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Special Issue Paper

Wearable Thermoelectric Generators for Body-Powered Devices

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This paper presents a discussion on energy scavenging for wearable devices in conjunction with human body properties. Motivation, analysis of the relevant properties of the human body, and results of optimization of a thermopile and a thermoelectric generator for wearable and portable devices are presented. The theoretical limit for power generation on human beings is evaluated and confirmed by experimental results. The requirements for wearable thermopiles are summarized. The results allow certain conclusions to be drawn concerning directions for future development of body-powered devices.

Key words: Thermoelectric generator, thermopile, wearable device, autonomous device, human body, thermal matching, energy scavenger

INTRODUCTION: FROM SCIENCE FICTION TO REALITY

Among other modern trends, there is growing interest in the market for wearable and pocket electronics. Such devices require autonomous operation, preferably with no need to replace or recharge batteries for a long time. The most straightforward and effective way to achieve this target is to decrease the power consumption of devices so that the battery lasts for years. This has been done long ago, e.g., in watches. Low-power electronics is a rapidly progressing domain that today offers opportunities that were just dreams yesterday. Therefore, this scientific direction is undoubtedly promising. In the second approach, recharging of batteries is performed on a regular or occasional basis using ambient light and photovoltaic cells on the outer surface of the device. However, the more functions that are implemented in the device, the more power it consumes. Therefore, photovoltaic cells frequently fail to provide sufficient power; for example, wearable wireless devices consume too much power, unless a very low duty cycle is set for radio transmissions or a very short transmission range is required. Improving the energy density of primary batteries and the efficiency of solar cells is a hot research topic, but these parameters are not expected to improve much in the coming years. Thus, the only feasible solution to make advanced devices with long-term autonomy is to increase their size in order either to include a bigger battery or to cover a larger area with solar cells. This would unavoidably make them too bulky or too heavy to be acceptable in the market for wearable and portable electronics. As a result, they turn into devices with secondary batteries that must be frequently recharged. Therefore, it is not surprising that the number of portable devices connected to a battery charger in the home has grown over the last decade. Fortunately, there is a third approach, i.e., powering wearable electronics, partially or fully, by using the natural temperature difference between the human body and the environment. The first market-oriented trial of this kind was carried out 10 years ago, when a low-power watch was powered by thermopiles fed with body heat.[1] At that time, enthusiastic scientists started to discuss body-powered mobile phones and even computers, meanwhile inventive science-fiction film-makers demonstrated a staggering fantasy and showed a chilling picture

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of an entire world of intelligent machines powered by sleeping mankind.[2]

At this point, the reader is about to ask: "What can actually be powered from the human body?" This paper aims to answer this question, i.e., it aims (i) to quantify the expectations from a thermoelectric generator (TEG) in body-powered wearable and pocket devices, (ii) to summarize the rules of reaching its top performance characteristics, and (iii) to specify the requirements for thermopiles for use on animals and human beings. Through analysis of a thermopile on the human body and study of the relevant properties of the human being itself, the target specifications for wearable TEGs are obtained.

HEAT SOURCE FOR WEARABLE THERMOELECTRIC GENERATORS

The human body resembles a thermostat that is set at about 37°C temperature. This thermostat has temperature regulation with an accuracy of about ±0.5°C on average, while the temperature of its outer surface (the skin) is variable. (When a person catches a cold, his or her setting frequently changes, i.e., a fever develops. The related "switch" is located in the hypothalamus.) Heat generation is related to metabolic activity. It is then dissipated in six basic ways. The first three ways of heat dissipation are from the skin: (a) radiation, (b) convection, and (c) evaporation, including insensible perspiration and sweating. The other three ways are: (d) forced heat and mass transfer in lungs, (e) conduction to surrounding liquid (while swimming or taking a shower) or solid objects, and (f) food and water intake, followed by removal of them from the body after digestion. In case (f), the average temperature of the food and water is lower than the body temperature. Typically, the designer of a TEG can neglect points (e) and (f) while the relative importance of points (a) to (d) may vary depending on many factors. By relating the metabolic rate of 1.2 METs for a person to the Dubois area (the total surface area of the body), a heat density of 7 mW/cm^2 on skin is obtained. One MET is defined as 1 cal/kg h, and is known as the basal metabolic rate that is typical for a person at rest. One MET is also defined by an oxygen consumption rate of about 3.5 mL/kg min. A rate of 1.2 METs corresponds to typical sedentary activity in the office.

