Thermoelectric Generator Design in Dynamic Thermoelectric Energy Harvesting

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Thermoelectric Generator Design in Dynamic Thermoelectric Energy Harvesting

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Abstract. This paper reports an analysis of thermoelectric generator design for dynamic thermoelectric harvesting. In such devices, the available energy for a given temperature cycle is finite and determined by the heat storage unit capacity. It is shown by simulation and experimentally that specific thermoelectric generator designs can increase the energy output, by optimizing the balance between heat leakage and dynamic response delay. A 3D printed, double-wall heat storage unit is developed for the experiments. Output energy of 30 J from 7.5 gr of phase change material, from a temperature cycle between ± 22 °C is demonstrated, enough to supply typical duty-cycled wireless sensor platforms. These results may serve as guidelines for the design and fabrication of dynamic thermoelectric harvesters for applications involving environments with moderate temperature fluctuations.

1. Introduction

Dynamic thermoelectric energy harvesting allows electrical power generation from temperature fluctuations in an environment, such as a vehicle body or an industrial machine [1-2]. It employs a heat storage unit (HSU), with a phase change material (PCM) to increase heat storage, insulated from the environment and in thermal contact with a thermoelectric generator (TEG), as shown in Figure 1. The other side of the TEG is attached to the thermal mass in which the temperature variation occurs. The HSU follows this variation with a time delay, creating a temperature difference ΔT across the TEG. As heat flows in and out of the HSU, through the TEG, it is transduced into electrical energy with efficiency directly proportional to ΔT. The thermal response depends on the HSU heat capacity C, latent heat L, and thermal resistance R between the HSU and the environment, giving an exponential temperature profile with a time constant RC during non-phase-change operation. The operation of such devices has been studied analytically and numerically [3], and various implementations have been reported, including real flight testing [4-5]. In this paper, the role of TEG design on performance is studied by analysis and simulation, and a 3D printed HSU prototype is introduced.

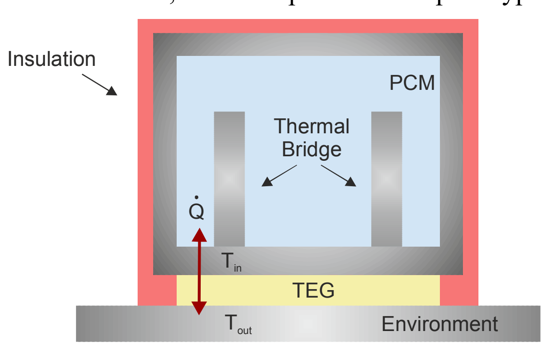

Figure 1. The concept of dynamic thermoelectric energy harvesting.

2. TEG design analysis and performance simulation

For the analysis of TEG performance in dynamic thermoelectric applications, a TEG of area A, thickness τ, N number of junctions and p and n materials with S_P and S_N Seebeck coefficients, and the same electrical and thermal resistivity ρ_E and ρ_{TH} are assumed. Assuming full area coverage with n and p pellets, the open circuit voltage, and the electrical and thermal resistances will respectively be:

$$V = N \cdot (S_p - S_n) \cdot \Delta T, \qquad R_E = \rho_E \cdot \frac{2 \cdot N \cdot \tau}{\frac{A}{2N}} = \rho_E \cdot \frac{\tau}{A} \cdot 4 \cdot N^2, \qquad R_{TH} = \rho_{TH} \cdot \frac{\tau}{A}$$

At a given ΔT and at matched electrical load conditions (maximum output power), the input thermal and output electrical power of the TEG will be:

$$P_{in} = \frac{\Delta T}{R_{TH}} \qquad P_{out} = \frac{V^2}{4R_E} = \frac{A}{16 \cdot \rho_E \cdot \tau}\left(S_p - S_n\right)^2 \cdot \Delta T^2$$

Defining the figure of merit ZT at device level:

$$ZT = N^2 \cdot \left(S_p - S_n\right)^2 \cdot \frac{R_{TH}}{R_E} \cdot T = \frac{1}{4} \cdot \frac{\rho_{TH}}{\rho_E} \cdot \left(S_p - S_n\right)^2$$

the device efficiency can be written as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\rho_{TH}}{16\rho_E}\left(S_p - S_n\right)^2 \cdot \Delta T = \frac{ZT}{4} \cdot \frac{\Delta T}{T}$$

