HEAT GENERATOR IN HUMANS AND ITS INTERACTION WITH WEARABLE THERMOELECTRIC ENERGY SCAVENGER

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Abstract: Thermal properties of human being have been studied in the case if it serves as a natural heat generator for a wearable thermoelectric generator (TEG). The study shows what happens with human body properties on the scale of centimeters in the case of a thermally conductive device located on the body. It is shown in the experiment that the local thermal resistance of human being depends on the heat flow, i.e., on the design of a TEG. The analysis of wearable TEG, in particular, the one with a low-dimensional thermopile inside is then performed.

Keywords: thermopile, thermoelectric generator, wearable device, thermal matching, energy scavenger

INTRODUCTION

The equations for design optimization of wearable TEG differ from those commonly used because of high thermal resistance of the environment. The maximum power, P_{max}, generated by thermally optimized TEG is:

$$P_{max} = Z\Delta T_{tp,\,opt}\,\Delta T/8R_{th,\,env}\,, \quad (1)$$

where Z is the thermoelectric figure-of-merit, $\Delta T_{tp,\,opt}$ is the temperature drop on the thermopile, which corresponds to the power maximum, ΔT is the temperature difference between the heat source (the body core temperature, typically about 37°C) and the heat sink (the ambient), and $R_{th,\,env}$ is the joint thermal resistance of the heat source (human body) and the heat sink. The optimal temperature drop equals to:

$$\Delta T_{tp,\,opt} = \Delta T/(2(1 + R_{th,\,env}/R_{th,\,em}))\,, \quad (2)$$

where $R_{th,\,em}$ is the thermal resistance of the "empty" TEG, which would be observed if the thermal conductivity of thermoelectric materials was equal to the one of air. This optimal temperature drop does not depend on the properties of the thermopile, therefore, the thermal design of both TEG and its interfaces with the heat source and sink are of primary importance. The following equation of thermal matching allows reaching the power maximum in a wearable TEG:

$$R_{TEG,\,opt} = R_{th,\,env}\,R_{th,\,em}/(2R_{th,\,env} + R_{th,\,em})\,, \quad (3)$$

where $R_{TEG,\,opt}$ is the optimal thermal resistance of the TEG. The optimal thermal resistance of the thermopile inside a TEG, $R_{tp,\,opt}$, can be obtained as:

$$R_{tp,\,opt} = R_p\,R_{TEG,\,opt}/(R_p - R_{TEG,\,opt}), \quad (4)$$

where R_p is the parasitic thermal resistance of the TEG observed in parallel to the thermopile.

Among the parameters needed for optimization of the TEG, only one is unknown, namely, the thermal resistance of human being. Its measurement and the analysis of a wearable TEG were carried out and being reported in this work.

HEAT GENERATOR FOR THE TEG

The dependence of the thermal resistance of human body on heat flow has been measured in two locations: in the left wrist, over the radial artery, and on the anterior side of the left leg, about 25 cm above the knee. A circular plate of 3 cm in diameter has been attached to the body by using elastic band. A thermopile has been glued to the plate for measuring the heat flow. On the other side of a thermopile, a metal plate has been glued. The outer plate of the TEG was cooled and the resulting open circuit Seebeck voltage was proportional to the heat flow. A K-type thermocouple has been glued to the other plate of a TEG touching the skin for monitoring the skin temperature. As has been seen in the experiment, the heat flow essentially exceeding natural heat flow caused slow drifting of the temperature of a large part of extremities during one hour, and more. Therefore, to minimize this adverse effect, another experiment has been conducted with halved contact area of the TEG with the body, namely, on 1.6×2.1 cm^2 area. The experiments have been conducted indoors, in the office, at a temperature within the 21.0°C to 23.7°C, with no air conditioning, on a sitting person, in a course of several days. The results are shown in Fig. 1.