When calculating the heat flow in persons performing moderate-effort exercises such as truck driving or aerobics (6.5 METs), tennis or bicycling (7 METs), or carrying groceries upstairs (7.5 METs), one arrives at a value of 38 mW/cm^2 to 44 mW/cm^2. This calculation is valid from the medical point of view. However, it fails to provide an accurate estimate of the heat flow through a thermopile on a person's skin. Actually, most of the heat released in the body during such activity is dissipated through sweating. Even under heavy physical load, the skin temperature usually does not rise above 35°C to 36°C, while typical skin temperature in the trunk with no load is 33°C to 35°C. It is obvious that such a minor temperature rise cannot dramatically increase heat flow from the skin. In fact, it is water consumption that increases. One milliliter of water evaporated per minute in the lungs and from the skin is equivalent to about 4 mW/cm^2 of heat flow on the skin. Unfortunately, it seems impossible to use the water evaporation from the skin of living beings in wearable TEGs. For a person resting in thermal comfort, the combined evaporation loss through the respiratory tract and from the skin is about 0.5 mL/min. Therefore, when designing a TEG, one must subtract about 2 mW/cm^2 from the heat flow obtained based on a metabolic activity of 1.2 METs. Taking into account that heat transfer in the lungs (refer to point (d) above) cannot be utilized, the designer must rely only on radiation and convection. As a result of the estimates presented above, we arrive at a heat flow of about 5 mW/cm^2 to be used for designing a TEG.

The heat flow through the skin is a variable parameter that depends on environmental conditions such as the ambient temperature, wind speed, the amount of incident solar radiation as well as many other factors. Therefore, to prevent energy shortage in a wearable device, a charge storage element, i.e., a supercapacitor or a small rechargeable battery, must be added. Such a storage element should redistribute the energy gained on an occasional basis evenly over the day. Because wearable devices must work on a variety of users, the TEG must rely only on the minimal metabolic rate observed, e.g., in office workers. If such devices are used for health care, i.e., if they can be worn by aged people, the available heat flow further decreases following the Harris–Benedict equations for metabolic rate.[3] Moreover, if a wearable device is required on the body only during daytime, the average power produced by a TEG decreases by a factor of 2.5–3, because the user will not definitely leave it on the body at night and in the evening. Additionally, medical research shows that the metabolic rate decreases at night to about 0.8 MET. However, it is incorrect to use this rate to calculate the heat flow on the skin at night. A TEG on a sleeping person cannot be located anywhere but on the head because this is the only part of the body which is not covered by a blanket, which provides good thermal insulation. As a result, the head (including sometimes the neck and hands/arms) becomes the only body part that provides effective heat dissipation. In this situation, as has been measured recently,[4] the heat flow from the head does not decrease at night, guaranteeing the same power generation as during daytime.

In this section, we discussed the heat flow based on the properties of the body. However, the heat flow discussion above, although correct from the medical point of view, is not necessarily sufficient for designing an efficient TEG. One must also take into account other aspects, such as the thermal properties of the device that is in contact with the skin.

HEAT FLOW THROUGH THE THERMOELECTRIC GENERATOR ON THE SKIN

To facilitate the discussion, we would like to ask the reader to perform a simple experiment by putting his or her hand on a large metal plate. The skin temperature sensors would immediately inform the brain through the sensation of cold that the heat flow has increased locally. The tool for increasing the heat flow in TEGs or for cooling of electronics, a radiator, is well known. Therefore, the first body-powered wireless devices have been supplied with a radiator (Fig. 1).[5,6] As a result, one can increase the heat flow through the TEG compared with the heat flow on open skin. Further increasing the thickness of the radiator would further increase the heat flow. However, devices thicker than 1–3 cm may become obtrusive, depending on the application and on the chosen location of a TEG on the body. The form factor can significantly reduce the market success of a TEG. This is the first barrier to increasing the heat flow locally. If a TEG thickness is equal to the thickness of a watch, then the heat flow on the skin increases by at least a factor of two. Experimental results show that the resulting power production per square centimeter of skin can be increased by a factor of more than four.[7]

