Thermoelectric Energy Harvesting of Human Body Heat for Wearable Sensors

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***Abstract*— The study of thermoelectric energy harvesting on people presented in this paper shows that although power generation is affected by many factors such as ambient temperature, wind speed, clothing thermal insulation, and a person's activity, it does not directly depend on metabolic rate as shown in the experiment. The relevant thermal properties of humans measured at different ambient conditions are reported. Several thermopiles are either attached with a strap directly to the skin or integrated into garments in different locations on human body, and power generation is extensively studied at different ambient conditions. Textile covering thermopiles is found not to essentially decrease power generation. Therefore, a hidden energy harvester is integrated into an office-style shirt and tested on people in real life. It generated power in 5–0.5 mW range at ambient temperatures of 15 °C–27 °C, respectively. The thermoelectric shirt with such an energy harvester produces more energy during nine months of use (if worn 10 h/day) than the energy stored in alkaline batteries of the same thickness and weight.**

***Index Terms*— Human body, thermoelectric, thermopile, wearable device.**

I. Introduction

Wireless sensors for preventive healthcare, monitoring chronic deceases and vital body signs are candidates for integration into clothing in the near future. They must be tiny, unobtrusive, completely hidden, reliable, and should function for the entire service life of a piece of garment with neither technical service nor battery replacement or recharging. As has already been reported, a thermoelectric energy harvester (TEH) of human body heat is a strong competitor to the battery in such applications [1], [2].

Energy harvesters integrated into wearable devices enable powering wireless sensor applications under condition that low power radio and electronics are used [1]–[3]. Careful designing of both low-power electronic modules and efficient energy harvester is the key to fully autonomous wearable systems. This paper reports latest experimental results on thermal properties of the human being under attached TEH. These are required for correct designing of the latter so as to reach maximum power. The target is not reaching maximum efficiency. The latter maximizes at very low power and is limited by parasitic heat transfer inside a TEH, i.e., by the heat flow bypassing the thermoelectric material.

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The research has allowed designing wearable thermoelectric modules with near-maximum possible efficiency. They were integrated in different ways into garments or just attached to a person and their performance characteristics were extensively studied in different ambient conditions. Finally, a completely hidden TEH has been fabricated and extensively studied in this paper.

II. Maximum Power of TEH

The maximum power produced by a thermopile on electrically matched load is, as known

$$P_{\max} = Z\Delta T^2/4R_{\text{tp}} \quad (1)$$

where $P_{\max}$ is the maximum power on electrically matched load, Z is thermoelectric figure of merit, $Z = S^2\sigma/k$, S is Seebeck coefficient, σ and k are electrical and thermal conductivities, respectively, ΔT is the temperature drop on the thermopile, and R_{tp} is its effective thermal resistance at maximum power. If ΔT was independent of R_{tp}, minimization of the latter would be beneficial. However, the heat flow through a thermopile, W, is equal to $\Delta T/R_{\text{tp}}$, and (1) is actually identical to

$$P_{\max} = ZW^2R_{\text{tp}}/4. \quad (2)$$

Material research is ongoing worldwide on increasing the factor Z [4]. However, one must take into account that R_{tp} is a nonlinear function of Z. Increase of the latter results in partial decrease of the former. This is because of Peltier effect that increases the effective thermal conductivity of thermoelectric material. The state-of-the-art factor Z reaches about $0.003\,\text{K}^{-1}$ in both p- and n-doped thermoelectric materials at room temperature [4]. At such a Z, the effective thermal resistance of a thermopile located on human skin decreases at maximum power by 32% compared to the open-circuit case. In production, thermoelectric modules show slightly lower Z because σ in case of a module refers to effective conductivity that account for finite metal-semiconductor contact resistance and resistance of metal interconnects between semiconducting legs of a thermopile.

At chosen Z, maximization of power according to (1) or (2) means reaching the maximum of $W\Delta T$ product. Both variables, W and ΔT, depend on thermal properties of the environment, namely, on thermal resistance of heat source and heat sink. This is because the heat is typically not generated at hot thermopile junctions and there is also a substantial temperature difference between its cold junctions and the ambient.