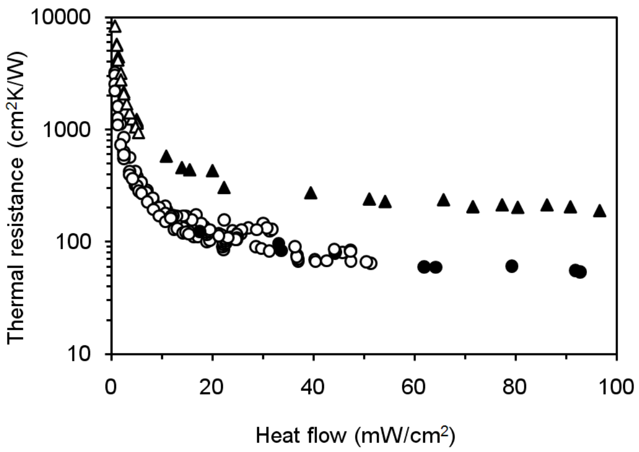

Fig. 1: Dependence of the thermal resistance of the wrist (circles) and leg (triangles) on applied heat flow. The results have been obtained on the area of 7 cm^2 (open data points) and 3.4 cm^2 (closed points).

The two measured locations reflect two very different conditions on the human body. On the leg, a thick layer of muscles results in a much higher thermal resistance than over an artery. The muscles are the dominant natural thermal insulator in the human body. In contrary, arteries are effective heat spreaders and heat exchangers. Therefore, much higher heat flow can be obtained through the TEG located in proximity to an artery. At high heat flows, thermal resistance in both locations stabilizes. It is about 200 cm^2K/W in the leg and about 50 cm^2K/W in the wrist. However, the typical heat flow observed indoors on the human skin is well below 10 mW/cm^2. At such conditions, the thermal resistance of the body is reversely proportional to heat flow, reaches high values and can even exceed the thermal resistance due to ambient air. Therefore, a wearable TEG cannot be optimized unless the true local thermal resistance of human body is used for the device optimization.

In any chosen location, the thermal resistance depends on the heat flow. The heat flow, in turn, changes with the ambient temperature and air speed (some wind, air flow, or the person moves in respect to air). As has been shown recently, a radiator on the outer side of wearable TEG enhances the heat flow. An example of the heat flow through such a TEG and its photo are shown in Fig. 2.

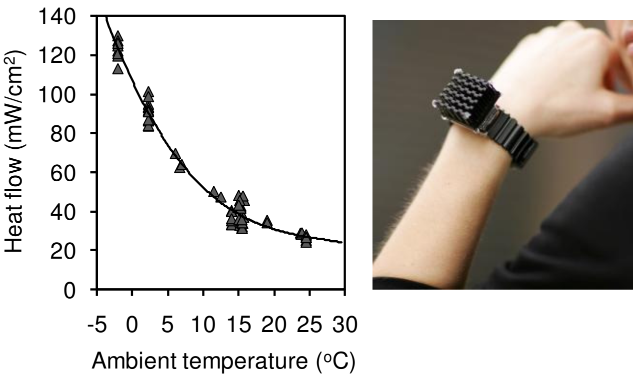

Fig. 2: Dependence of the heat flow in the wrist on ambient temperature measured on a standing or sitting person by using a TEG with a radiator, and its photo.

This TEG has been used for the measurement of body's thermal resistance at different ambient temperatures. As shown in Fig. 3, at low temperatures, it only slightly increases in the wrist, on the radial artery, but essentially decreases in the leg. Not stating that such a big TEG shown in Fig. 2 is impossible as a wearable TEG, the author believes that truly unobtrusive TEG must be thinner, several millimeters thick, and not thicker than a typical watch. However, the heat flow in a thinner TEG decreases. The thermal resistance of human body, in contrary, increases with such a TEG. On the leg, a TEG with a plate on its outer side shows four times lower heat flow in comparison with the TEG shown in Fig. 2. The thermal resistance of the leg in such case increases by a factor of 2. However, such a thin TEG has a much better chance to be accepted.

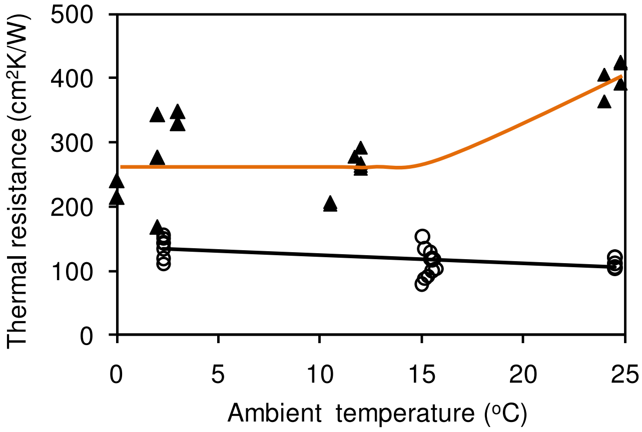

Fig. 3: Dependence of the thermal resistance of the wrist (circles) and leg (triangles) on ambient temperature. The results have been obtained on an area of 5 cm^2 of standing or sitting person.

