Thermal Matching of a Thermoelectric Energy Scavenger with the Ambience

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Abstract

Powering autonomous devices by using thermoelectric conversion of wasted heat, flowing from low temperature sources to the ambience, is complicated by the high thermal resistance of the heat sink (air) and, frequently, of the heat source (e.g., walls of buildings, animals and man). In this work, we define general conditions required to make a thermoelectric converter effective in such scenario of energy scavenging. The necessity of the work has been prompted by the fact that while modeling the scavengers one cannot assume as constant neither the temperature difference, nor the heat flow. We show that there are simple equations that allow thermally optimizing such systems to reach top performance of energy scavengers. The related consequences and some specific applications are discussed, in particular, the limit for power generation on human beings is obtained.

Introduction

Scavenging thermal energy is not an easy task: because of obvious energy saving reasons, wasted heat flows are usually minimized with the use of thermally isolating materials. The remaining heat flows and temperature differences available for energy scavenging are therefore comparatively small. However, these still wasted heat flows will be definitely used in coming years targeting to eliminate the need of primary batteries in most of autonomous devices placed inside buildings, machinery, or in closed compartments, and forming autonomous networks.

The research on thermal energy scavengers at IMEC started in 2003 addressing the most difficult task, i.e., powering wearable devices using thermoelectric generators (TEGs). The complexity of the task was caused by both very small temperature difference and high thermal resistance of the heat source (a human being) as well as of the heat sink (still air). While designing the first micromachined thermopiles in 2003 for application on human body, the thermal optimizations have been conducted numerically by varying the thermal resistances of the parts of the TEG and the air inside it. Basing on these results, understanding of the necessity of thermal matching of a TEG to the environment has come and its principles are presented in this paper.

Thermal matching: the temperature drop on a TEG

The thermal circuit of any TEG can be represented, in the simplest case, with three thermal resistors, Fig. 1, left, where R_{so} and R_{si} are the thermal resistances of a heat source and the heat sink, respectively, and R_{TEG} is the one of the TEG. If using parallel thermal connection of commercial thermopiles in a TEG, R_{TEG} is in general smaller than the other ones and only by means of a careful optimization it is possible to make it comparable or even larger than the one of the serial thermal resistors. This means that while optimizing the device, thus changing its thermal resistance, neither constant temperature difference at the ends of the TEG, nor constant heat flow through the TEG can be assumed. The TEG cannot be designed independently of the environment and matching of its thermal resistance to the ambience has to be considered. For the sake of discussion, the thermal resistors of the heat source and the heat sink are merged into a single resistor, denoted as R_{sp}, (where "sp" stands for serial parasitic), see Fig. 1, right. It represents mainly the thermal resistance of the ambience but also includes the thermal resistance of the TEG components thermally connected in series to thermopile resistor R_{tp}. Finally, the TEG has parasitic heat exchange in between the hot and cold plates, R_{pp} (parallel parasitic thermal resistance). It can include the thermal conductance of the air in between the hot and cold plates, radiation heat exchange, and thermal conductance of holding elements like screws, glue, thermally isolating sidewalls of the device body etc., i.e., any elements thermally interconnecting hot and cold sides of the device.

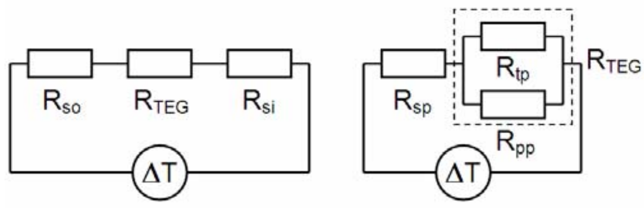

Figure 1. Thermal circuits for energy scavengers.

Let us consider a simplified case of a TEG, assuming that R_{sp} is independent of temperature and that only the air contributes to R_{pp}, so that $R_{pp} = R_{air}$. We assume that the TEG has hot and cold plates of the same area A. The two parallel resistors in Fig. 1, right, are:

$$R_{tp} = \frac{h}{k_{tp} a}, \quad (1) \qquad \text{and} \qquad R_{air} = \frac{h}{k_{air}(A-a)}, \quad (2)$$

where h is the height of thermoelectric legs and hence also the distance in between the two plates, k_{tp} and k_{air} are the thermal conductivities of the thermoelectric material and air, respectively, and a is the total cross area of thermoelectric legs. Making a transition to thermal conductances, the temperature drop on a thermopile is given by:

$$\Delta T_{tp} = \Delta T \frac{G_{sp}}{G_{sp} + G_{TEG}}, \quad (3)$$

which, using (1) and (2), can be transformed into:

$$\Delta T_{tp} = \Delta T \frac{G_{sp} h}{G_{sp} h + k_{tp} a + k_{air} (A - a)}. \quad (4)$$

