

OPTIMIZATION OF HEAT FLOW FOR PHASE CHANGE THERMOELECTRIC HARVESTERS

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Abstract: Thermoelectric energy harvesting has been limited to applications with large temperature gradients locally available. A recently proposed solution is to use a heat storage unit, with a phase change material, thereby creating a spatial temperature difference ΔT from temporal temperature variations. With this technique thermoelectric harvesting can be extended to applications such as avionics, where the environmental temperature changes with time. For such devices, a limited amount of heat energy per unit volume is available for a given temperature cycle and therefore the optimization of heat flow is critical. In this paper a heat flow simulation model is used to quantify the effects of thermal conductivities and the geometries of thermoelectric generators and heat storage units on overall device performance. The critical design requirements are the minimization of ΔT loss in the phase change material, selection of thermal conductances for optimal heat flow rate, minimisation of heat leakage, and ensuring that the phase change is completed within the available temperature range and time period. Total electrical energy of up to 10 J per gram of phase change material could be expected from such devices.

Keywords: energy harvesting, phase change materials, avionics, aircraft sensors

INTRODUCTION

Energy harvesting is a promising alternative power-supply technology for wireless applications where batteries are impractical. Motion, temperature gradients and light are the main ambient energy sources that can be exploited, using a variety of transduction mechanisms. For a given application, the viability and effectiveness of an energy harvesting technology will depend on the type and quantity of ambient energy available as well as on power demand and size/weight limitations. For wireless sensors, the energy source must be close to the sensing location, and the harvesting device must deliver enough energy while maintaining a size comparable to that of the sensor. Reviews of energy harvesting technologies from motion and thermoelectricity are available in the literature [1-3].

Thermoelectric harvesting devices are scalable and relatively easy to integrate. In addition, Thermoelectric Generators (TEGs) are relatively mature devices compared to other energy harvesters, because the same technology is used for cooling and heating applications. However, the efficiency of TEGs depends largely on the available temperature difference ΔT , and hence thermoelectric harvesting has been limited to applications where a large ΔT is available at the device location. This has been a major drawback for critical applications such as body sensor networks and structural monitoring. Recently, a new type of thermoelectric harvesting device has been proposed, introducing a heat storage unit (HSU) to transform temporal temperature variations into a spatial temperature difference ΔT [4,5]. As the temperature outside the HSU varies, heat flows to/from the HSU, through a thermoelectric generator. Critically, the heat capacity of the HSU is enhanced by using a Phase

Change Material (PCM). This device concept greatly broadens the applicability of thermoelectric harvesting as the ΔT location restriction is overcome.



Fig. 1: A prototype device before the application of thermal insulation [2].

A prototype implementation for avionic applications has been presented in [5] and is shown in Fig. 1. This design was based on COMSOL heat flow simulations to optimise the power-to-weight ratio for outside temperature cycles experienced in the aircraft structure (excluding the heated passenger compartments) during typical flights. A hemispherical geometry was chosen to minimise heat leakage, and a custom TEG of thermal conductivity $k = 0.86$ W/mK was attached at the bottom. The PCM material used was 10 g of water. The device yields 23.3 J of electrical energy, during a temperature cycle from $+20^{\circ}\text{C}$ to -20°C and back. This flight scenario is shown as curve S1 in Figure 2, along with other scenarios corresponding to flights from/to airports with

different ground temperatures. The TEG k-value was much higher than that of the insulation (Polyurethane, 0.02 W/mK) and therefore heat leakage was small. Conversely, the TEG k-value is comparable to that of water, meaning that a large fraction of ΔT is lost within the PCM. This effect significantly reduces the overall energy conversion performance of that particular implementation.