Among other studied locations for a TEG, the trunk has been found as an appropriate heat source. However, it shows very broad range for the thermal resistance, and the proper particular location must be chosen while designing a wearable TEG. The measurements have shown a four-fold variation of the thermal resistance over the anterior part of the trunk. In Table 1, the lowest thermal resistance recorded on the chest is reported together with the data obtained on other locations.

Table 1: The thermal resistance of human being in different locations at high heat flow enhanced by a radiator of a TEG (Fig. 2).

Location	**Thermal resistance, cm^2K/W**	
	Indoors	**–4 to +2 °C**
Wrist (dorsal)	440 (avg.)	-
Wrist (rad. artery)	110	140
Chest	130 (min.)	140 (min.)
Forehead	160–230	-
Leg (anterior)	400	280

WEARABLE ENERGY SCAVENGER

Wearable TEGs supplied with a radiator cause large heat flow in humans, especially at low ambient temperatures, at forced convection and appropriate clothes worn. As measured at ambient temperatures of –4°C to +3°C, they do not cause sensation of cold at a heat flow of 25 to 130 mW/cm^2, depending on chosen location on the body. Therefore, the TEG shown in Fig. 2 has demonstrated power generation of 1 to 1.4 mW/cm^2 in stabilized conditions at a temperature of –2°C. Indoors, the power produced by a watch-thick TEG typically does not exceed 25 to 30 mW/cm^2. Fig. 4 gives an idea about possible level of conversion efficiency in wearable TEGs. The shown data have been obtained with the TEG located on the radial artery (see Fig. 2) and by using the TEG of an electroencephalography system worn on the head [1].

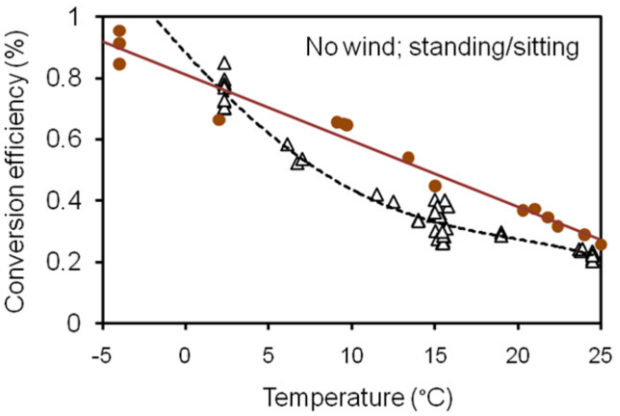

Fig. 4: Dependence of the thermoelectric efficiency of a TEG with a radiator on ambient temperature measured on the wrist (triangles) and head (circles) of a standing or sitting person.

By using the data on the thermal resistance of human being reported in previous Section, the simulation of performance characteristics of a wearable TEG has been performed. The simulation was conducted for a thin TEG shown in Fig. 5a and still air. The device resembles a stack of big coins of 3 cm in diameter. An off-the-shelf thermopile is mounted between two 1-mm-thick Al plates. In the calculations, the thickness of a TEG was varied within the 2.5 to 10 mm. The optimization was performed for each thickness and ambient temperature so as to obtain maximum power. The output voltage is not discussed because there are effective ways to up-convert a voltage of, e.g., 20 mV to the voltage required for a particular application [2]. The device is integrated in a piece of clothing, and its inner volume is filled with air. It is assumed that the heat transfer coefficient on the outer surface of clothed human being is the same as on the device. The subject has a core temperature of 37°C, the thermoelectric figure-of-merit Z is 0.003 K^{-1}, the thermal resistance of supports and encapsulation is 400 K/W per 1 mm distance between the plates, the emission coefficient of the outer surface of the radiator is 90%, and no radiation and convection takes place inside the TEG.

The first simulation was performed at constant thermal resistance of the body of 250 cm^2K/W and ambient temperature of 22°C. It is assumed, that the TEG is located on the human trunk and the average heat transfer coefficient for a vertical plate with a characteristic length of 30 cm is used. The optimal thermal resistance of a thermopile required for reaching the thermal matching condition, the optimal temperature difference on the thermopile, the power, and the power per unit volume of the TEG are shown in Figs. 5b, 5c. Despite the fact that the power generated by the TEG thicker than 5 mm increases, the power per unit volume of such TEG decreases. It maximizes at a thickness of about 4 to 6 mm, which is important for minimization of the TEG volume and weight.