This formulation demonstrates the TEG efficiency independence from geometry. The efficiency depends only on the properties of the materials. In direct TEG applications, where thermal resistance matching is optimal, a design with suitable R_{TH} is typically selected. In dynamic thermoelectric harvesting, a high R_{TH} is desirable, to increase the $R_{TH}C$ time constant of the system and hence the ΔT that is achieved during a temperature sweep across the TEG [3]. On the other hand, a high R_{TH} results in increased leakage through the HSU insulation. Therefore, an optimum R_{TH} value must exist, that achieves a balance between $R_{TH}C$ and leakage, for maximum total energy from a given temperature cycle. This was studied by simulation, using the model presented in [3]. As an example case, a 30 mm a-side cubic HSU with 7.5 g of water as PCM and a TEG with properties corresponding to a Marlow TG12-2.5 TEG and parametrized dimensions was assumed. An insulation thickness of 4 mm was also assumed. The cumulative electrical energy output from a simulated 3 K/min temperature cycle between ± 20 °C was calculated, for different TEG area values. The results for insulation thermal conductivities of 0.1 W/mK and 0.01 W/mK are presented in Figure 2. They show that the overall maximum possible performance is achieved by thicker TEGs, and selecting a specific surface coverage area. However, if a the TEG area is bound by other limitations, such as cost and market availability, the optimum thickness varies. In practice, these results can serve as a guide for TEG selection. This method can be applied to other HSU geometries, TEG specifications and temperature profiles, by modifying the simulation parameters accordingly.

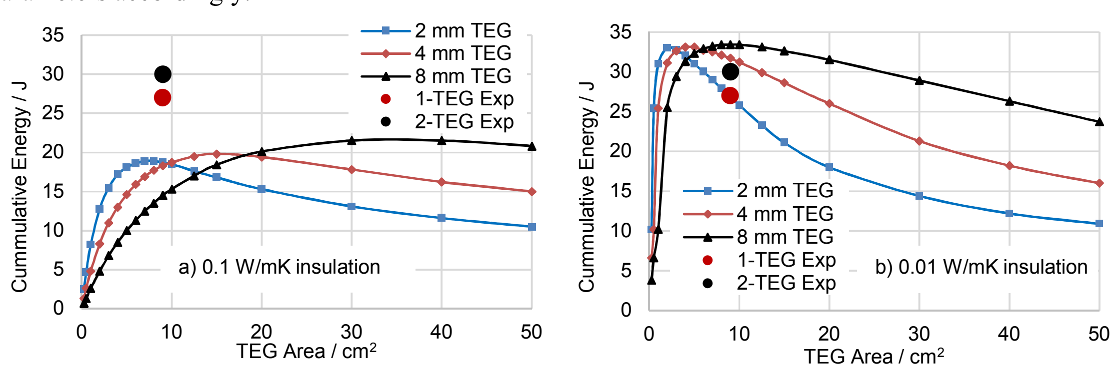

Figure 2. Cumulative energy from simulated 3 K/min cycles between ± 20 °C, for different TEG area and thickness. A 30 mm a-side cubic HSU with 7.5 g of water and 4 mm thick insulation was assumed. Figure 2a on the left assumes 0.1 W/mK whereas Figure 2b on the right assumes 0.01 W/mK insulation.

3. Fabrication and experimental results

A 32 × 32 × 26 mm HSU box was fabricated by Acrylonitrile-Butadiene-Styrene (ABS) 3D printing, with 3 mm walls. The side walls were designed to include a 1 mm internal airgap for enhanced thermal insulation. A 10 g Al internal heat bridge and 7.5 g of water as the PCM were used. The HSU was integrated with one and two (in thermal and electrical series) Marlow TG12-2.5 TEGs with dimensions 30 × 30 × 4 mm, in order to investigate the effect of TEG thickness to the device performance. Tests were performed using a 4 K/min temperature cycle between ±22 °C using a Tenney Engineering Inc. BTR mL environmental chamber. The TEG outside temperature and open circuit voltage were monitored using an Omega HH374 data logging thermometer and a VA18B data logging multimeter.