The open circuit voltage is given by:

$$V = \frac{\alpha \Delta T G_{sp} h}{(G_{sp} h + k_{air} A) + a (k_{tp} - k_{air})}, \quad (5)$$

where α is Seebeck coefficient. Expressing the electrical resistance of a thermopile through its resistivity ρ, the power on the matched electrical load can be written as:

$$P_{el} = \frac{\alpha^2 \Delta T^2 G_{sp}^2 h}{4\rho} \cdot \frac{a}{[(G_{sp} h + K_{air} A) + a(k_{tp} - k_{air})]^2}, \quad (6)$$

At its derivative $dP_{el} / da = 0$, the maximal power corresponds to $a = a_{opt} = (G_{sp}\, h + k_{air}\, A) / (k_{tp} - k_{air})$, so that:

$$P_{\max} = \frac{\alpha^2 \Delta T^2 G_{sp}^2 h}{16 \rho (k_{tp} - k_{air})^2}. \quad (7)$$

Substituting a_{opt} into Eq. (4), the temperature difference ΔT_{tp}, corresponding to the maximal power, is:

$$\Delta T_{tp,opt} = \frac{\Delta T}{2} \cdot \frac{G_{sp}}{G_{sp} + G_{TEG,0}}, \quad (8)$$

where $G_{TEG,0} = k_{air}\, A / h$ denotes the thermal conductance of the same TEG, but with no thermocouples in between the plates, i.e., of the empty TEG; this is the parasitic thermal conductance of a TEG. Eq. (8) shows that if the thermal conductance of the air in empty TEG $G_{TEG,0} << G_{sp}$, which means negligible parallel parasitic thermal conductance, the optimal temperature difference is half of ΔT, and it is the maximal possible in the optimised device. For example, this means that the maximal possible temperature drop on the optimized thermopile on human skin at a skin temperature of 30 °C and an air temperature of 22 °C is not (30-22)/2 = 4 °C, but (37-22)/2=7.5 °C, where 37 °C is the deep body core temperature. It is because not the skin, but the body is the generator of heat.

Thermal matching: the equations

In general, G_{sp} is a nonlinear function of temperature because it includes air convection and thermal radiation terms: we denote it with G_{amb}, or the thermal conductance of the ambience. In this case Eq. (8) cannot be treated analytically. For the time being, we assume to have determined numerically the optimal parameters. We denote them as $\Delta T_{TEG,opt}$ and $G_{amb,opt} = 1/R_{amb,opt}$; the latter can be used then to find the optimal cross section of thermoelectric material a_{opt}. Let us compare the temperature drop on the TEG with no thermocouples in it and at the optimal cross section of thermoelectric material. At $a = 0$,

$$\Delta T_{TEG,0} = \Delta T \frac{G_{amb,0}}{G_{amb,0} + G_{TEG.0}} = \Delta T \frac{R_{TEG,0}}{R_{TEG,0} + R_{amb,0}}, \quad (9)$$

while at optimal a=a_{opt}, as follows from Eq. (8), it becomes

$$\Delta T_{TEG,opt} = \frac{\Delta T}{2} \frac{G_{amb,opt}}{G_{am,opt} + G_{TEG,0}} = \frac{\Delta T}{2} \frac{R_{TEG,0}}{R_{TEG,0} + R_{amb,opt}}. \quad (10)$$

From Eqs. (9) and (10), the ΔT_{tp} at optimal a is:

$$\Delta T_{TEG,opt} = \frac{\Delta T_{TEG,0}}{2} \frac{R_{amb,0} + R_{TEG,0}}{R_{amb,opt} + R_{TEG,0}}. \quad (11)$$

Eq. (11) deserves some comments. If the thermal resistance
of the ambience is constant, i.e., $R_{amb,0} = R_{amb,opt}$, Eq. (11) simplifies to:

$$\Delta T_{TEG,opt} = \Delta T_{TEG,0} / 2. \quad (12)$$

Independently of the temperature behavior of the ambient resistance, Eq. (12) also holds if

$$R_{TEG,0} >> R_{amb,0} \quad (13) \quad \text{and} \quad R_{TEG,0} >> R_{amb,opt}. \quad (14)$$

In the optimized device, Inequalities (13) and (14) should hold, at least in a weak form (with "much more" replaced with "more"), furthermore, in typical situations of the energy scavengers, the ambient resistance does not vary greatly with temperature. For these reasons, Eq. (12) instead of Eq. (11) can be usually used as a condition for optimizing the device.