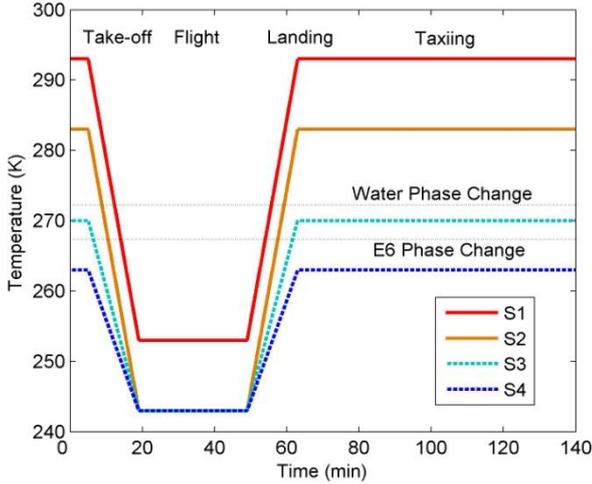


Fig. 2: Aircraft structure temperature profile for various flight scenarios, with freezing temperature of water and the proprietary material E6 indicated.

DESIGN CONSIDERATIONS

The performance of this new type of thermoelectric harvesting device strongly depends on the HSU heat flow dynamics. For a given application and environmental temperature cycle, the total available energy will depend on the PCM properties and mass. However, the total energy that can be converted into electrical form also depends on HSU geometry, thermal conductivities, and the TEG – environment interface. This is because of the strong dependence of the efficiency of TEGs on the ΔT across them during transduction [1].

In order to select an HSU geometry and the thermal properties of its various components, certain conflicting requirements must be balanced. For a given outside temperature profile, an excessive heat flow rate may lead to a low overall ΔT , and hence low efficiency. An insufficient heat flow rate may result in exploitation of only a fraction of the total available energy, because the PCM may not have time to complete its phase change cycle. Therefore, maximization of energy output requires a particular overall thermal conductance between the HSU and the ambient.

In addition, the thermal conductivity of the TEG should be considerably lower than that of the PCM, k_{PCM} , and also of the TEG – environment interface. On the other hand the overall thermal conductance of the TEG should be considerably higher than that of the insulated HSU walls, to minimize heat leakage.

NUMERICAL MODEL

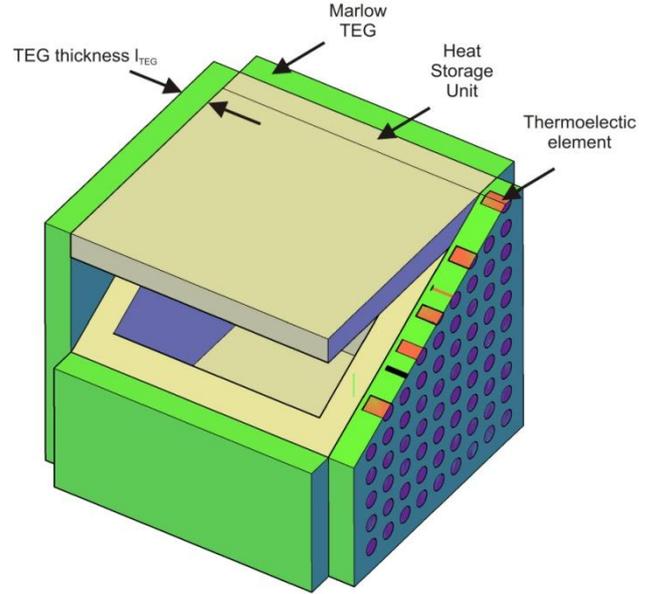


Fig. 3: A cubic HSU geometry with the capability of hosting TEGs on all 6 faces.