Returning to the body properties, two important aspects have to be accounted for. First of all, there are so-called core organs. Their temperature is maintained at 37°C, or as close as possible, at any energetic costs for the body. Just three core organs, the liver, brain, and heart, account for over half of daily energy expenditure at rest. The head is one of the best candidates for energy scavenging.[8] The second important component of the body is a pump with a tree-like pipeline network called the cardiovascular system. Arterial blood is heated to the core temperature when leaving the heart and is distributed throughout the body, spreading heat in addition to oxygen. The arteries are therefore the second important heat supplier for a wearable TEG.[9]

The body is not a high-quality heat source for a TEG because it shows large internal thermal resistance.[8,9] Therefore, even if a perfect heat sink were attached to the skin, the heat flow would be limited by the thermal resistance of the body. As has been reported,[5] in the watch location, i.e., on the outer side of the distal forearm, the heat flow is limited to about 30 mW/cm^2. Measurements have been performed using a thermopile attached to the skin, provided with a large piece of aluminum maintained at room temperature and serving as a perfect heat sink. The overall thermal resistance of the measurement setup was 50 cm^2 K/W, determined mostly by the thermopile. Positioning the same thermopile on the radial artery instead allowed a threefold increase of heat flow. However, these measurements were accompanied by a sensation of cold. This is the second and main limitation on the heat flow that can be allowed through the TEG. According to users' opinion while wearing different TEGs on the wrist and on the head, the limit on heat flow due to discomfort falls in the range from 15 mW/cm^2 to 25 mW/cm^2. The exact value varies from person to person and depending on the location of the device on the body due to (i) different extent of sensitivity to cold, which results from the different density of skin cold sensors, and (ii) different local thermal resistance of the body; for example, as measured with wrist TEGs,[10] devices located on the radial artery induced much fewer complaints at a heat flow of 24.8 mW/cm^2 than did TEGs located on the outer side of the distal forearm at 18.8 mW/cm^2.

The local thermal resistance of the body,[9] which is reciprocal to the internal conductance,[11] is the thermal resistance between the body core and the chosen location on the skin. Typically,[8,9,11] the thermal resistance is on the order of several hundred cm^2 K/W. It varies largely over the body,

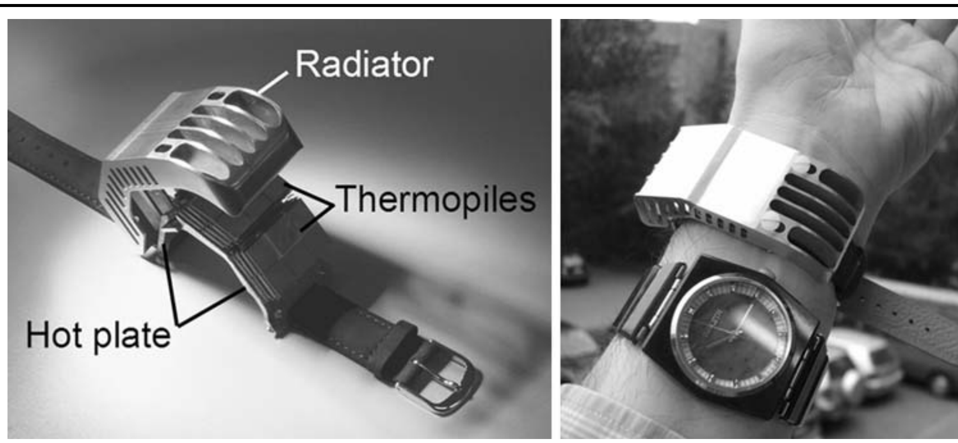

Fig. 1. Photographs of the first body-powered wireless sensor node fabricated in 2004 with an open radiator (*left*) and on the wrist next to a watch (*right*).

decreasing on arteries and in proximity to core organs. It also varies dramatically with ambient temperature, weather, clothes worn, metabolic rate, etc. The vasomotor response also affects the thermal resistance of the body, but only in extremities. This occurs mainly in a cold environment, but it is also frequently observed even in typical indoor temperatures. The resulting dependence of the skin temperature variation on ambient temperature is related to the location on the body where the measurements are performed.[9,11] The simplest way to check whether vasodilatation or vasoconstriction is currently taking place in a person is to touch their hands: are they cold or warm. At low ambient temperatures, a wrist TEG in the watch location does not proportionally increase the generated power. First, this is because of vasoconstriction and minimized cutaneous blood flow. Second, this is explained by the decreased temperature of the arterial blood in extremities, to a large extent caused by the countercurrent heat exchange with veins.[8,12] The vasomotor control at the body level varies the well-heated skin surface, thereby changing the effective area for convective and radiation heat exchange. Therefore, it allows energy-efficient maintenance of the core temperature. In particular, this means that, e.g., a wrist TEG designed for 22°C, when worn under a coat or overjacket, should not be cold in winter. In contrast, a TEG on the head can become uncomfortable to wear already at 19°C, as has been recently measured.[13]

