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Energy Harvesting Using Thermoelectric Materials

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ABSTRACT:

Energy harvesting from human body has been undergoing an interesting and quick development thanks to the technological availability of new electronic components and the growing of different applications, in particular, for biomedical and social impacts on human beings' daily life. As energy harvesting techniques, especially thermoelectric generator (TEG) technologies, develop during recent years, its utilization in powering electronic devices is attempted from many aspects. We aim at developing a thermo electric generator which could extract heat from the human body and convert it to voltage. This module will be coupled with a heat sink which will help in maintaining the temperature gradient required to produce voltage. The module will be interfaced with an energy harvesting circuit which would store the electrical energy produced. This energy will then be used to power up devices when the conventional means to charge them are not available. The thermo electric generators perform best at higher altitudes since the temperature there is low and we don’t need heat sinks to maintain the temperature gradient.

Keywords : Energy harvesting, Thermocouples, DC-DC converter

1. INTRODUCTION

Small and cost-effective thermoelectric generators scavenging energy from the environment could potentially provide power autonomy to miniaturized and/or wearable electronic products operating at very low power. In Human beings and, more generally speaking, warm-blooded animals (e.g., dangerous and endangered animals, cattle, and pets), can also be a heat source for the devices attached to their skin [1].

The human body is subject to the same laws of physics as other objects, gaining and losing heat by conduction, convection and radiation. Conduction between bodies and/or substances in contact; convection involving the transfer of heat from a warm body to a body of air above it or inside the human body and here the blood, gases and other fluids is the medium, radiant heat transfer is a major mechanism of thermal exchange between human body and the surface surrounding environment. These three effects in most situations operate together. In human body, metabolic processes generate its own heat as well, similar to a heat producing engine.

Human body behaviors try to be in stable state therefore, it absorbs and emits energy to be in equilibrium, stimulation is applied to the body surface, this make the activity of metabolism induced to body surface [2]

The operating voltages and power consumption of present –day semiconductor Integrated Circuits (IC) are continually decreasing. The International Technology Roadmap for Semiconductors (ITRS) by Semiconductor Industry Association (SIA), projects that the lowest operating voltage which was 1.0 V in 2004 will reach 0.5 V in 2016. Nano-watt and micro-watt sensor, transceiver and data logging systems are in existence today. Ultra Low Power, Ultra Low Voltage wireless sensor systems are finding use in Medical, Automotive and Industrial Applications. Human body heat powered devices and appliances are no longer futuristic predictions. Future applications would include personal electronics such as mobile phones and mp3 players powered by thermo electric modules embedded into clothing. [3]

1.1 Motivation behind this:

In recent years, energy harvesting has become a popular term in both academic and industrial world, as traditional power generation resources, such as fossil fuels and nuclear fission, are either facing global shortage crisis or simply being quite costly. In contrast, the resources for energy harvesters are usually naturally present, for instance, the temperature gradient from the combustion engine, electromagnetic energy from communication and broadcast, motion from human movement, just to name a few. Currently, areas of research interests mainly consists of piezoelectric energy harvesting, pyroelectric energy harvesting, waste heat recovery, electromagnetic energy harvesting, ambient-radiation energy harvesting, etc. However, current technologies of energy harvesting are capable of producing only enough power to drive relatively low-power electronics. Also, high volume applications of these technologies depend on further enhancement of the energy harvesting efficiencies.

TEGs are devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" (or "thermoelectric effect"). Their typical efficiencies are around 5-10%. TEGs are solid-state devices which have no moving parts. Sub-branches of TEG have been developed to cater the needs of specific target applications, such as radioisotope TEG for spacecraft and automotive TEG (ATEG) for automobiles. Moreover, some house-hold applications based on bio-fuel have been realized, as well as power supply for wearable electronics.

Recently, TEG is often mentioned together with photovoltaic as promising energy harvesting device in the near future. Photovoltaic has a longer history of application. But when it comes to the effective applicable time, TEG is in fact advantageous in that it has no dependence on factors such as daylight hours and changes of seasons. [4, 5]

This paper aims at generating the energy from the human tissue warmth to provide uninterrupted power.

2. THERMOELECTRIC GENERATOR

Thermoelectric generator (TEG) is a device that converts thermal energy directly into electrical energy. A typical TEG structure is shown in Figure 1. Early TEG devices utilize metallic TE material, whereas more recently manufactured TEGs use alternating n- and p-type semiconductor materials. The TEG structure is “sandwich like”, with thermoelectric materials “sandwiched” by two heat exchanger plates at its two ends respectively. One of the two exchangers has high temperature, and hence, it is called the *hot side* of the TEG; while the other has low temperature and is called the *cold side* of the TEG. There are electrical-insulate-thermal-conductive layers between the metal heat exchangers and the TE material. The two ends of *n*- and *p*-type legs are electrically connected by metal.