In order to quantify the considerations presented in the previous section, a simple heat flow model was developed. A general geometry of an HSU is illustrated in Fig. 3. A uniform temperature in the PCM and temperature independence of all thermal resistances are assumed. Finally, only the PCM contribution to heat storage is taken into account. Under these assumptions, Fourier's law of heat flow can be written as:

$$\frac{\partial Q}{\partial t} = \left(\frac{k_{TEG} \cdot S_{TEG}}{l_{TEG}} + \frac{k_w \cdot S_w}{l_w} \right) \cdot \Delta T \quad (1)$$

where Q is the heat energy inside the HSU and k_{TEG} and k_w are the thermal conductivities of the TEG and the HSU walls respectively. The parameters S_{TEG} , S_w , l_{TEG} and l_w are the surface area and thickness of the TEG and HSU walls respectively. If T_{IN} and T_{OUT} are the inside and outside temperatures respectively, then $\Delta T = T_{OUT} - T_{IN}$. Q will also be related to T_{IN} through the specific heat capacity c_p and mass m of the PCM:

$$Q = m \cdot c_p \cdot T_{in} \quad (2)$$

During phase-change operation T_{IN} will be constant, while during non-phase change operation, a differential equation can be derived by combining equations (1) and (2):

$$\tau \cdot \dot{T}_{in} + T_{in} = T_{out} \quad (3)$$

where τ is the time constant of the system, defined as:

$$\tau = c_p \cdot m \cdot \frac{1}{k_{TEG} \cdot S_{TEG} / l_{TEG} + k_w \cdot S_w / l_w} \quad (4)$$

While analytical equations can be calculated from the above analysis, the solutions are of different form for heat flow during phase-change and non-phase-change operation. Therefore it is more practical to implement the solution numerically. From any state of the system $[T_{IN}(n), T_{OUT}(n)]$, the new state $[T_{IN}(n+1), T_{OUT}(n+1)]$

after a time step Δt can be calculated, for a given T_{OUT} variation profile, from the following equations:

$$T_{IN}(n+1) = \begin{cases} T_{IN}(n) + (T_{OUT}(n) - T_{IN}(n)) \cdot \Delta t / \tau & \text{(non - phase change)} \\ T_{IN}(n) & \text{(phase change)} \end{cases} \quad (5)$$

$$Q(n+1) = \frac{kS}{l} \cdot (T_{OUT}(n) - T_{IN}(n)) \cdot \Delta t \quad (6)$$

From this analysis, the ΔT variation can be calculated for a given environmental temperature variation and a particular device design. Then, the expected output electrical power and total energy can be found, if the dependence of the TEG efficiency on ΔT is known. The standard theoretical equation for the efficiency of a TEG with figure of merit Z , at average temperature T and hot-side temperature T_h is [5]:

$$\eta_{TEG}(\Delta T) = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_h - \Delta T}{T_h}} \quad (6)$$

SIMULATION RESULTS

This simulation model has been used to predict the performance of various device designs, particularly for avionic applications. For the T_{OUT} variation cycle, a typical $[+20^\circ \text{C} \rightarrow -20^\circ \text{C} \rightarrow +20^\circ \text{C}]$ profile of the aircraft structure temperature during a flight, provided by Airbus, was used. This flight scenario is plotted as a red curve (S1) in Fig. 2. A hemisphere HSU structure was assumed, with 1 mm thick polyurethane isolation (0.02 W/mK), 10 g of PCM and a HSU size as for the device shown in Fig. 1 [5]. For a 3.5 mm thick TEG, the total electrical energy was calculated, using k_{TEG} as a varying parameter. The efficiency of the TEG was calculated from (6) using a ZT value of 0.71, which corresponds to the specifications of the TEG used in [5]. The results are shown in Fig. 4. For low k_{TEG} values, low output energy is observed. This is because the PCM does not have the time to enter or complete the first phase-change during the flight, meaning that the corresponding latent heat is not exploited. For high k_{TEG} values, T_{IN} follows closely T_{OUT} , resulting in a low ΔT and hence, low output energy. A maximum energy of 138 J is predicted, for an optimum k_{TEG} value of 1 W/mK. This result shows that the k_{TEG} value which was selected, based on COMSOL simulations, for the implementation in [5], is nearly optimum. The large difference between the simulated output energy (138 J) and the experimental result (23.3 J) is attributed in part to the extensive ΔT loss inside the PCM, as the heat conductivity of water is 0.58 W/mK, lower than that of the TEG.