Let us estimate how much power per square centimeter of skin can be generated by a wearable TEG. According to the thermoelectric theory, conversion efficiency can be estimated as $Z\Delta T/4$, where Z is a figure of merit and ΔT is the temperature difference on a thermopile.[14] Assuming heat flow of 20 mW/cm^2, Z of 3×10^{-3} K^{-1}, skin temperature of 34°C, and air temperature of 22°C, one arrives at a power of 180 μW/cm^2. However, as should be clear from the next section, this power cannot be reached. The reason is the much smaller actual temperature difference on the thermopile, which is due to (i) the necessity for a large temperature difference between the radiator and the air to dissipate the heat, (ii) the limited size of the radiator, (iii) the high thermal resistance of the body, and (iv) the requirement of thermal matching of a TEG to the environment (discussed below). As a result, the actual temperature difference on the thermopile is much smaller than the 12°C observed between the skin and the air. To obtain a more accurate estimate of power generation, in the next section, analysis of a TEG is conducted in conjunction with the properties of the human body.

THERMOELECTRIC GENERATOR: REQUIREMENTS AND DESIGN

The thermal circuit of a TEG on the skin is shown in Fig. 2. The human body with a core temperature of 37°C and the ambient air at 22°C form natural thermal generator, thermally shunted in a nude person between the points T_{skin} and T_{BL} (the boundary layer of air). A TEG placed in contact with the skin isolates the latter from the air and plays the role of a thermal load on this generator. The heat flow, W, and the temperature drop on the TEG, ΔT_{TEG}, are:

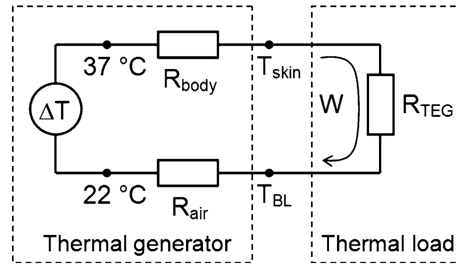

Fig. 2. Thermal circuit of a thermoelectric generator located on the skin.

$$W = (T_{\text{core}} - T_{\text{air}})/(R_{\text{body}} + R_{\text{air}} + R_{\text{TEG}}), \quad (1)$$

$$\Delta T_{\text{TEG}} = (T_{\text{skin}} - T_{\text{BL}}) = R_{\text{TEG}}(T_{\text{core}} - T_{\text{air}})/(R_{\text{body}} + R_{\text{air}} + R_{\text{TEG}}). \quad (2)$$

Accounting for the typical thermal resistance of thermopiles available on the market, the heat flow and temperature drop on a TEG are affected to a large extent by the properties of the thermal generator. Therefore, the common practice of quoting the parameters of thermopiles designed for use on persons as those obtained at a fixed temperature difference on the thermopile is not correct. This is because it does not allow estimation of the actual performance of a TEG on the skin unless its thermal resistance and the detailed embodiment of the TEG are reported. The thermal resistors composing the thermal generator are variables and depend on each other. The air temperature is also variable therefore the temperatures appearing at the two sides of a TEG, i.e., the skin temperature and the temperature of a boundary convection layer, are variables too.

The main difference between a thermal energy scavenger such as a wearable one and traditional applications of TEGs is that the device should be thermally matched to the thermal generator. This is because of the high thermal resistance of the latter. Thermal matching is the thermal equivalent of electrical matching of a generator to its load.[15] Because the thermal resistance of the body and of the ambient air is high, the thermopile inside a TEG must have high thermal resistance too. Therefore, the thermoelectric material must occupy only a small part of the TEG in the plane normal to the direction of a heat flow. As a result, the parasitic conduction through the air inside the TEG (as well as through the other interconnecting components such as holders or the encapsulation) affects the performance of such a thermopile, thermally shunting it. Therefore, for further analysis, it is important to replace R_{TEG} in Fig. 2 with two parallel resistors, R_{tp} and R_{par}, for a thermopile and for a parallel parasitic thermal resistance, respectively. Then, the optimal thermal resistance of a TEG can be obtained from the equation of thermal matching[15] as:

$$R_{\mathrm{TEG,optimal}} = R_{\mathrm{par,0}}(R_{\mathrm{body}} + R_{\mathrm{air}})/\left[2(R_{\mathrm{body}} + R_{\mathrm{air}}) + R_{\mathrm{par,0}}\right], \quad (3)$$

where $R_{\mathrm{par,0}}$ is the parallel parasitic thermal resistance in a TEG upon imaginary removal of the thermoelectric material from it.