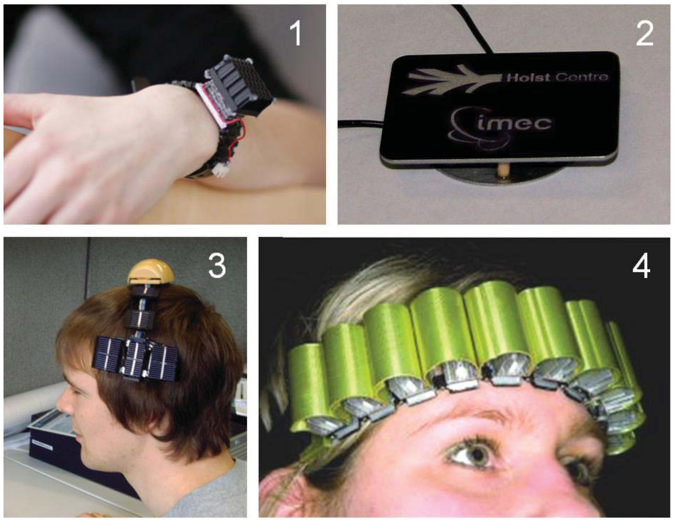
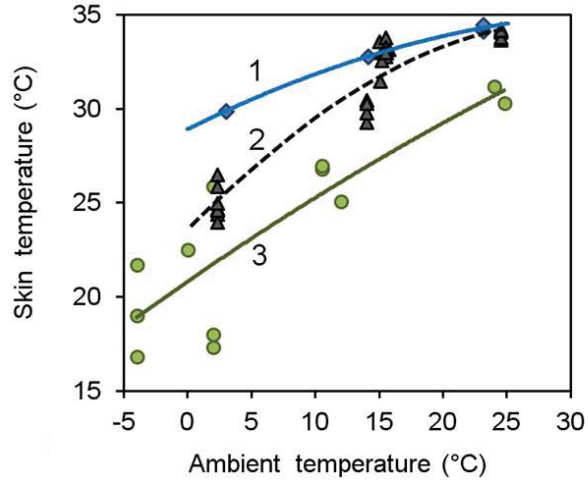


Fig. 1. Wearable TEHs used in this paper for measurements of thermal properties of humans and power generation on people at different ambient conditions. (1) TEH with a $3 \times 3 \times 1.5$ cm radiator. (2) 6.5-mm-thin TEH with a thermopile between two plates; it is similar to the TEH modules used in an electrocardiography shirt [1], [2]. (3) and (4) TEHs recently used in two self-powered electroencephalography systems [1], [6].



(a)

(b)

Fig. 2. (a) Dependence of skin temperature under a TEH #1 shown in Fig. 1 on ambient temperature in different locations. (1) In the middle of chest. (2) On the wrist, over the radial artery. (3) On the anterior leg, about 25 cm above the knee, i.e., far from arteries. The TEH increases heat flow above natural one because of large radiator and therefore locally decreases skin temperature under the hot plate. Lines: polinomial fits. Clothing: weather conditions, e.g., (b) gloves are worn at low ambient temperature for keeping hands warm.

In case of very small or very large thermal resistance R_{tp}, either ΔT or W approaches zero, respectively. Therefore, in both cases, the generated power P approaches zero, too. The power reaches maximum when the product of heat flow by temperature drop maximizes. From the thermal impedance matching theory [5], a wearable thermopile must have high thermal impedance of the order of those observed in the ambient air and human being. For a TEH optimization, knowledge of those thermal impedances is required. As the former is well-known, the experimental study in this paper was concentrated at measurement of heat flows, skin temperature and thermal resistance of humans at different ambient conditions and in different locations on a person.

III. Relevant Thermal Properties of Humans for Designing Wearable TEHs

Several TEHs have been fabricated and used in this paper for experimental study of power production on humans, Fig. 1. The thermopiles (from Thermix, Kiev, Ukraine) typically had a footprint of less than 1 cm^2 per thermopile, however, they were usually provided with a much larger "hot" plate (the one touching the skin) for decreasing the thermal resistance of human body (devices 2 to 4, Fig. 1). For decreasing the thermal resistance of ambient air, a "cold" plate or a radiator was always attached to the cold side of thermopiles.

A thermopile with known thermal resistance is a good tool for heat flow measurements. It is obtained using open-circuit voltage, V_{open}, as $W = V_{\text{open}}/(2SnR_0)$, where n is the number of thermocouples, and R_0 is R_{tp} at open circuit. Therefore, the TEHs were also used in the study for this purpose. The skin temperature was measured with a thermocouple located between the TEH and skin. The tympanic temperature was measured with infrared ear thermometer. Fig. 2 illustrates dependence of skin temperature of a person on ambient temperature in three different locations. At ambient temperature of 25 °C, the skin temperature closely approaches body core temperature of 36.8 °C (in this experiment). Typically, the chest, head and warmest zone of the wrist (close to the radial artery) approach it first on the person in the office. Therefore, these body parts are good for energy harvesting. The chest is however more sensitive to local cooling in cold weather, and for comfort of the person, heat flow must be substantially limited. Therefore, in the experiment at low ambient temperatures, maximum power was obtained in a TEH worn on the wrist despite lower skin temperature [7].

The human skin has nonuniform temperature over the body. This nonuniformity increases at low ambient temperatures. Therefore, the temperature difference between the body core and skin depends on chosen location on the body and ambient temperature. This means the thermal resistance of heat path in the body from its core to the skin may depend on location of TEH, clothes (they increase the skin temperature) and wind speed. It also must depend on air temperature. To prove this guess, the skin temperature was measured with a thermistor in the middle of forehead of clothed person at ambient temperatures of 16 °C to 33.5 °C in still air. Such variation of temperature was expected to significantly change the thermal