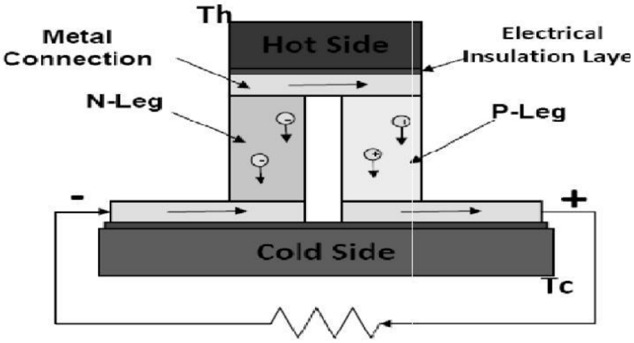

Figure 1 Simplified illustration of TEG.

The thermal-electrical conversion is done by a phenomenon generally referred to as “Seebeck effect”, which is named after one of the scientists who discovered it. TEGs are solid-state device, which means that they have no moving parts during their operations. Together with features that they produce no noise and involve no harmful agents, they are the most widely adopted devices for waste heat recovery.

2.1 The Physics of Thermoelectric Generation

2.1.1. Seebeck Effect

To put it in a simple way, Seebeck effect is the conversion of temperature differences directly into electricity. In the basic version of TEG, the conductor materials used to generate Seebeck effect are two different metals or semiconductors. The term *thermopower*, or more often, *Seebeck coefficient* of a material, is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material. The Seebeck coefficient has units of V/K, though it is more practical to use mV/K. The Seebeck coefficient of a material is represented by S (or sometimes σ), and is non-linear as a function of temperature, and dependent on the conductors’ absolute temperature, material and molecular structure.

Table 1 Seebeck coefficients for some common elements[1]

Material	Seebeck Coeff.	Material	Seebeck Coeff.	Material	Seebeck Coeff.
Aluminum	3.5	Gold	6.5	Rhodium	6.0
Antimony	47	Iron	19	Selenium	900
Bismuth	-72	Lead	4.0	Silicon	440
Cadmium	7.5	Mercury	0.60	Silver	6.5
Carbon	3.0	Nichrome	25	Sodium	-2.0
Constantan	-35	Nickel	-15	Tantalum	4.5
Copper	6.5	Platinum	0	Tellurium	500
Germanium	300	Potassium	-9.0	Tungsten	7.5

In Figure 1, the materials used in the two legs are n- and p-type semiconductors. If we denote their respective Seebeck coefficients to be S_n and S_p, the open circuit voltage V_{oc} generated by this TE couple is then governed by the equation:

$$V_{oc} = \int_{T_C}^{T_H} \left(S_n(T) - S_p(T) \right) dT$$

1

If the Seebeck coefficients are approximately constant for the measured temperature range in the TE legs (which is often true), Equation 2.1 can be simplified as:

$$V_{oc} = \left(S_n - S_p \right) . \left(T_h - T_c \right)$$

2

If the temperature difference ΔT between the two ends of a material is small, then the Seebeck coefficient of this material is approximately defined as:

$$S = \frac{\Delta V}{\Delta T}$$

3

where ΔV is the voltage seen at the terminals.

Thermopower is a collective result of different effects, among which two mechanisms provide major impact, and they are *charge-carrier diffusion* and *phonon drag*.

In a TEG where two ends of the *n*- and *p*-type legs are at different temperature levels, charge carriers in the leg material tend to diffuse in the direction which can help to reach thermodynamic equilibrium within the leg. That is to say, the hot carriers (charge carriers originally at the end with higher temperature) will move toward the cold side of TEG, and cold carriers move toward the hot side. If temperature difference is intentionally kept constant, the diffusion of charge carriers will form a constant heat current, hence a constant electrical current. Take *n*- and *p*-legs of TEG in Figure 1 as an example, the heat source, i.e. the side with higher temperature, will drive electrons in the *n*-type leg toward the cold side, crossing the metallic interconnect, and pass into the p-type leg, thus creating a current through the circuit. Holes in the *p*-type leg will then follow in the direction of the current. The current can then be used to power a load.

If the rate of diffusion of hot and cold carriers were equal, there would be no net change in charge within the TE leg. However, we need to take into account the impurities, imperfections and lattice vibrations which scatter the diffusing charges. Since scattering is energy-dependent, the hot and cold charge carriers will diffuse at different rates, which then create a potential difference, i.e. an electrostatic voltage, in the leg. This electric field, on the other hand, opposes the uneven scattering, and equilibrium will be finally reached given enough time. The above analysis brings about the conclusion that the thermopower of a material depends greatly on impurities, imperfections, and structural changes, with the latter affected often by temperature and electric field.

Another major impact on thermopower is phonon drag. A phonon is a quantum mechanical description of a special type of vibrational motion, in which a lattice uniformly oscillates at the same frequency. Phonons are not always in local thermal equilibrium; they move against the thermal gradient. They lose momentum by interacting with electrons (or other carriers) and imperfections in the crystal. The phonon-electron scattering is predominant in phonon drag in a temperature region approximately defined by equation:

$$T \approx \frac{1}{5}\theta_D \tag{4}$$

where θ_D is the Debye temperature. This temperature is approximately around 200 K. At lower temperatures there are fewer phonons available for drag, and at higher temperatures they tend to lose momentum in phonon-phonon scattering instead of phonon-electron scattering. In the phonon-electron dominant scattering, an electron charge distorts or polarizes the nearby lattice, as it moves past atoms in the lattice. While the vibration of the lattices, i.e. phonons, will tend to push the electrons to one end of the material, losing momentum in the process. This effect leads to a decrease in the electron mobility, which results in a decreased conductivity, while at the same time contributes to the already present thermoelectric field. Since the magnitude of the thermopower increases with phonon drag, it may be beneficial in a thermoelectric material for direct energy conversion applications.