Let us estimate what thermal resistance should be provided in a watch-size wearable TEG. In order to decrease the largest serial parasitic resistor, R_{air}, in the circuit in Fig. 2 we assume that a pin-featured radiator similar to the one reported earlier[9] forms an interface with the ambient air. We suppose that a distance of 8 mm is provided from the radiator to the hot plate. At approximately 6°C to 7°C temperature difference between the radiator and ambient air, which is needed for dissipation of the heat in the case under consideration, the radiator provides a thermal resistance to the air as low as about 700 cm^2 K/W. We assume a thermal resistance of 300 cm^2 K/W for the human body and account only for the air between the hot plate and the radiator (i.e., no additional holding elements between them except the thermopile) with a thermal resistance of 3×10^3 cm^2 K/W. At these conditions, from Eq. 3, we obtain an optimal thermal resistance of 600 cm^2 K/W. At this thermal resistance, the power production in the TEG is maximized. This occurs, from Eq. 1, at a heat flow of 9.4 mW/cm^2, and, from Eq. 2, at a temperature drop of 5.6°C on a thermopile, which is almost three times lower than the temperature difference between the body core and the ambient air.

As a result of the above analysis, the logical design choice for a TEG to reach maximum power generation in an energy scavenger, e.g., on a person, is to include (i) a hot plate much larger than the size of a thermopile, and (ii) a radiator of similar size, Fig. 3. The hot plate should preferably be thermally isolated from the air with, e.g., a layer of nanoporous material, thereby increasing the amount of heat transferred to the thermopile and hence to the radiator. The inner surface of the radiator must have a low absorption coefficient in the infrared spectral region. Its outer surface, in contrast, must have an emission coefficient close to 100%.

Strictly speaking, the device discussed above is for use in indoor applications. For outdoor use, the outer surface could be, in addition, made with low absorption in the visible and near-infrared regions

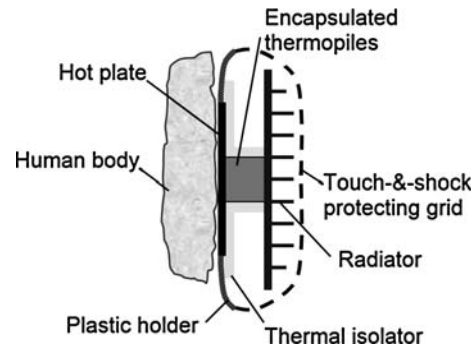

Fig. 3. Design of a wearable watch-size TEG on the skin.

to prevent heating by sunlight. A touch-and-shock protecting structure, e.g., a grid with high transparency for both convective heat transfer and radiation could be necessary. An air gap of several millimeters between the hot plate and the radiator is also useful as this allows the air heated by the part of the human body located below the TEG to pass between the hot plate and the radiator.

THERMOELECTRIC GENERATORS IN CLOTHING

Clothes change the heat flow pattern from the skin, decreasing heat flow on covered areas and increasing it in the hands. This is useful for both devices worn on open skin surface and those embedded into a garment. For the former, the skin temperature increases, for the latter, the textile additionally creates thermal and vapor barriers, thereby decreasing the temperature of the boundary layer of convection on its outer side. For example, a light office clothing ensemble, including long-sleeve shirt (0.25 Clo), trousers (0.25 Clo), briefs (0.04 Clo), socks (0.02 Clo), and thin-soled shoes (0.02 Clo), provides a thermal insulation of 900 cm^2 K/W. Of course, such insulation is not due to the thermal resistance of a fabric, which is, e.g., for a 0.3-mm cotton shirt, about 42 cm^2 K/W, i.e., 20 times smaller. The true reason for the good thermal insulation provided by clothes is the microclimate created between the skin and fabric. This microclimate is characterized by decreased convection and radiation heat exchange. It also has slightly increased relative humidity, thereby decreasing evaporative heat transfer. The main temperature drop therefore occurs in this air layer, but not in the fabric itself. The related message addressed mainly to textile manufacturers is: weaving thermoelectric wires into a fabric cannot provide useful power output. Accounting for the higher thermal conductivity of thermoelectric materials compared with that of clothing materials and taking into consideration the necessity for thermal matching, the feasible performance characteristics of such energy scavenger seem of little interest.