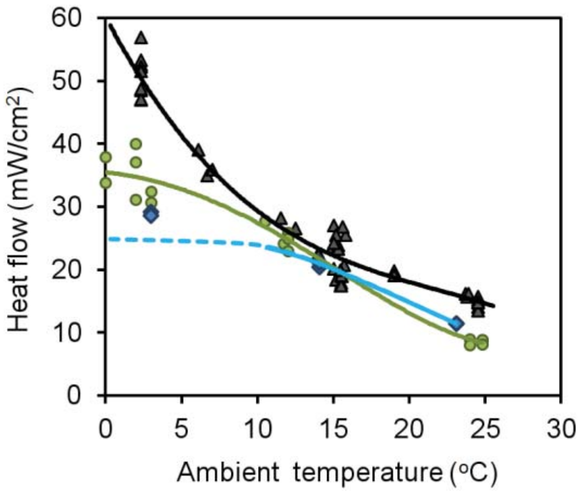


Fig. 3. Dependence of heat flow through the TEH #1 on temperature in three locations measured on the standing or sitting person. Triangles: over the radial artery in the wrist. Circles: on the anterior leg about 25 cm above the knee. Diamonds: in the middle of the chest.

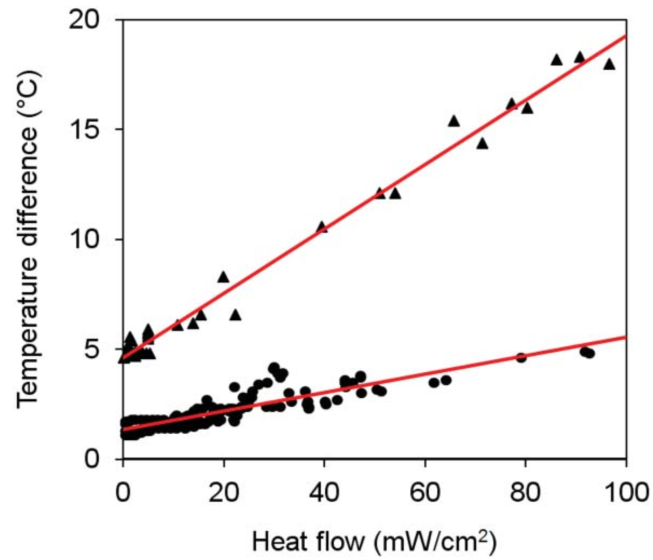


Fig. 4. Dependence of core-to-skin temperature difference on heat flow measured using TEH #2 in two locations of sitting person. Circles: over the radial artery in the wrist. Triangles: on the anterior leg. Lines: linear fits.

resistance of extremities due to vasomotor response, but not to affect the thermal resistance in trunk, neck (near arteries) and head. The experiment was conducted on a person resting in a chair. It has shown that a human being demonstrates variable core-to-skin thermal insulation depending on ambient temperature even in locations proximal to body core organs like brain, see [8] for details.

The experiment also confirms dependence of body thermal resistance on chosen location on the body. As shown in Fig. 2, the skin temperature varies at fixed ambient temperature depending on location of the TEH. The dependence of heat flow on ambient temperature measured in the same locations as in Fig. 2 using the same TEH #1 is shown in Fig. 3. Within the 10 °C to 15 °C range, the heat flow enhanced by the radiator was very similar in all three locations. However, the radial artery seems to be the best choice because beyond this temperature range the heat flow is highest among the studied locations. Solid lines in Fig. 3 are polynomial fits. Almost all experimental points correspond to sensation of comfort. There was however two experimental points (on the chest, diamonds, at a temperature of 3 °C), where the person reported sensation of cold. Therefore, the maximum heat flow on the chest should not reach the measured value. The dashed part of the fitting curve shows approximate expectation for the maximum heat flow. As one can see, the chest that is always warm due to clothes shows the minimum acceptable heat flow. Using the temperature difference between the body core (typically 37 °C) and skin temperature, Fig. 2, one may obtain the dependence of thermal resistance for a human being on ambient temperature in the chosen location. The typical thermal resistances observed in several locations were reported in [7], [9], [10]. It is worth mentioning that the maximum heat flow observed through a TEH on the wrist, Fig. 3, coincides with the lowest thermal resistance of human body. A thermal resistance of about 110 cm^{2}K/W has been measured in this location with TEH #1 at room temperature. At zero degrees Celsius, on the same person wearing appropriate cloth ensemble (Fig. 2b) it increased a little to 140 cm^{2}K/W.

There is also a dependence of body thermal resistance on heat flow at fixed both ambient temperature and location of the TEH. In the experiment performed on a sitting person at temperatures within the 21 °C to 23.7 °C range, the TEH #2 was attached to the anterior leg, about 25 cm above the knee, using an elastic band. The radiator was cooled to different extent and the open-circuit voltage generated by TEH was recorded after temperature stabilization. Simultaneously, the skin temperature was measured using a thermocouple glued to the hot plate and located between the skin and the TEH. Then, the TEH was relocated to the inner side of the wrist and positioned over the radial artery, Fig. 2b, and the experiment was repeated. Periodically, the ambient temperature was measured. The tympanic and oral temperatures were measured with infrared thermometer and found very stable (36.9 ± 0.1 °C) during the experiment that took a few days. The results are shown in Fig. 4. The experiment shows linear dependence of temperature difference between the body core and hot plate on heat flow through a TEH.