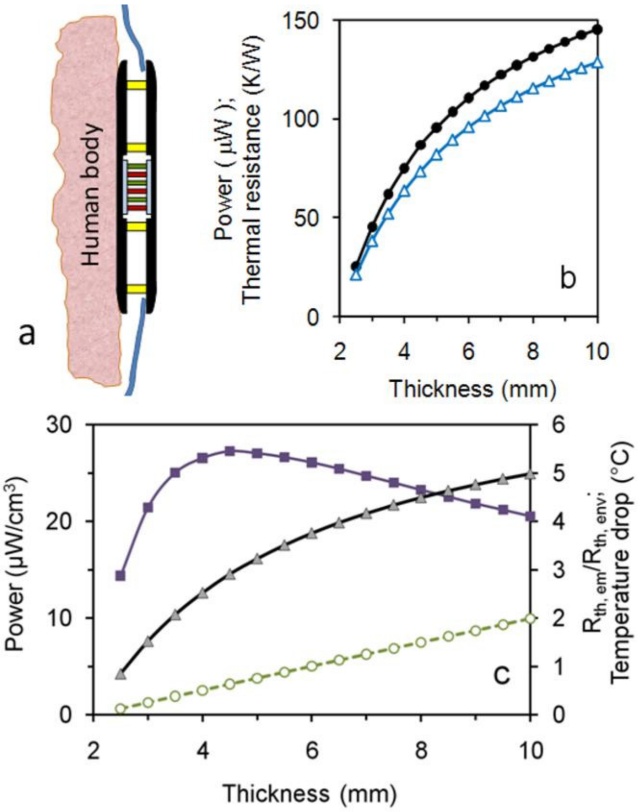

Fig. 5: (a) Design of the simulated TEG on the body, (b) Simulated dependence of the maximum power (circles) and optimal thermal resistance of the thermopile (triangles), and (c) Simulated dependence of the optimal temperature drop on the thermopile *(triangles), the ratio of thermal resistances of "empty"* TEG to the environment (circles), and the power per unit volume (squares) on thickness of the TEG.

It has to be mentioned that at $R_{th, em}/R_{th, env} < 1$, which happens at a thickness of a TEG of less than 6 mm, even a half of theoretical power cannot be reached.

Based on the results shown in Fig. 5c, the second simulation has been performed, where the thickness of a TEG has been fixed at 3, 4, and 6 mm. For the calculation of heat transfer coefficient, it is assumed, that 30 cm of the human body is located below the TEG. The thermal matching of the TEG, Eq. (3), has been performed at still air and ambient temperature of 20°C, i.e., for typical indoor conditions. The results of simulation of a TEG on the human leg are shown in Fig. 6. The thermal resistance of a thermopile required to reach the maximum of power at 20°C changes from about 38 K/W to 96 K/W if the thickness of a TEG increases from 3 mm to 6 mm. The power increases together with the TEG thickness, from 1.6 $\mu W/cm^2$ to 4 $\mu W/cm^2$ at a temperature of 25°C, and from 3.5 $\mu W/cm^2$ to 8.7 $\mu W/cm^2$ at a temperature of 20°C. Therefore, if the TEG thickness decreases by a factor of two, from 6 mm to 3 mm, the area and volume to produce the same power increase by a factor of 2.5.

At 0°C, the conversion efficiency increases to 0.2% in a 3-mm-thick TEG, and to 0.5% at a thickness of 6 mm. The heat flow increases either. As a result, at

0°C, the power increases by a factor of about 5.7 and reaches 0.34 mW in a 6-mm-thick TEG, or up to about 50 µW/cm^2, and to 80 µW/cm^3. The wind or forced air convection (e.g., in case of a walking person) further improves power generation.