There is however a more effective way of fabrication such an energy-scavenging garment, i.e., embedding a small thermoelectric unit into clothes. Such a unit could resemble the devices discussed in previous sections. If more power is required, several units could be used. This solution for "thermoelectric clothes" seems more logical than direct weaving of thermopiles into a textile. Furthermore, clothing in the future could be provided with a universal thermoelectric charger to which different wearable and portable devices could be plugged in and worn for recharging. It seems logical that a wearable thermoelectric generator should be hybridized with photovoltaic cells for the best possible power production per unit area occupied on the skin. The first hybrid power supply has recently been demonstrated in a wearable electroencephalography system.[16]

REQUIREMENTS FOR WEARABLE THERMOPILES

The required optimal thermal resistance of a thermopile for use in the example described in this paper can be obtained from Eq. 3 by replacing $R_{\mathrm{TEG,\ optimal}}$ with two parallel resistors, R_{tp} and R_{par}. Simplifying the calculations, we replace R_{par} with $R_{\mathrm{par,0}}$. Upon these replacements, the optimal resistance of a thermopile at the point of thermal matching is found to be 750 cm^2 K/W. Therefore, the first strict requirement for wearable thermopiles is that they must have a high thermal resistance per square centimeter of skin. The second requirement comes from the fact that a voltage of at least 1 V should be provided for effective use in electronics. Various ways exist for effectively upconverting a voltage of 0.2 V and less. However, self-powered wearable devices must not suddenly stop working at high ambient temperatures. Therefore, at a temperature of, e.g., 22°C, a TEG must preferably produce on the matched load not less than 1 V.

Evaluation of the performance characteristics of different types of commercially available thermopiles if located on the skin is not difficult. The required set of typical characteristics is Z or ZT, Seebeck coefficient, resistance, thermal resistance, power and voltage at the specified temperature difference, number of thermocouples, and the dimensions of the plates. However, various thermopiles in the research stage have much smaller dimensions than thermopiles on the market. In such cases, parasitic thermal resistance becomes extremely important and must be accounted for when evaluating the performance characteristics of these thermopiles in wearable devices. Therefore, the set of characteristics provided by the manufacturers must be accompanied by the net temperature difference between the junctions and the dimensions of the thermocouple legs. Alternatively, either parasitic serial and parallel thermal resistance in the thermopile or the thermal resistance of the thermocouple legs should be reported. These additional characteristics would allow correct modeling of thermopiles on the human body and prediction of how well they are suited to the target application.

Returning to the equation for the conversion efficiency of a thermopile, which is $Z\Delta T/4$, the limit of power generation on man can be evaluated. In the analysis of the equation of thermal matching, we have obtained an optimal temperature difference of 5.6°C to appear between thermopile junctions, therefore $Z\Delta T/4 = 0.4\%$. With a thermal resistance of the thermopile of 750 cm^2 K/W, the heat flow through the thermopile is 7.5 mW/cm^2. A heat flow of 1.9 mW/cm^2 is transferred through the air inside the TEG, and this parasitic heat flow corresponds to an optimal situation. At optimal heat flow through the thermopile of 7.5 mW/cm^2, the maximum power in the calculated device is 31 μW/cm^2. This is the limit of power generation for the chosen input parameters. Of course, this value depends on many other parameters. Firstly, it depends on the ambient temperature and thickness of the device. However, the chosen ambient conditions are typical. The applied properties of the human body are very close to the best possible. Therefore, it will be difficult to build a compact device which could outperform the calculated case under the conditions specified above.