The slope of dependences, i.e., $\mathrm{d}T/\mathrm{d}W$, is the thermal resistance of the studied material, namely, the human tissue *in vivo*. The fitting lines in Fig. 4 give a thermal resistance of 147 cm^{2}K/W on the leg and 42 cm^{2}K/W on the radial artery. In principle, these values enable TEH modeling and design optimization. However, there is a general problem. At zero heat flow, a difference of a few degrees Celsius is observed between the core and skin temperatures. As seen in Fig. 4, this offset varies depending on TEH location. It must also vary with wind speed (or a speed of person movement in respect to still air), metabolic rate and the shape of radiator. It is believed that the offset is related to the facts that: 1) the radiator of TEH is immersed in a heated body-induced convection layer, but TEH has high thermal resistance, therefore, the cold plate/radiator temperature may approach the temperature of convection layer, 2) even at zero heat flow on open skin, there

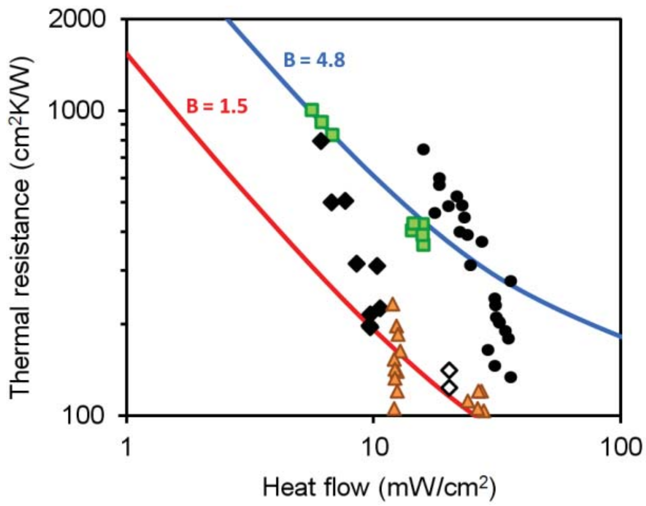


Fig. 5. Dependence of thermal resistance of human body defined by (3) on heat flow. Lines: experimental results obtained using the data of Fig. 4 at different factor B (1.5 K for the radial artery and 4.8 K for the leg). Experimental points have been measured using four different TEHs in following locations. Triangles: over the radial artery in the wrist. Squares: on the anterior leg. Diamonds: in trunk and arm. Open diamonds: with the lowest thermal resistance registered in the middle of the chest. Circles: on the outer side of the wrist where a watch is typically worn.

is heat transfer through sweat vaporization, and 3) only a part of heat dissipated through the TEH is produced in the body core, so there is no strong thermal link to the core in extremities, especially during exercise.

The offset complicates the design optimization of a TEH. Indeed, changing the shape of a TEH or a radiator during optimization affects the offset. Therefore, it was proposed in [11] to use a parameter called thermal resistance of human body, R_h. It accounts for a nice reference point, namely, the near-constant core temperature in a healthy subject, as

$$R_h = (T_{\text{core}} - T_{\text{skin}})/W. \tag{3}$$

This approach simplifies the thermal circuit of a wearable TEH [12] by giving a 'ground' point fixed at 37 °C. The experimental data on R_h have been reported in [7], [9]–[11], [13]. Examples of TEH modeling using R_h can be found in, e.g., [5], [13], [14].

Under chosen ambient conditions, the maximum power of wearable TEH can be reached in locations with low body thermal resistance, such as a forehead or an artery passing close to the skin, e.g., in the neck or wrist. The data presented in Fig. 4 are recalculated to the thermal resistance and plotted as two curves in Fig. 5. These curves mark the area for thermal resistance of human being to be used in typical indoor conditions. They can be described by the equation

$$R_h = B(1/W + 28)[\text{cm}^2\text{K/W}] \tag{4}$$

where the factor B is 4.8 K for the top curve (on the leg) and 1.5 K for the bottom curve (the radial artery), and W is heat flow in W/cm^2. These two curves reflect very different conditions on the human body: on the radial artery, the lowest thermal resistance is observed, so the maximum power can be obtained in a TEH, while the measurement point on the leg is located in the zone of thickest muscles and far away from the artery, so the thermal resistance is very high and the power is near its minimum. In the distal area of extremities the situation can be worse, but the designer of TEH will certainly not place it there. Therefore, it is believed at this stage of the research that in case of wearable TEH, B should be always within the 1.5 to 4.8 K range. (This statement refers to average values with possible deviation of R_h by a factor of two for any particular experimental point). As example of realistic ranges for the thermal resistance of the body and heat flow, the experimental data are plotted in Fig. 5 as experimental points. These data have been obtained using TEHs #1 and #2, Fig. 1, at ambient temperatures within the 23 °C to 24.8 °C range in different locations on the body. Some other TEHs, with larger radiators, namely, $16 \times 36 \times 38$ mm and $33 \times 45 \times 50$ mm were also used within the 19.7 °C to 22.5 °C range (circles in Fig. 5). (These large-size TEHs frequently caused complaints of users stating that the device induced sensation of cold. Nowadays, they are no longer used in our research).