The measured temperature and voltage response of the 1-TEG and 2-TEG devices are shown in Figure 4, along with the corresponding power and cumulative energy, which were calculated by considering the 5 Ω electrical resistance of each TEG ($P_{OUT}=(V_{OC}/2)^2/R_E$). The results demonstrate 27J and 30J for the single and double TEG device respectively. In comparison with the simulation results of section 2 (red and black dots in Figure 2), the fact that the 2-TEG device gives a better performance indicates that these devices lie in the RC – limited range rather in a leakage-limited range. To confirm this, the devices were also tested using a 2 K/min cycle between 25 °C and 10 °C, where the slower temperature variation should lead to a clearer performance difference. The results are shown in Figure 5, demonstrating 22% better performance for the double TEG device.

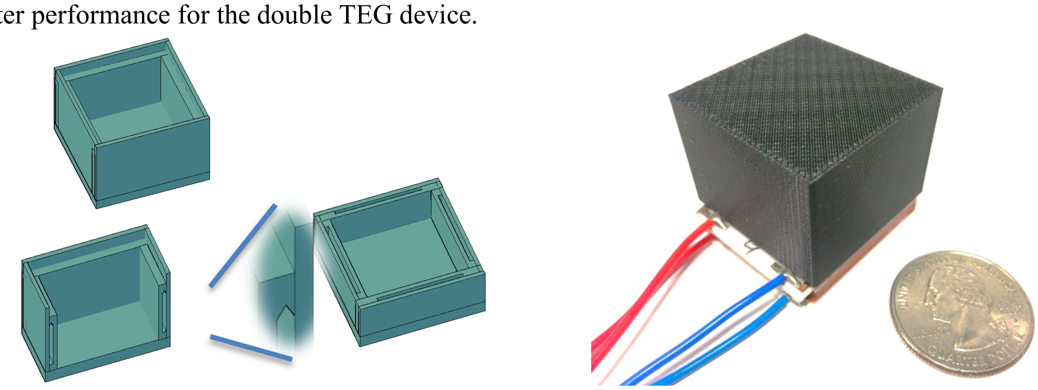

Figure 3. (left) Double wall insulation heat storage unit, designed for 3D printing. (right) Assembled device with 3D printed HSU and two TEGs in serial thermal flow orientation.

4. Conclusions

In this paper, the design of TEG devices for dynamic thermoelectric applications was studied. An analytical formulation of performance was outlined, showing that the TEG geometry, though it does not affect the device transduction efficiency directly, it determines the thermal and electrical resistance and thereby the ΔT that is achieved across the device. In direct thermoelectric harvesting, an R_{TH} equal to the total series thermal resistance is optimal (for a given TEG material). In dynamic thermoelectric harvesting, the optimal R_{TH} depends on the balance between leakage and dynamic response delay ($R_{TH}C$), and hence on the insulation thermal resistance and the temperature variation speed.

A 3D printed HSU was fabricated, allowing the implementation of airgap walls for improved thermal insulation. An energy density of 3.6 J / ml of PCM and 4 J/ml of PCM was demonstrated from single and double TEG implementations of the device, from a 4 K/min temperature cycle between ±22 °C. This corresponds to 0.88 J/ml per device and 0.86 J/ml per device respectively. The demonstrated energy levels are enough to supply typical duty-cycled, wireless sensor platforms. As an example, for every temperature cycle, a 100 mW active mode sensor node can be powered for 5 minutes of continuous active operation, or for over 8 hours of 1% duty cycling. Further tests from a slower, 2 K/min temperature cycle show 22% better performance for the double TEG device, in accordance with the analysis and the simulation results. These results may serve as guidelines for the development of dynamic thermoelectric harvesting devices for applications involving moderate temperature rates.

