A Study of Heat Sink Performance in Air and Soil for Use in a Thermoelectric Energy Harvesting Device

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Abstract

A suggested application of a thermoelectric generator is to exploit the natural temperature difference between the air and the soil to generate small amounts of electrical energy. Since the conversion efficiency of even the best thermoelectric generators available is very low, the performance of the heat sinks providing the heat flow is critical. By providing a constant heat input to various heat sinks, field tests of their thermal conductances in soil and in air were performed. A prototype device without a thermoelectric generator was constructed, buried, and monitored to experimentally measure the heat flow achievable in such a system. Theoretical considerations for design and selection of improved heat sinks are also presented. In particular, the method of shape factor analysis is used to give rough estimates and upper bounds for the thermal conductance of a passive heat sink buried in soil.

Introduction

Solid state thermoelectric generators offer high reliability power generation, and have been employed in unmanned spacecraft, as well as in terrestrial applications. In the past, thermoelectric modules have been built with relatively large thermocouples and with low specific power densities that limits their use to high temperature difference or low voltage applications. Current research in thermoelectrics at JPL has focused on the development of microgenerators that can maintain relatively high specific power densities even at small temperature differentials [1]. In such a device, the thickness of each thermocouple is on the order of tens of microns.

One particular application that has been suggested in the literature (see [1], [2]) is to use the natural difference between air and soil temperatures and a thermoelectric microgenerator (TEMG) to slowly charge a battery cell at low power. Sensors and communication devices would use the charged battery to operate at high power for a short period, perhaps once a day. Such an "energy harvester" would be a high reliability and low maintenance solution for providing power to electronics in remote locations.

Conceptually, the design of an energy-harvesting device is simple. A schematic representation of the device is shown in figure 1. Two heat exchangers, one exposed to the air at ground level and the other at some depth below ground provide heat flow across a TEMG. During the day the air exchanger heats up, and a heat pipe carries the heat across the generator and to the underground exchanger where it is dissipated into the soil. An advantage to this system is that at night, when the air cools down and the temperature profile is reversed, the generator can still produce significant amounts of power. In typical temperature conditions, such a device is expected to be able to produce about 22 mW of electrical power during its charge cycle [1].

Since the efficiencies of modern thermoelectric devices are still quite low, optimization is a crucial aspect of this project. In particular, the nature of the heat flow across the device plays an important part in maximizing power generation. Theoretical observations [2] and empirical findings [3] have shown that, to maximize output power, the internal thermal conductance of the TEMG should be equal to the sum of all external thermal conductances. External conductances are determined by contacts between parts and between the surroundings and the exchangers, as well as the internal conductances of the parts. To understand this result intuitively, note that if the internal conductance of the TE device is too high, then the temperature difference and therefore the thermal-to-electric efficiency will be small, but if the conductance is too low, then the heat flow will be reduced.
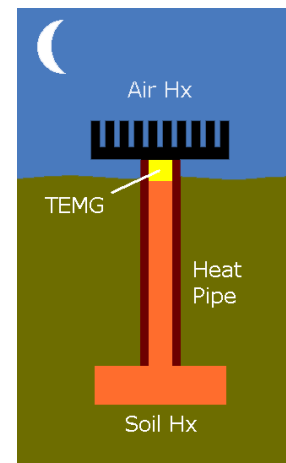

Figure 1: Simplified diagram of an energy harvesting device. "Heat exchanger" is abbreviated as "Hx."

The internal thermal conductance of the TEMG can be controlled fairly readily [2], but little research has been done to determine the thermal conductance of a passive heat sink in contact with soil. A primary goal is to find, if only a rough estimate, some theoretical basis for predicting the conductance of a given heat sink, and to test these results in the field.   It is shown that a heat transfer analysis using *shape factors* gives a rough but simple way to estimate the thermal conductance of a ground-side heat sink.