Despite certain scattering of experimental points obtained in every location, Fig. 5 confirms that (4) is valid for using it for the design optimization of a TEH. For a general optimization of a TEH irrespective of its possible location on the human body, it is recommended using (4) with $B \approx 3$ K. However, such an optimized TEH could show up to a few-fold deviation of power from the calculated value depending on its location. Therefore, the TEH designing must preferably be performed for the specified location on the human being.

IV. Demonstration of Maximum Power of Wearable TEH

The key factor for reaching power maximum in a TEH is its thermal impedance matching to the thermal impedance of the environment [5], which is the electro-thermal equivalent of electrical matching of the load and generator impedances. In the simplest form, the thermal circuit of a TEH and equations for its design optimization were presented, e.g., in [15]. At the thermal impedance matching point, the maximum power generated by wearable TEH on electrically matched load is

$$P_{\max} = Z(T_{\text{core}} - T_{\text{air}})^2/[16(1 - N^{-1})(R_h + R_{\text{air}})] \tag{5}$$

where T_{air} and R_{air} are the temperature and thermal resistance of ambient air, and N is a dimensionless thermal insulation factor, defined in [16] as

$$N = R_{\text{empty}}/(R_h + R_{\text{air}}) \tag{6}$$

where R_{empty} is the thermal resistance of the TEH embodiment, which would be observed upon removal of thermoelectric material from TEH, so-called "empty" TEH. This is a design-related parameter: the higher N, the lower is adverse effect of parasitic heat flow in the TEH on power. Thus, both a thick TEH (high R_{empty}) and a TEH occupying large area (low both R_h and R_{air}) are preferable for reaching maximum power.

Although such a TEH may reach unacceptable form factor, it reaches peak power. For the experiment in this paper, the TEH #1 with a size of $3 \times 3 \times 3$ cm was fabricated for

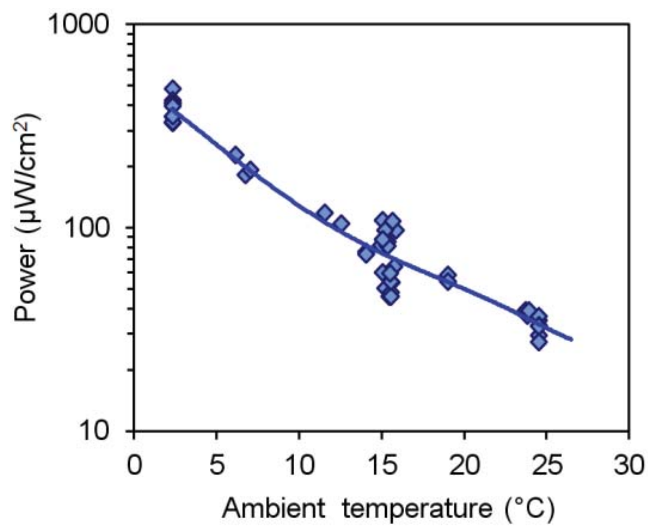


Fig. 6. Dependence of power generated by TEH #1 on ambient temperature. Power is shown per unit footprint area of the radiator on electrically matched load. Device was located over the radial artery in the wrist as shown in Fig. 2(b). Results are obtained on a sitting or standing person. Line: polynomial fit.

practical demonstration of maximum power in a wearable TEH. It was placed on the radial artery as shown in Fig. 2b. The results are shown in Fig. 6.

It is believed that the data shown in Fig. 6 reflect the near-maximum power per unit footprint area of TEH, which can be obtained on a standing or sitting person in thermal comfort with no wind, no direct sunlight. The maximum power is about 60 μW/cm^2 indoors and about 600 μW/cm^2 at a temperature of 0 °C. These values were calculated per unit area of the radiator (9 cm^2). The hot plate area was however smaller (5 cm^2) than the footprint of radiator. Therefore, the measured maximum power corresponds to about 100 μW per cm^2 of skin indoors and over 1 mW/cm^2 at ambient temperature of 0 °C. These are estimates for the maximum power of a TEH, which can be obtained unobtrusively (with no sensation of cold) on average on a sitting or standing person with a thermoelectric material showing a Z of 0.0025 K^{-1}. In practical applications, the produced power may essentially fluctuate around these average values and at any particular moment deviate from the average by a factor of 2 to 3, in typical situations.

From the experiments reported above, the head, trunk and zones proximal to arteries are the best locations for demonstration of maximum power in a wearable TEH. It has to be mentioned that the heat flow on skin changes its direction at ambient temperature of 36–37 °C. This temperature corresponds to minimum power generation [17]. In real life, the average power of a TEH does not decrease to zero; it just shows its minimum [18]. At higher ambient temperatures, power increases again.