Considering that

$$\Delta T_{TEG,0} = R_{TEG,0} W_{TEG,0} \quad \text{and} \quad \Delta T_{TEG,opt} = R_{TEG,opt} W_{TEG,opt}, \quad (15)$$

the condition of Eq. (12) can be rewritten as:

$$R_{TEG,opt} W_{TEG,opt} = R_{TEG,0} W_{TEG,0} / 2. \quad (16)$$

In those cases, where the thermal resistance of the ambience dominates, the heat flow does not depend on the thermal resistance of a TEG, and Eq. (16) simplifies to:

$$R_{TEG,opt} = R_{TEG,0} / 2, \quad (17)$$

thereby stating that the thermal resistance of thermocouples and of the air are equal to each other. This condition is widely used in designing the TEGs. As the goal of the optimization is to make the thermal resistance of the TEG comparable or larger than the one of the ambience, in most cases, Eq. (17) cannot be used and must be replaced with Eq. (12) or, even better, with Eq. (11).

We proceed now with the optimization of the TEG. First, we replace $\Delta T_{TEG,opt}$ and $\Delta T_{TEG,0}$ in Eq. (11) with Eqs. (15). Then we eliminate the heat flows using:

$$W_{TEG,0} = \frac{\Delta T}{R_{amb,0} + R_{TEG,0}}, \quad (18)$$

$$W_{TEG,opt} = \frac{\Delta T}{R_{amb,opt} + R_{TEG,opt}}. \quad (19)$$

After such replacements, we solve Eq. (11) for $R_{TEG,opt}$ and obtain:

$$R_{TEG,opt} = \frac{R_{amb,opt} R_{TEG,0}}{2R_{amb,opt} + R_{TEG,0}}. \quad (20)$$

Eq. (20) can be solved by iterations. In the beginning, the value of $R_{amb,0}$ can be used instead of $R_{amb,opt}$. Upon obtaining the first approximation value of $R_{TEG,opt}$, the values of $W_{TEG,opt}$ and $R_{amb,opt}$ can be recalculated more accurately; the latter then can be used in the next iteration. Only several iterations are usually required for excellent accuracy.

As far as only two parallel thermal resistors compose the TEG, the required thermal resistance of the thermopile $R_{tp,opt}$ can be easily obtained from the value of $\Delta T_{TEG,opt}$. The optimal area of thermoelectric material a in the TEG is:

$$a_{opt} = h / k_{tp} R_{tp,opt} . \qquad (21)$$

The minimal number of thermocouple legs, while satisfying the requirement for the output voltage on the matched load V_m, is given by:

$$n = \frac{2V_m}{\alpha \Delta T_{TEG,opt}} . \qquad (22)$$

Finally, the required cross section s of thermopile legs should not exceed $s = a / n$.

Thermal matching: the application on man

As an example of application of the method described, let us consider a thermopile with the same minimal lateral leg dimensions as in [1] with their size of 80 μm × 80 μm × 600 μm. For calculations, we assume that the hot plate has a thermal contact with the skin in the outer side of the wrist over a circular area of 3.14 cm^2, while the radiating area is 7 cm^2, so that the device body resembles a watch. The hot and cold plates are separated by 1.3 mm, which is the thickness of the thermopile including the ceramic plates. The power produced depends on the number of thermocouple legs, therefore, at a certain number, corresponding to the optimal cross area of thermoelectric material, the matching condition of Eq. (11) is satisfied. The normalized power computed numerically for an air temperature of 22 °C is shown in Fig. 2 versus the $\Delta T_{TEG} / \Delta T_{TEG,0}$ ratio. Each point of the curve corresponds to a different value of a. The maximal power, point (1), is observed at $\Delta T_{TEG} = \Delta T_{TEG,0} /2$.

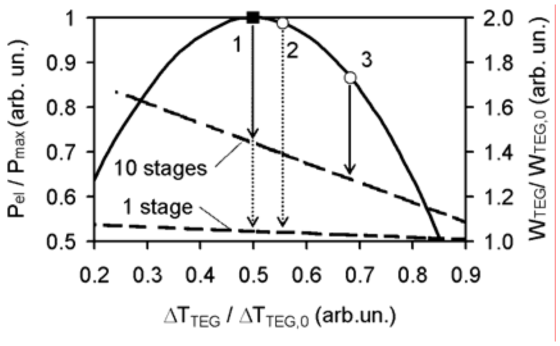

Figure 2. Thermal matching of a TEG to the ambience: normalized power (solid line) and normalized heat flow (dashed lines). The arrows show the heat flows corresponding to three marked points.