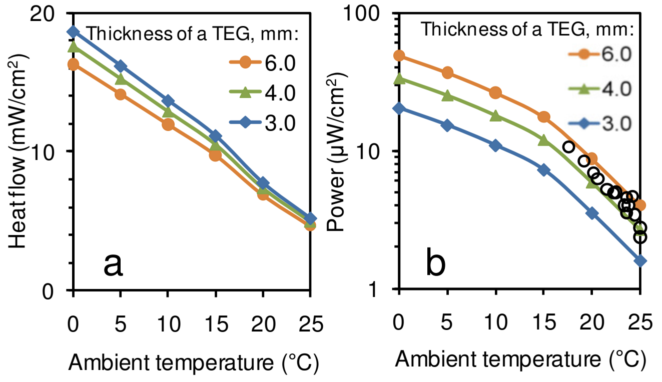

Fig. 6: Simulated dependence of (a) heat flow in the TEG of different thickness, and (b) power on temperature. Open circles show the average power measured in the 6.5 mm-thick TEG of an ECG shirt [3].

Even at the worst modeled conditions, i.e., at 25°C and on a resting person, the modeled TEG of 3 cm in diameter should generate 11 and 28 µW at a thickness of 3 and 6 mm, respectively. Such a power is enough for a simple wireless sensor node. However, the cost of a thermopile on the market essentially exceeds the cost of a battery. Therefore, the third simulation was performed, where a small-size or micromachined thermopile was placed in the same TEG, Fig. 7a, 7b. The height of thermocouples in this simulation varied from 2 mm (an off-the-shelf thermopile) to 10 µm (a hypothetic surface micromachined thermopile), while maintaining a 25% fill-factor on a die. In case of a miniaturized thermopile, the contact resistance between its legs and interconnecting metal layer starts to adversely affect the power. Therefore, a contact resistance of less than 100 Ω µm^2 or enlargement of electrical contacts is needed to prevent some decrease of power shown in Fig. 7c. For example, at a contact resistance of 10 Ω µm^2, the smallest thermopile should produce 74% of the power available by using an off-the-shelf thermopile. However, its cost could be decreased thereby opening the door to the market.

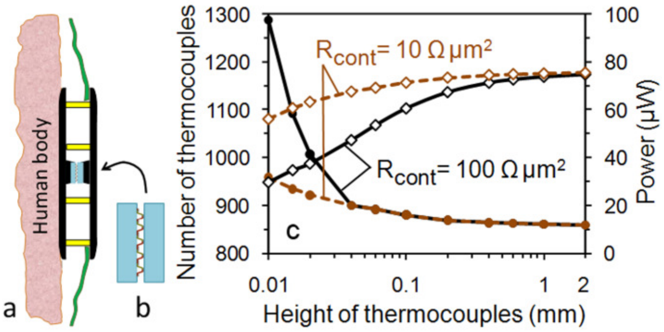

Fig. 7: Simulated (a) TEG with (b) a thermopile, and (c) The dependence of number of thermocouples (circles) needed to reach 0.5 V on the matched load and maximum power at different contact resistance.

CONCLUSION

The theory of thermal matching as an extension of general thermoelectric theory is discussed in this work in application to thermoelectric energy scavengers. In the theory, the harvester is treated as a thermal load of the environment. The analysis is followed by the conclusion that thermal optimization of such a device does not depend on thermal properties of a thermopile and thermoelectric material. In contrary, the thermal resistance of the heat source (the human being, in case of a wearable TEG) is important for harvester optimization. The experiment shows that the former depends on heat flow, i.e., on the design of a TEG.

The maximum power measured in a TEG with a radiator is 1.4 mW/cm^2 at ambient temperature of –2°C. In unobtrusive thermally optimized TEG, i.e., in a thin one, the heat flow at typical indoor conditions (Fig. 6a) does not exceed 10 mW/cm^2. The experiment shows that the thermal resistance of human being increases at such a low heat flow (Fig. 1) and must be accounted for the TEG and thermopile optimization.

The thermal resistance of human being measured at different ambient temperatures in different locations on the body has enabled evaluation of the general theoretical limits of power generation on humans. The simulation of a wearable TEG has been performed at different ambient temperatures assuming a ZT of 0.9, i.e., at the state-of-the-art figure-of-merit.

The results of simulations of performance characteristics of miniaturized and micromachined thermopiles in a wearable TEG are presented either. The results confirm that the thermocouple size in a wearable TEG can be effectively reduced to micrometers with minimal loss in produced power, and with significant improvement in output voltage. It is shown that a micromachined thermopile in a wearable device must show a contact resistance not exceeding 100 Ω µm^2. Based on the results of simulations, it is expected that cost-effective MEMS thermopiles may become in the future a strong competitor to a battery as a power supply for wearable low-power electronics.

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