From (5), (6), the power depends on a form factor of a TEH. Therefore, for comparison of power generated by different devices, one may use power produced per unit volume of TEH. Comparison of devices on power per unit area occupied on the skin is not correct because the factor N varies within the large range. In Fig. 7, the power produced by different

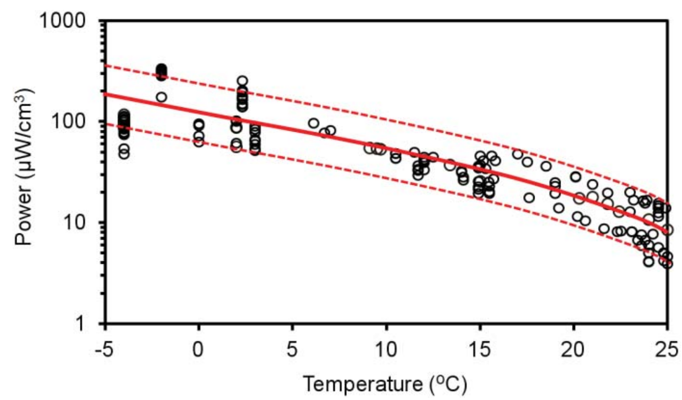


Fig. 7. Dependence of power of four different TEHs shown in Fig. 1 per unit volume on ambient temperature measured on sitting, standing, and walking people. TEHs were worn in different locations on the body. Lines: guides for eyes. Solid line: average power. Dashed lines: deviation from the average by a factor of two. The air between radiator and skin is also accounted for the volume.

devices in practical applications is shown versus ambient temperature. The data have been obtained using four devices shown in Fig. 1 in different locations on the body (forehead, on hear, wrist, trunk, legs), at different typical activities (sitting, standing, working in the office, walking indoors/outdoors) and at different ambient conditions (in wind or still air, at different temperatures). Some data points refer to average power production in 14 TEHs #2 integrated into a shirt [2]. The volume of a TEH used for calculations was equal to its thickness multiplied by the area of cold plate or the radiator. Fig. 7 shows that despite very different size and shape of TEHs, they can successfully be compared to each other using power per unit volume of the device.

Further increase of power in a wearable TEH can only be obtained through improvement of material quality, i.e., through increasing the factor Z, see (5). However, the author does not expect to witness rapid progress in this area.

V. Integration of a TEH in Clothing

Four ways of integration of TEH #2 into clothes have been investigated, Fig. 8. The TEH had a round hot plate of 3 cm in diameter, a 5 mm-thick two-stage thermopile with 256 BiTe thermocouples from Thermix (Kiev, Ukraine), and a cold plate with dimensions of $40 \times 30 \times 1$ mm. The thickness of TEH was 6.5 mm. The thermopile with a footprint of 8×9 mm showed a thermal resistance of 76 K/W. This is much less than required for reaching optimal thermal impedance matching with the environment [5]. Therefore, the latter, i.e., $R_h + R_{\text{air}}$, was decreased by using large interfaces, namely, hot and cold plates. The thermopile was encapsulated using 0.2 mm-thick polyethylene. For shock protection of the thermopile, four thermally insulating pillars of 1 mm in diameter were placed between the plates of TEH, Fig. 8a.

In the first way of integration of such a TEH, the hot plate was placed in direct contact with skin under a textile, while the cold plate was at about 4 mm from the cotton layer, Fig. 8a. Although the cold plate works in the most efficient way in this scheme (both sides of it participate in heat exchange with ambient air), appearance of metal plates in a piece of clothing seems not the most attractive solution on the market.

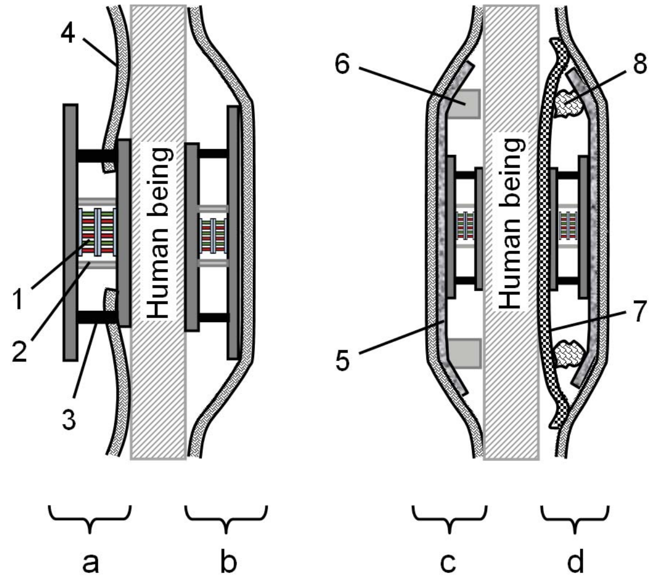


Fig. 8. (a)–(d) Four ways to integrate TEH #2 in garments (not in scale). Numbers denote: (1) thermopile, (2) polyethylene encapsulation, (3) thermally insulating spacers, (4) textile, (5) a carbon fabric heat-spreading layer, (6) neoprene foam spacers, (7) an additional textile layer, and (8) cotton-based spacers. (a) TEH passes through the hole made in textile. (b) TEH is placed under the textile layer. (c) Heat-spreading layer is glued to the cold plate and to the cotton, while foam spacers enable keeping some distance between the heat-spreading layer and skin. (d) Additional layer of cotton is glued to the TEH and sewed inside of clothing.