The analysis of numerical simulations shows that this is because the ambient resistance is only weakly dependent on temperature. In addition, the thermal resistance of the ambience is larger than the one of the generator. So, the device is in a condition, where the heat flow is nearly independent of R_{TEG}, Fig. 2, so that Eq. (17) approximately holds. Using Eq. (17) for determining the number of thermocouples corresponding to the optimal power would have generated a small error giving the point (2), Fig. 2. One may see that it is not very far from the true matching point (1), however, this is because in our device the Inequalities (13) and (14), even in their weak form, are not satisfied.

Small-size thermopiles available on the market do not fit the requirements for the thermopile legs coming out of the modeling of an optimal thermopile because their aspect ratio is much smaller than needed. An appropriate aspect ratio then can be obtained by stacking thermopiles on top of each other [2]. This increases the R_{TEG} and hence the output power. For example, in case of a 10-stage thermopile, the power increases in 5.7 times. Larger number of stages could further increase the power, but the device would be too thick and therefore inconvenient for the users.

The normalized power for a 10-stage TEG, Fig. 2, coincides with the similar curve for a one-stage device. The heat flow is, however, different. Inequality (14), even in its weak form, is not yet satisfied in the 10-stage TEG; the $R_{TEG,0}$ is still 84% of $R_{amb,opt}$, however, the change in heat flow is already 44% at the matching point (1). It further increases after satisfying Inequality (14) in its weak form. This confirms that heat flow cannot be assumed as constant while modeling and that Eq. (17) cannot be used for optimization: its use would have given the point indicated as (3) in Fig. 2, far away from real maximum.

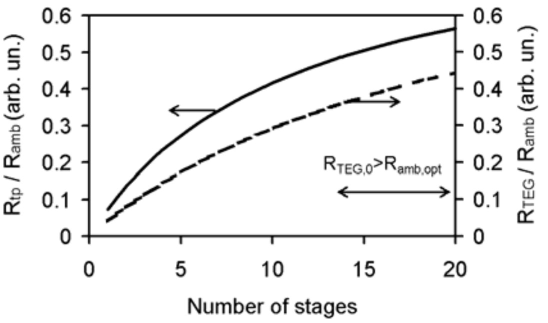

Figure 3. The ratios of the thermal resistance of the thermopile and of the TEG to the one of the ambience versus the number of stages at thermal matching, i.e., at $a=a_{opt}$.

The ratios $R_{TEG,opt} / R_{amb,opt}$ and $R_{tp,opt} / R_{amb,opt}$ are shown in Fig. 3 versus the number of stages. One can notice that the thermal resistance of a TEG does not halve at the matching point (i.e., $R_{TEG,opt} \neq R_{tp,opt} /2$), reflecting the difference with both parallel and serial matching.

Some aspects of thermal matching of TEGs on humans

As shown above, multi-stage thermopiles allow the thermal matching, but it occurs at a very high effective aspect ratio, which is the ratio of the length of all the thermocouple legs on top of each other to their width. There are, however, some other helpful practical ways of easily tuning the thermal resistance of the TEG components to fulfill the thermal matching requirements at smaller aspect ratio or at smaller number of the stages.

First, when applying thermal matching conditions to the TEG on human skin, Inequality (14) in its weak form demands to provide a thermal plate-to-plate isolation of at least 2 000 cm^2K/W, which can be done only at their distance of about 1 cm from each other. Anyway, this space is required for a multi-stage thermopile. On the other hand, the free/forced convection layer near the body, e.g., around the wrist, has usually similar or less thickness, therefore, the radiator can be moved out of the convection layer and the heat transfer into the air improves.

Second, if using small-size thermopiles, like, e.g., MEMS thermopiles, the TEG becomes almost empty [3], so that the plate-to-plate radiation heat exchange can be effectively suppressed using the plates with low emission coefficient.

Third, proper positioning of the TEG on human being offers much lower thermal resistance of the body than its average value [2, 3].

Forth, a small radiator instead of a cold plate effectively reduces the thermal resistance of ambient air [2].

Finally, the thermal resistance of the body itself can be decreased using a radiator as shown in [3] through changing the local heat flow in humans under the device.