Another important goal of this project is to experimentally demonstrate the feasibility of an energy-harvesting device in a typical application. A prototype heat exchanging was designed, constructed, and tested in the field.   TEMG fabrication is still in development, so a dummy element with known thermal conductance was used instead to measure the possible heat flow across an actual generator. The results

show a good first step towards a workable device, but further enhancements will be required to reach optimal power output.

Materials and Methods

In order to measure the thermal performance of different heat sinks, a simple steady conductance experiment was designed. The experiment is represented schematically in figure 2. One or more small 2W resistive heaters is inserted into the heat sink at approximately where the heat pipe would be attached. A thermocouple T_2 is also inserted into the main body of the heat sink. The entire apparatus is buried 30 cm underground. Another thermocouple T_1 measures the soil temperature. A constant voltage source provides nearly constant heat $\dot{Q}$. The thermocouples are connected to a computer data collecting station that records the temperatures at ten-minute intervals. This setup is allowed to run for at least 72 hours. A similar, though less accurate experiment, can be used to test an air-side heat sink.
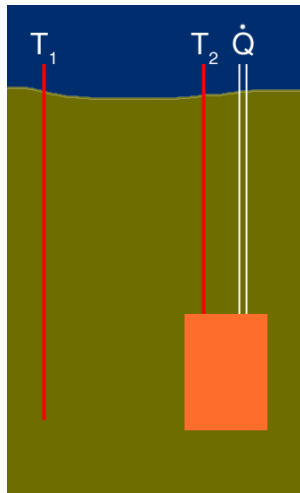

Figure 2: Schematic representation of conductance experiment.

After approximately 12 hours, the system will reach a close-to-equilibrium state where the sink and soil temperatures will fluctuate slightly with the daily changes in air temperature (about ±1 K). However, these fluctuations are in phase, so that the temperature difference is nearly constant. Thus, the thermal conductance is given by the steady conduction equation

$$c = \frac{\dot{Q}}{\Delta T} \tag{1}$$

The conductance will still vary somewhat with time, but over a period of a few days an average within reasonable error bars can be computed.

The testing site was located on small patch of soil outside the laboratory. For most of the day, trees shaded the area, but the sun did shine directly on the site for short periods. Nearby lawn sprinklers came on at 5am each morning for approximately one hour. During the day, air temperature varied between 18 and 31°C in the shade, and peaked at 35°C during sunlit periods. At night, temperatures dipped to 15°C.

Four soil-side heat sinks were tested on this site. The first three consisted of lengths of 3.2 cm diameter copper rod. The first was 5 cm in length and oriented vertically, known as the "5 cylinder." Two longer rods of length 25 cm and 45 cm

were used in a horizontal orientation. These are listed as the "25 rod" and "45 rod," respectively. The last heat sink, the "Starfish," consisted of a 5 cm by 5 cm copper cylinder with eight 15 cm fins attached radially. A power transistor heat sink to be used as the air-side heat exchanger in the prototype was also tested to compare the results to the manufacturer's specifications.

Figure 3: Prototype energy harvester. Inset: Brass dummy element.

The prototype energy harvester is pictured in figure 3. At the top, the power transistor heat sink serves as an air-side heat exchanger. The brass dummy element ($c = 1680$ mW/K) was soldered to a copper plate, which was in turn covered in thermal grease and bolted to the sink. A water-based heat pipe (30 cm long, 1 cm diam.) was soldered to the element with low temperature Wood's metal. The other end of the pipe was also soldered with Wood's metal to the Starfish copper heat sink. The heat pipe is wrapped in polyethylene insulation to prevent outward heat flow.

Thermocouples were inserted at various points in the system, including two on either end of the brass element. The entire device was buried in the testing site, and temperature data was recorded for a period of 60 hours at ten-minute intervals. Since the thermal conductivity of brass is well known, the heat flow across a hypothetical generator can be calculated easily with (1).

Results

The thermal conductances of the different heat sinks are presented in table 1. The daily periodic fluctuations in temperature account for the margin of error in the measurements.

