nanowires [3]. Optimizing phonon scattering on the atomic scale, nanoscale, and mesoscale dramatically increases the efficiency of thermoelectric materials [4] and is the likely direction of future thermoelectric research.

The power output of thermoelectric devices is significantly affected by heat exchanger and thermoelectric module geometries. Previously studied heat exchanger geometries include fins exposed to air [5] and spirals, zig-zags, and fins directing a liquid heat transfer

medium [6]. Most thermoelectric modules are either bulk-based or thin films [7]; a unique variant of bulk-based modules are two-stage, or stacked, modules [8]. Optimization studies of bulk thermoelectric elements [9] and thin films [10] detail the factors involved in maximizing the power output of thermoelectric devices.

Among other applications, thermoelectrics are often deployed in environments containing a steady-state spatial temperature gradient as a means of waste-heat recovery [11]. Because thermoelectric conversion efficiencies are on the order of 5% [12], thermoelectric waste-heat recovery applications are most competitive when considerations of reliability and high energy losses override cost and efficiency; such applications include industrial steam condensers [13] and remote oil pipelines [14]. Additionally, thermoelectric tailpipes and radiators in automobiles exploit waste heat from hot exhaust gas [15] and engine coolant [16], respectively, to power internal car electronics. Thermoelectrics have also been considered for applications in remote locations using natural temperature gradients such as those powered by direct [17] or concentrated [18] solar radiation [19] and those found in the ocean [20].

Using a heat transfer model, Bomberger et al. [21] showed that TPG in temporally-varying temperature environments can generate power by converting the temporal temperature fluctuations into a spatial temperature difference across the thermoelectric. This conversion is achieved by placing two heat exchangers with

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significantly different thermal inertias on either side of a thermoelectric plate. As the temperature of the environment changes with time, the temperature of each heat exchanger will respond at different rates, creating the spatial temperature difference required for power generation. TPG based on temporal temperature gradients is highly promising for small-scale power harvesting in remote environments where other power generation technologies are not practical. We report experimental results of TPG from dynamic temperature environments, verifying the aforementioned study's results [21], and determining the feasibility of TPG under different experimental conditions.

2. Experimental setup

2.1. Device characterization

We propose a simple relation to characterize these devices in an effort to optimize them for specific applications. By rearranging Newton's law of convection, $\dot{Q} = hA(T_a - T)$, and using a simple expression for the rate of temperature change of thermal mass, $\dot{Q} = \rho V C_p dT/dt$, a relationship is derived for the rate of temperature change of a heat exchanger primarily undergoing convective heat transfer:

$$\frac{dT}{dt} = \frac{h}{\rho C_p} \left(\frac{A}{V} \right) (T_a - T) = K(T_a - T) \quad (1)$$

where T , h , ρ , C_p , and A/V are the temperature, convective heat transfer coefficient, density, specific heat capacity, and surface area-to-volume ratio of the heat exchanger, respectively, T_a is the ambient temperature, and K is a proportionality constant termed the thermal response rate coefficient; all properties are assumed to be independent of temperature. Equation (1) is quantitatively accurate only for small heat exchangers with negligible internal temperature gradients, but its qualitative implications hold regardless of size. The thermoelectric power output depends strongly on the relative rates of temperature change of the two heat exchangers on either side of the thermoelectric plate, or $K_{\text{rapid}}/K_{\text{slow}}$. Clearly, the heat exchangers can be optimized with respect to geometry and material selection within the economic and size constraints of the application.

2.2. Device construction

Using this theory, we built five devices with varying heat exchanger sizes and configurations, as shown in Fig. 1. Consistent with Bomberger [21], a series of 10 cm long copper rods attached to a heat-spreading copper plate and a truncated quartz sphere were selected as the rapid and slow heat exchangers, respectively. The thermoelectric elements were composed of bismuth telluride, the industry standard thermoelectric material for low-temperature

(<400 K) TPG applications [22]. The heat exchangers were bonded to the thermoelectric plate using thermally conductive silver epoxy. Acrylic support plates were constructed to secure the vertically upright copper rods; the supports were assumed to have a negligible effect on effective rod surface area and heat transfer coefficient. The devices were supported by various stands that minimally contact the quartz spheres, as shown in Fig. 1. Device specifications are given in Table 1; for ease of reference, each device is referred to by the diameter of its quartz sphere.

2.3. Experimental methodology

Each device was placed in a temperature-controllable chamber (Espec ECT) and connected to an external resistor approximately load-matched to the internal resistance of the thermoelectrics. After allowing the device to equilibrate at 34 °C, the temperature of the chamber was sinusoidally varied from 20 °C to 48 °C to match the amplitude of a diurnal cycle. The voltage across the resistor and the environmental temperature were logged using a digital multimeter (Keithley 2100) and a thermocouple data acquisition device (Omega TC-08). Power was calculated for each measurement using $P = V^2/R$.

3. Results and discussion

3.1. Comparison of experiment and simulation

The methods detailed in Bomberger [21] were used to create theoretical power profiles. Simple device properties, including the heat exchanger masses, thermoelectric Seebeck coefficients, and resistances, were measured experimentally. The heat transfer coefficients of the heat exchangers were found experimentally using the procedure given by Russell et al. [23]. Additionally, we chose to study radiative environments separately in order to obtain results for applications without solar radiation and reduce sources of experimental error, even though solar radiation was a significant component of the modeling study [21]. With these modifications, the model is in reasonable agreement with experiment without requiring the use of a fitting parameter. Experimental and theoretical power profiles for one device size (110 mm) are compared in Fig. 2 for an environmental oscillation period of 1 h, illustrating the close match between theory and experiment. As expected, the power profile exhibits a frequency that is double the oscillation frequency of the environmental temperature; the rapid heat exchanger is warmer than the slow heat exchanger during positive excursions of the environmental temperature, resulting in the first power peak, and cooler than the slow heat exchanger during negative excursions, resulting in the second power peak. The device generally takes about three cycles to attain dynamic equilibrium with the environmental temperature profile; therefore, the amplitudes of the first three power peaks of the power profile differ from those of subsequent peaks. The shape of the power profile approximately repeats after the first three peaks.

Table 1
Specifications of the five devices.

Sphere diameter (mm)	Sphere truncation distance (mm)	Number of copper rods	Copper rod diameter (mm)	Thermoelectric area (mm ²)	Number of thermoelectric couples
22	4	4	4.76	15 × 15	31
50	11	9	4.76	36 × 36	49
80	13	4	9.53	50 × 50	127
110	15	5	9.53	62 × 62	127
130	13	9	9.53	62 × 62	127

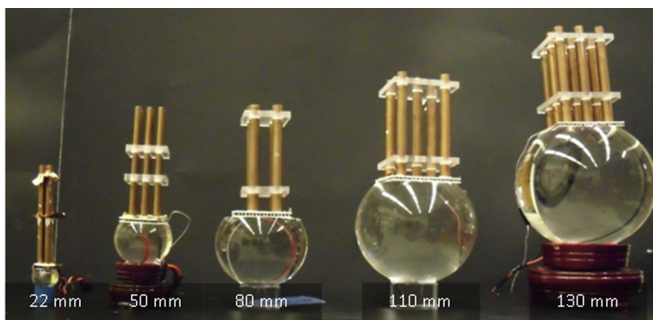


Fig. 1. Device geometries tested (labels indicate sphere diameters).

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