A TEG in a wearable or portable device must sustain shocks and be resistant to water (rain, laundry). Therefore, the necessity for encapsulation and shock protection will decrease this limit. Analyzing practical design cases, a value of about 25 μW/cm^2 seems to be the limit at a ZT of 0.9. As a confirmation of this limit, at a ZT of 0.85, a watch-size wrist TEG[7] shows about 21 μW/cm^2 at 24°C while a power of 30 μW/cm^2 only is obtained in a 2.9-cm-thick TEG[13] at 23°C. The authors consider 30 μW/cm^2 to be the limit in about 1-cm- to 1.5-cm-thick TEG at a ZT of 1. This limit corresponds to the average power generation and does not mean that at certain moments the power might be, e.g., twice as large.[7] If however the TEG is located in a poor position or surrounded by the body-induced convection layer, this limit may easily become inaccessible. Despite the fact that the human body can provide a heat flow to a wearable TEG for generating well over 300 μW/cm^2 (and, at certain conditions, over 1 mW/cm^2), the resulting sensation of cold does not allow this limit to be reached. A power of over 80 μW/cm^2 accompanied by a sensation of cold has been registered in TEGs worn by three volunteers in 2004 averaged over 24 h. With a strong sensation of cold, a power of 280 μW/cm^2 has been measured earlier outdoors, at a temperature of 5°C.

CONCLUDING REMARKS

Analysis of a thermoelectric generator shows that wearable computers powered using body heat are not feasible. Even personal digital assistants (PDAs) that consume at least ten times less power than laptops still have too large a power consumption to be powered by the human body heat. About 0.5 W is needed for their operation during only 1 h/day, and if worn 8 h/day they would still require 60 mW from the TEG and over 10% of the body heat. Such an amount of power can be provided only with photovoltaic cells outdoor, but on a larger area than the size of a PDA. Of course, the development of power reduction techniques and low-voltage low-power electronics which is ongoing, could soften power requirements. However, the market trend is to add more functionality if power reduction is reached, thereby returning the power consumption to the initial level. At a low clock speed, i.e., less than 100 MHz, and in energy-saving display modes, the power consumption of a PDA can be decreased to about 100 mW, but this is still not low enough.

Geographical positioning system (GPS) devices currently consume approximately the same power as PDAs. A new generation of GPS chip sets, which is expected to emerge soon, will hopefully offer over tenfold power savings. For a traveler far from civilization, it becomes possible to power such a device for some 10 min per day for on-demand positioning requests. However, only in remote locations such as some mountain or desert areas do power outlets not exist. Furthermore, in outdoor applications, much smaller solar cells outperform any body-powered TEG.

Cellular phones require less power on average, but the power consumption in talk mode is large, close to the that of PDAs and GPS devices. As a result, several tens of milliwatts is the typical estimated consumption of cellular phones. Work on the reduction of standby and active power consumption of mobile phones is ongoing, but even a comparatively low standby current of 0.1 mA is still too high. New communication standards and new approaches on the device and network levels, in principle, could make self-powered cellular phones possible. Therefore, a headgear with solar cells powering a cellular phone for a limited talk time per day seems feasible in the near future for people visiting remote sites. However, it is not obvious that thermoelectric generators will be used for powering cellular phones. A small portable or embedded dynamo seems much more realistic. There is a complementary way of providing power for people such as mountaineers travelling by foot in remote locations: the long-distance energy provider and transceiver can be located in a shoe and charged using the mechanical energy of walking. In this case, a GPS device or a cellular phone needs very low power for wireless communication with the shoe. Then, and only for people travelling by foot, both devices and even a PDA could be charged from the body, provided limited active time for the user. However, the tired traveler would prefer to carry lightweight solar sells instead of spending additional physical efforts at each step to mechanically recharge the batteries.

Fig. 4. Two-channel wireless electroencephalography system with a 2.5-mW thermoelectric generator.

Targeting practical use of body heat in devices, researchers can pay attention to low-power applications instead of the devices mentioned above. Devices consuming about 1 mW or less, such as health monitoring sensors, can be proposed as candidates for self-powering. First examples of body-powered wireless devices, namely, the pulse oximeter,[17,18] working at 62 μW power consumption, and a two-channel electroencephalography system[13] (0.8 mW), as shown in Fig. 4, have been demonstrated recently. However, the fabrication cost for thermopiles per device should be decreased by about 100-fold, or more, to compete successfully with batteries on the market. This is a difficult, but not impossible, task. The development of modern film technologies for thermopiles is required to move body-powered devices into mass production.

Will the number of portable devices connected to a battery charger at our home decrease? The answer is "no." On the contrary, it will further increase. However, low-power devices such as sensors, health monitoring, and some other wearable and portable devices can be effectively powered from the body, thereby eliminating the need for external power provision. Implants will also be powered thermoelectrically, but this is a different story.

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