The heat flow and ΔT across the brass dummy element over a 60 hour period are presented in figure 4. A negative heat flow indicates the reversed night temperature profile described in the introduction. The large positive heat spikes are sunny periods, and the small early morning dips are due to the sprinkler system.
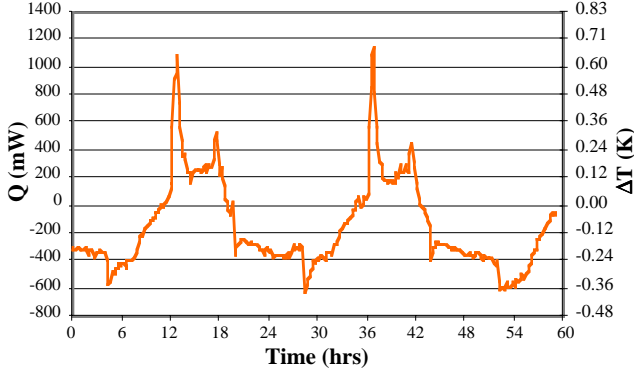
Brass Element

Figure 4 chart: Q (mW) left axis from -800 to 1400; ΔT (K) right axis from -0.48 to 0.83; Time (hrs) axis from 0 to 60.

Figure 4: Heat and ΔT across brass dummy element in prototype. Heat flow is calculated using the steady conduction equation and conductance of brass element (1680 mW/K). The time axis starts at midnight.

	Q (mW)	c (mW/K)
5 cylinder	320	251±25
	820	237±20
	1930	202±10
25 rod	2900	650±50
	3490	570±50
45 rod	4230	1220±100
Starfish	2902	1270±90
	3490	1320±100
	3820	1350±100
Air Sink	3820	1400±300

Table 1: Results from thermal conductance experiments.

Discussion

The heat transfer problem of a passive heat sink immersed in soil has received little attention in the literature; most likely due to lack of applications. Complicated thermal modeling could provide thermal performance predictions, but it is also desirable to have a simpler and faster method to make rough estimates. A *shape factor analysis* reduces the problem to a simple steady conduction model, and gives, if nothing else, upper bounds on the thermal conductance of a heat sink in soil.

In the most general form, a shape factor problem involves two isothermal surfaces at temperatures T_1 and T_2 separated by an isotropic medium with thermal conductivity k. The heat flow across the two surfaces is then given by

$$\dot{Q} = kS(T_2 - T_1) \qquad (2)$$

where S is the *shape factor*, a value based on the geometry of the system. S typically has units of length, but there is no intuitive meaning associated with it. Most heat transfer textbooks will have a table of shape factors for different systems (see [4] for example).

In the soil heat sink problem, the two surfaces in question are that of the soil and that of the heat sink. The soil is assumed to be a semi-infinite solid, that is, infinite in all directions except on top; this surface is taken to be isothermal. Two useful shape factor formulas in this case are:

Buried sphere: $\dfrac{2\pi D}{1 - \dfrac{D}{4z}}$

$$(3)$$

Buried horizontal cylinder: $\dfrac{2\pi L}{\ln(\dfrac{4z}{D})}$

where z is the depth of the object, D is its diameter, and L its length.

In table 2, the predicted conductance kS and average measured conductance is listed each heat sink. In the case of the 5 cylinder, the shape factor for a sphere with 5 cm diameter was used. The Starfish shape factor represents a upper bound for the conductance: a sphere with a diameter equal to the diameter of the heat sink. The soil thermal conductivity value is assumed to be the generally accepted value of 10 mW/K [5]. Some empirical formulas for soil thermal conductivity [6] are available; they generate a value between 6 and 12 mW/K depending on soil type and water content.

Sink	kS (mW/K)	c (mW/K)
5 cyl	220	230
25 rod	440	610
45 rod	800	1220
Starfish	(max) 2140	1310

Table 2: Predicted conductances using shape factor method (first column) and averaged experimental results (second column). Assumes $k = 10$ mW/K.