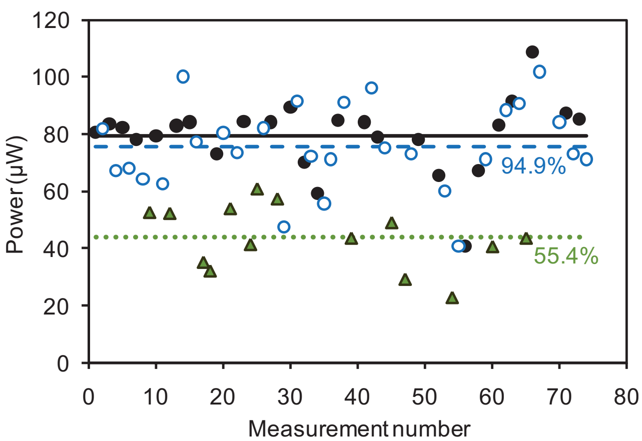


Fig. 9. Power generated by TEH #2 in the office depending on the way of its integration in a shirt. Compared with TEH open to ambient air [(closed circles; correspond to Fig. 8(a)], the power only slightly decreases if the TEH is placed under cotton [(open circles; correspond to Fig. 8(b)], but decreases to a half of it if air gap is observed between the cotton and cold plate (triangles). Lines: corresponding average levels.

Therefore, in the second way of integration, the TEH was just placed between the cotton of an office-style shirt and skin. A weak elastic band held the device on the chest at about 10–12 cm below the chin. Then, comparative measurements were conducted in the office at three positions of cotton: 1) tight to the cold plate, Fig. 8b, 2) cotton pulled from TEH to make about 5–10 mm air gap between the cold plate and cotton, and 3) the cotton was pulled to left and right a little leaving the TEH completely open, similar to the case shown in Fig. 8a. The results on power generation are shown in Fig. 9.

Fig. 10. Four of eight thermopiles assembled on additional piece of textile. Two such pieces of textile were sewed from the inner side of the shirt.

The results shown in Fig. 9 give almost the same average power (about 95%) in case 1) compared to case 3). The air gap between the TEH and cotton, case 2), results in the worst power generation, only about a half of power compared to cases 1) and 3). Therefore, hiding a TEH under textile is feasible at negligible loss of power if cotton is in contact with cold plate. Cotton acts as the radiator of TEH.

To make a large-area cotton radiator, a piece of carbon fabric was glued inside a T-shirt to cotton, and the cold plate of TEH was glued to carbon fabric, Fig. 8c. Simultaneous comparative measurements of two TEH units, Figs. 8b and 8c, has shown a 30% increase of power due to heat-spreading layer made of carbon fabric. For fabrication of a shirt with such TEH units, an additional textile layer was added to the design, Fig. 8d. It slightly decreases power due to its thermal resistance, but makes the TEH completely hidden between two cotton layers and comfortable to the user.

Targeting at comparing the power of the shirt with hidden TEH to a similar thermoelectric shirt with metal plates, Fig. 8a, reported in [2], sixteen thermopiles have been integrated on the front side of a shirt. Their hot plates have been glued to a piece of cotton, and after wiring, Fig. 10, they were assembled as shown in Fig. 8d. Two pieces of carbon fabric of 375 cm^2 each have been used on the left and right sides of the shirt. The shirt is shown in Fig. 11. Unlike in earlier developed thermoelectric shirt [2], there are no elastic bands in the shirt. The thickness of thermopiles used in the newly developed shirt was decreased to 3.5 mm (equal to the thickness of buttons) at the same other characteristics as of two-stage thermopiles discussed above. The decreased thickness increases parasitic heat flow in the TEH, but improves its acceptance by the user.

VI. Performance Characteristics of the Thermoelectric Shirt

The characterization of the TEH was conducted on people working in the office or walking indoors, and also during outdoor activities. At ambient temperatures below 18 °C, the person was standing or walking outdoors for short time, about 10 min maximum. Therefore, low ambient temperatures did not affect the overall body heat content and thermal comfort. The measurements show the hidden TEH with 16 thermopiles

Fig. 11. Shirt with hidden integrated TEH.

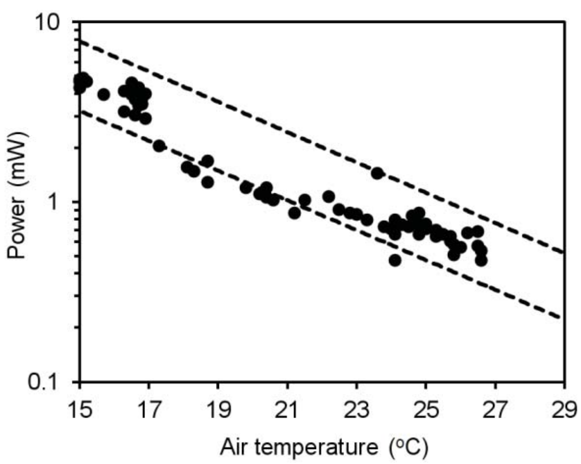


Fig. 12. Power generated by the TEH hidden in a shirt at different ambient temperatures and activities (points). For comparison, two dashed lines illustrate power in a TEH of electroencephalography shirt with metal plates located beyond the external surface of a shirt [2]: on a walking person (top) and standing/sitting person (bottom).