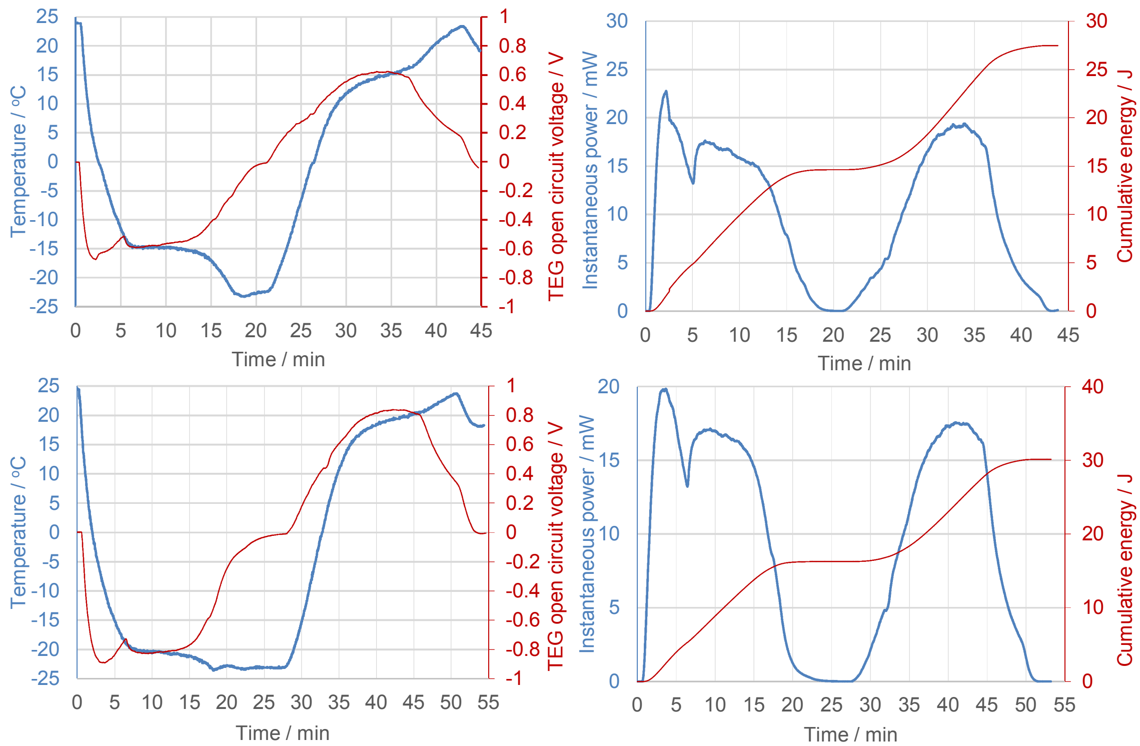

Figure 4. Measured temperature, voltage, power and energy response of the single (top) and double (bottom) TEG devices, demonstrating 27 J and 30 J of cumulative energy respectively from a 4 K/min temperature cycle between ±22 °C.

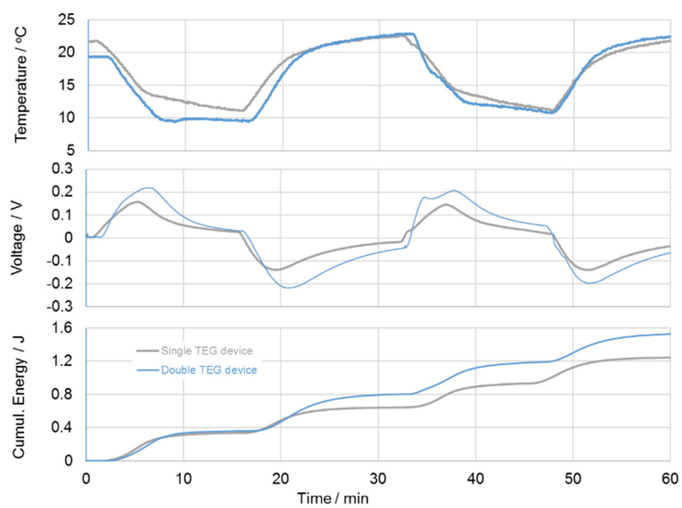

Figure 5. Response under 2 °C/min temperature variation between 22 °C and 10 °C. An energy increase of 22% is demonstrated for the double TEG device.

5. References

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