In order to solve this problem, the possibility of using a different geometry with a lower optimum k_{TEG} value was investigated. A cubic HSU with 2.4 mm thick TEGs on all 6 faces was assumed. Simulations were run for two different PCM materials and quantities. The results are shown in Fig. 5. The first PCM is water while the second (E6) is a PCM Products Ltd material with a freezing point at -6°C and similar c_p and k to those of water [6]. The HSU

cube side for the 10 ml devices was 25 mm, while for the 30 ml devices, it was 35 mm. Optimum values for k_{TEG} five times lower than that of the PCM were found, showing promise for a substantial increase of overall performance. The total electrical energy output is in the range of 10 J per gram of PCM.

While lowering the k_{TEG} value is advantageous for the TEG performance, it increases the heat leakage through the sides of the HSU. This effect was quantified by assuming two independent paths for the heat flow and defining the heat flow efficiency as the percentage of total heat that goes through the TEG.

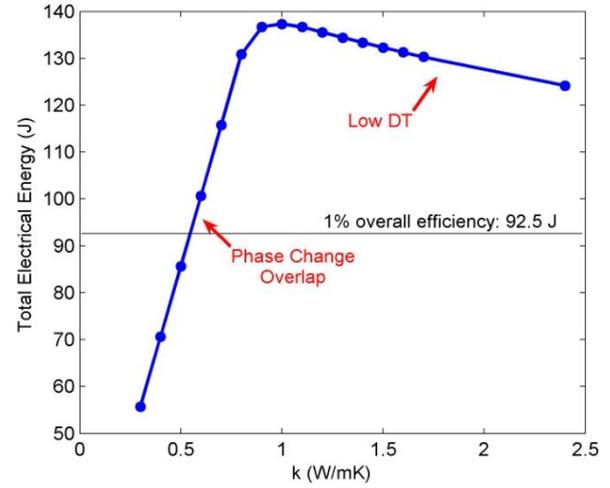


Fig. 4: Performance of a hemisphere HSU structure demonstrating an optimal k of 1 W/mK. Calculations correspond to flight scenario S1.

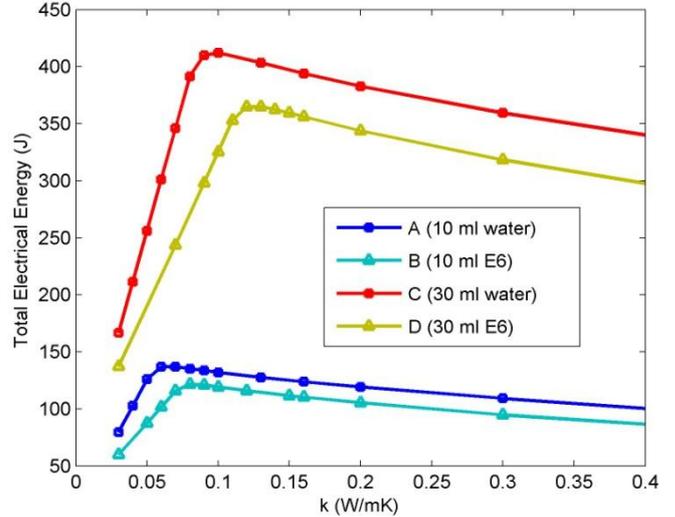


Fig. 5: Performance of 6-TEG cubic HSUs for two PCM types and volumes (flight scenario S1 of Fig. 2)

The corresponding calculations for various device geometries are shown in Fig. 6. In a fully covered cubic structure (A in Fig.6) minimum leakage is expected. In the case of a high k_{TEG} value (0.84 W/mK), cubic structures with just two (B) or one (C) TEGs show heat flow efficiencies of 90% and 78% respectively. For low k_{TEG} values, the corresponding efficiencies are 56% and 33% respectively. Similar results are observed for hemispheric structures. These results indicate that substantial heat leakage is

expected for low k_{TEG} device designs, and this leakage could be reduced by using more than one TEG. This solution may however come at the cost of additional overall weight.