and no elastic bands produces approximately the same power (see experimental points in Fig. 12) as 14 units of TEH #2 with elastic bands and external cold plates reported earlier [2] (lines in Fig. 12). An average power of 1 mW (at 1.2 V on the matched electrical load) observed in the office at 22 °C doubles if the person walks in a corridor. The effect is caused by forced air convection, but not related to increased metabolic rate in a walking person. The power also doubles at ambient temperature of 17 °C, i.e., it increases to 2 mW on a standing or sitting person, and to 4 mW on a walking person, Fig. 12. This thermoelectric shirt seems to be the most comfortable device among the wearable TEHs developed to the moment. Of course, the power might have been slightly higher if the thermopiles were always pushed to the skin. The additional cotton layer located between the skin and hot plate also adversely affects the power, but it affords better comfort, especially in case of sweating.

The shirt is not slim and the thermopiles are not always well attached to the skin all the time. Nevertheless, despite

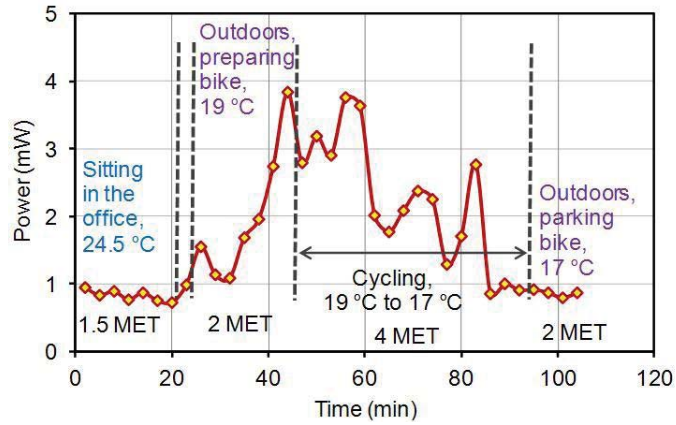


Fig. 13. Power generation during cycling at a metabolic rate of four METs. Shown is the power generated by the thermoelectric shirt with hidden integrated TEH. The energy expenditure is shown in units of a basal metabolic rate (MET).

periodic disconnection of some of units from the skin and the related power loss, the power is very close to the case where elastic bands push them to the skin [2].

For demonstration of power at increased metabolic rate, a one-hour outdoor experiment was performed during exercise. Cycling was chosen for this experiment as a typical example of an exercise. The maximum power was reached on a standing person before the exercise. During the cycling, the power gradually decreased and finally reached the level observed in the office, Fig. 13. One may also draw attention to the fact that during last minutes of cycling at 4 MET, the power was the same as afterwards, on a standing person, and also the same as the one observed in the office before cycling (1.5 MET).

Another experiment performed in this paper on a cyclist wearing a TEH on the wrist was reported in [8]. These experimental results confirm our earlier observations that, in typical situations, the power generated by wearable thermopiles does not depend on metabolic rate, but on overall body heat content and air speed in respect to the person, especially, on the latter. It also depends on sweating rate. In the beginning of exercise, the power increases for a while because of forced air convection. The same increase was observed on the standing cyclist (35 to 45 min in Fig. 13), where the power rose because of wind. Then, it dramatically decreased because of exercise-induced sweating. This power drop is explained by decrease of skin temperature due to extensive sweat vaporization. Therefore, the statements made in some papers on energy harvesting concerning dramatic power rise proportionally to metabolic rate were incorrect. Indeed, at fixed skin and ambient temperatures, any metabolic rate results in the same heat flow (but the rate of sweating is variable). Sometimes, a certain rise of heat flow during exercise is only observed in extremities due to vasodilatation if hands were relatively cold before the exercise.

VII. Conclusion

The experimental maxima of power in a wearable TEH with a Z of $0.0025\,\mathrm{K}^{-1}$ have been demonstrated, Figs. 6 and 7. At any studied ambient conditions, no sensation of thermal discomfort was reported. The TEH in the shirt does not require any modifications to existing garments: it is just glued and sewed to the shirt purchased in a shop. The device is comfortable because of cotton layer on the skin and a radiator made of carbon fabric and cotton. It is a reliable power supply for low-power wearable electronics such as health-monitoring devices. For example, wireless electrocardiography requires about 0.4 mW today [1], [2] and in the near future it is supposed to drop below 0.1 mW. The hidden TEH seems to be a good power supply for low-power wearable electronics like health-monitoring devices. It is quite competitive with batteries of the same thickness and weight. The cost of TEHs is still by a factor of 10 higher than of batteries. However, modern fabrication technologies for thermopiles can change this ratio in favor of TEH in the near future. The demonstrator shirt with a TEH is being handled in the same way as other clothing, i.e., with periodic machine washing and ironing.

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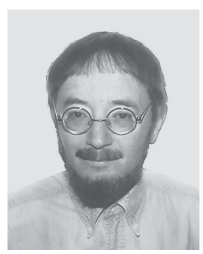

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