While not a perfectly accurate analysis, it does provide rough estimates of heat sink performance. Perhaps most importantly, it gives a plausible upper bound for the conductance without any involved thermal modeling. The Starfish design seems to work well for its size at 60% of its theoretical upper bound, but further tests with different fin length and number could improve performance.

Subjecting this problem to shape factor analysis does require bending some of the normally required assumptions. Clearly, neither surface in this system is likely to be isothermal in practice. The soil surface receives a large heat input from the sun, and fluctuates significantly during the day. This problem is somewhat alleviated by measuring the soil temperature at depth. The heat sink is unlikely to affect the soil temperature significantly, so the soil temperature at depth may give a clearer picture of what the soil surface temperature would be without the sun's heat. The heat sink surface should be relatively isothermal given copper's high thermal conductivity.

This problem also normally requires steady (time-independent) conduction between the two surfaces. As discussed in the Methods section, while the conduction may not be completely steady, the variation in ΔT is small and periodic.

Unlike its companion problem in soil, the performance of air-cooled heat sinks is a bread-and-butter heat transfer problem, due to its extensive applications in microelectronics (see [7] for a reasonable introduction to the subject). The thermal conductance of the power transistor heat sink given in the manufacturer's specifications is 1490 mW/K, not far from and well within the margin of error of the measured value of 1400±300 mW/K.

Given the low efficiencies of thermoelectric microgenerators at small ΔT, the results from the prototype test do not appear promising. For small ΔT and Bi_2Te_3-based generators, a reasonable approximation can be derived [8] for the electrical power output P:

$$P = (0.0005 \ K^{-1}) \ \dot{Q} \ \Delta T \qquad (4)$$

A plot of predicted power over time is given in figure 5. This is only an rough order-of-magnitude estimate of power output as the conductance of an actual TEMG may be different from that of the brass element. This falls well short of expectations, but this first attempt did show some room for improvements. According to the temperature data, most of the temperature drop in the system was across the heat pipe—up to 4.5 K out of the 10 K total across the air and soil. Further investigation seems to indicate that at low ΔT and heat flux, this particular heat pipe design will not perform adequately. In hindsight, this is not surprising since water-based heat pipes are optimized for high temperatures and large ΔT, and designed to be oriented with the hot side below the cold side. A different heat pipe design, optimized for low temperature and small ΔT operation, or removal of the heat pipe altogether may greatly improve efficiency.
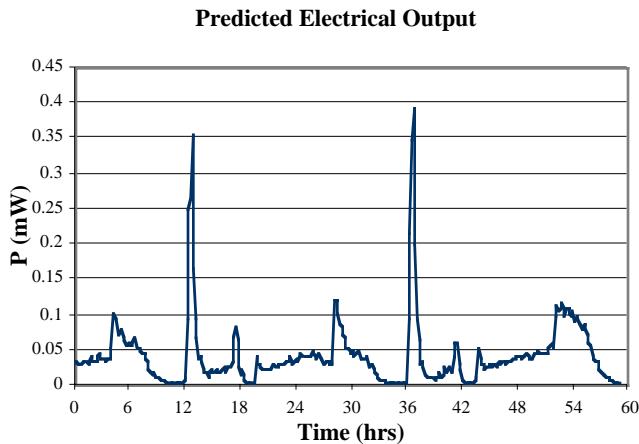
Predicted Electrical Output

Figure 5: Predicted electrical output for the prototype device; calculated with equation (4).

Conclusions

The method of shape factor analysis can be used to give rough estimates and upper bounds for the thermal conductance of a passive heat sink buried in soil. This is vital for determining the expected heat output and for optimizing an energy-harvesting device.

A device that uses a thermoelectric module to harvest energy from the natural temperature difference between soil and air is feasible, but to achieve the desired electrical power output, more work will have to be done to increase heat flow. Improved heat pipe design is required to improve the performance of the device.

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