Thermal matching of MEMS thermopiles

Thanks to the laws of scaling, small MEMS thermopiles

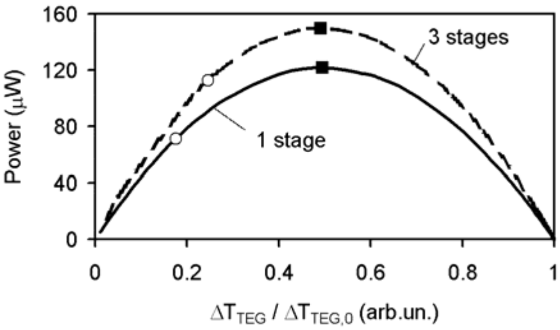

Figure 4. Matching of the MEMS TEG with the ambience (squares) and parallel matching of thermopiles (circles) to the air in a TEG (similar to points 2-3 in Fig. 2).

can be as effective as commercial thermopiles. The rules of designing the TEG remain the same as discussed above. A tall thermally conducting pillar, however, has to be added to the TEG for thermal interconnection of the thermopile chip with the well-separated plates [3]. Fig. 4 illustrates thermal matching of 3 μm-tall BiTe micromachined thermopile with 1 μm^2 leg cross section of the design reported in [4] in a 3 cm × 3 cm TEG at a temperature of 22 °C. Taking into account the helpful hints of the previous section, a pin-featured radiator [2] replaces the cold plate and provides a thermal resistance in the human body of 200 cm^2K/W.

Numerical calculations show that even the TEG with one-stage 3 μm-tall thermopile on humans, can be effectively thermally matched with the ambience, providing $R_{TEG,0} = 1.4R_{amb,opt}$, which shows potential advantage of the MEMS thermopiles for wearable devices as compared with the existing industrial technology. Comparing the parallel matching of two resistors composing the TEG, Fig. 1, one can notice that the thermal matching required (squares in Figs. 2, 4) calls for smaller thermal resistance of the TEG in case of commercial thermopiles, Fig. 2, and for the larger one in case of MEMS thermopiles, Fig. 4. One can mention that despite very small height of the micromachined thermopile, a power exceeding 16 $\mu W/cm^2$ can be obtained.

Thermal matching in wearable devices of tomorrow

Application of the thermal matching for designing the TEGs with different types of thermopiles gives the limit for power generation on human beings equal to 30 $\mu W/cm^2$ (on 24-hour average) at an ambient temperature of 22 °C and a ZT of 1. The TEGs fabricated in 2005-2006, have already closely approached this limit producing 20 $\mu W/cm^2$ at a ZT of about 0.8 – 0.85.

The modeling of advanced MEMS thermopiles with large aspect ratio [5] shows that in order to make universal wearable thermoelectric energy scavenger for all seasons, the thermal matching must be performed for the air temperatures very close to skin temperature, e.g., for 35 °C. The smaller lateral size of the thermocouple legs is needed as compared with the TEG optimized to 22 °C, in addition, the number of thermocouples must be more than double. The TEG then will produce over 2 V at an air temperature of 35 °C which is more than enough to power advanced electronic circuits. Therefore, wearable devices with such thermopiles will be powered all year round. The other approach is to use large rechargeable Li cell to keep self-powered devices working when the temperature difference minimizes in summer time. Then, the matching is to be performed for a typical ambient temperature, e.g., to 22 °C. The thermal mismatching in summer does not exceed about 10% because the thermal resistance of the body decreases while approaching 36 °C air temperature. According to the modeling, this device still produces a power of 0.5 $\mu W/cm^2$ at a voltage of 1.1 V at 35 °C, however, the power production becomes only periodical within the 35–37 °C; it still occurs due to natural fluctuation of the air and skin temperatures in a real life.

Conclusions

Thermal matching of energy scavengers to the ambience is required to maximize the generated power. It serves as a thermal equivalent of electrical matching of a generator to its load. The derived thermal matching equations result in a specific design of TEGs for autonomous devices, which include radiator, multi-stage commercial thermopiles or a micromachined thermopile on a tall pillar, and at least several millimeters separation in between the plates of the TEG. It is shown that the thermal optimization is valid for any thermopile irrespective of its particular design. The design method is extensively tested in applications on man. In a moderate climate, a power of about ZT/30 mW/cm^2 on average can be reached. This value is a limit imposed by thermal matching conditions and by personal acceptance of the device on a body. The energy scavengers fabricated in 2005-2006, which are thermally matched to the environment, show power generation near the theoretical limit.

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