Another critical aspect in designing a phase-change thermoelectric power supply is to ensure that phase-change occurs within the outside temperature variation range. The effects of different flight scenarios on the performance of the 30 ml E6 and water devices of Fig. 6 are shown in Fig. 7. Depending on the scenario, the maximum energy can vary by 10 - 40 %. The optimum k_{TEG} values also shift for different scenarios. However, an energy decrease by more than an order of magnitude is observed for the cases where the phase-change does not occur.

For avionic applications in particular, this result shows that water may not be a suitable PCM, as there are flight cases involving airports being occasionally (or even usually) at temperatures below 0°C .

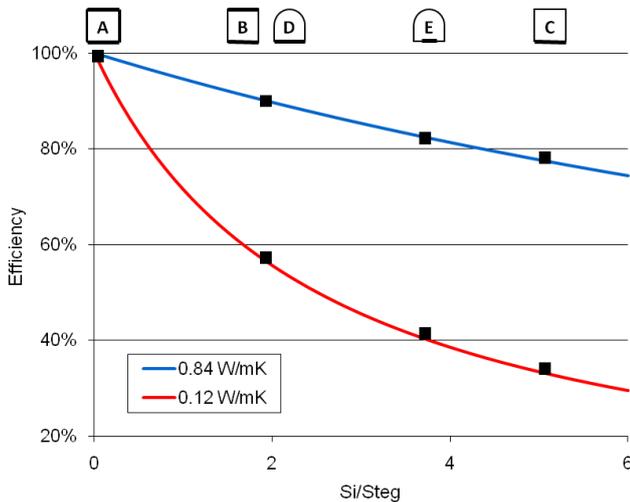


Fig. 6: Efficiency vs insulated/active surface ratio for TEG k values as indicated. Lettered shapes show device geometry, with dark lines indicating TEG position(s). The TEG and insulation thicknesses were assumed to be 2.4 mm and 1 mm respectively.

CONCLUSION

The applicability of thermoelectric energy harvesting devices has been greatly broadened by the introduction of a heat storage unit that allows the exploitation of temporal temperature changes. In particular, the use of phase change materials for heat storage greatly enhances energy availability. The performance of such devices depends on the TEG properties, the HSU heat flow response and the PCM used.

Heat flow simulations show that in order to maximize the energy output, a device design must balance the following requirements:

- Low heat flow rate, for maximum ΔT
- High heat flow rate, for phase change completion
- Low $k_{\text{TEG}} / k_{\text{PCM}}$ ratio to minimize ΔT loss

- High $k_{\text{TEG}} / k_{\text{W}}$ ratio
- Phase change within the temperature range

Each of these design requirements has a critical impact on the overall performance. Phase-change thermoelectric harvesters can be expected to provide energies of around 10 J per gram of PCM material. In addition they provide a solution to the location limitations of thermoelectric harvesters. Therefore, this type of thermoelectric harvesting could potentially address the power supply requirements of wireless sensors in applications involving temperature changes.

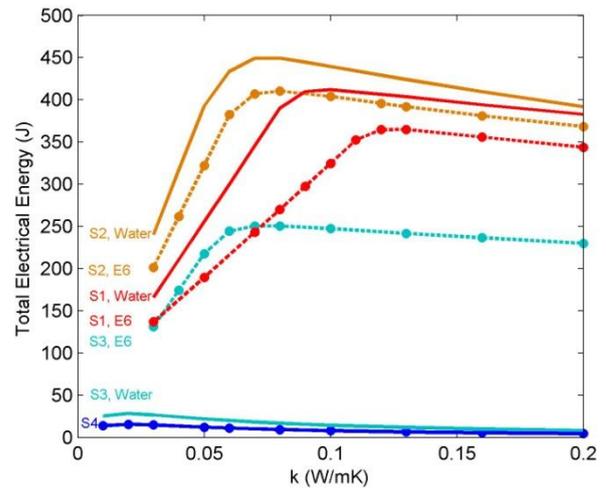


Fig. 7: Performance comparison for the flight scenarios of Figure 2.

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