2.1.2. The Reversed Seebeck Effect

In 1834, the French physicist Jean-Charles Peltier discovered that when a current I is made to flow through the junction of two different metals, heat is evolved at the upper junction, producing a higher temperature T_1, while a lower temperature T_2 presented at the lower junction. The heat absorbed by the lower junction per unit time is equal to

$$Q = \Pi_{AB} I = (\Pi_B - \Pi_A) I \quad (5)$$

where Π_{AB} is the Peltier coefficient of the entire thermocouple, and Π_A and Π_B represent the coefficient of each material. Typically, p-type semiconductor material has positive Peltier coefficient while n-type material has negative Peltier coefficient. It is apparent that Peltier effect in fact has the reversed physics of Seebeck effect. One way to understand the phenomenon of Peltier effect is that, when electrons flow from a region of high density to a region of low density, they try to maintain electron equilibrium that existed before the current was applied, by absorbing energy at one end and emitting it at the other. A series of these thermocouples can be connected in order to enlarge the effect.

Peltier effect is most often applied to thermocouples to make solid-state heat pumps. A very popular application of Peltier effect is thermo-electric cooling (TEC).

2.2 Figure of Merit “ZT”

For thermoelectric materials, the ability to produce high energy conversion efficiency is the most important standard in determining the performance of materials. The *figure of merit* (FOM) is a very convenient measure for comparing the potential efficiencies of devices built with different materials. The FOM for thermoelectric devices is defined as

$$Z = \frac{S^2}{\kappa \cdot \rho} \quad (6)$$

where ρ is the electrical resistivity, κ is the thermal conductivity, and S is the Seebeck coefficient. The conventional unit for Seebeck coefficient in calculating FOM is μV/K. More commonly used measure is the dimensionless FOM, ZT, where T is the average temperature $(T_2+T_1)/2$ in the device. If it is necessary to take into account both legs in the thermocouple, the dimensionless FOM can be expressed by the following equation:

$$Z T_{avg} = \frac{(S_p - S_n)^2 T_{avg}}{\left[(\rho_n \kappa_n)^{1/2} + (\rho_p \kappa_p)^{1/2} \right]^2} \quad (7)$$

where T_{avg} is the average temperature between the hot and cold side of the device, and the subscripts *n* and *p* denote the *n*- and *p*-type semiconductor. For recently produced TE materials, $ZT = 1$ are considered good, while ZT values of the range of at least 3-4 is considered to be essential for thermoelectrics to compete with mechanical generation and refrigeration in efficiency.

It is obvious from Equation 6 that to improve the value of FOM, we can either increase Seebeck efficient, or decrease thermal conductivity. These are also the focus of current TE material research. With the advancements of nanotechnology, these targets can be achieved by manipulating the nanostructure of the materials.

2.3 TEG Materials

Metals have been the main materials used in building TEGs, until the middle of 20th century, when Ioffe noticed semiconductor materials due to their high Seebeck coefficient and their phonon-transport-dominated heat conduction. Despite metals’ merit of high ratio of electrical to thermal conductivity, modern TE materials are mainly semiconductors. The performances of TEGs are largely affected by the features of materials used. Hence, the selection and combination of TE materials is vital for the design of a good TEG. It is necessary to examine and compare the existing families of TE materials. Chalcogenides material family is main contributor to TEGs, among them bismuth telluride (Bi_2Te_3) and its alloys are very good TE materials below room temperature. Bi_2Te_3 can be alloyed with Sb_2Te_3 or Bi_2Se_3 so as to considerably reduce thermal conductivity. However, since tellurium is scarce, toxic and volatile at high temperatures, its usage is limited. Lead telluride (PbTe) was found to have good thermoelectric properties at temperatures in the range of 300-700 K. Similar thermoelectric materials such as PbS and PbSe, also belong to chalcogenides system.

SiGe alloys are superior materials for thermoelectric generation and is typically used for both *n*- and *p*-legs in high temperature (>900 K) TEGs. However, the ZT of these materials is fairly low, particularly for the p-type materials.

3. MATERIALS AND

METHODS 3.1 Thermo-generator

We used the commercially available TEC1-12706 for our project. The product has the following specifications:

- Operational Voltage: 12V
- Current Max: 6 Amp
- Voltage Max: 15.2 V
- Power Max: 92.4 Watts
- Couples: 127
- Dimension; 40 X 40 X 3.5mm
- Power Cable Length: 250mm (approx)

Results obtained: The voltage obtained from the TEG was subject to various factors like the room temperature and also varies from person to person. The following are the results obtained from the TEG when measured at different surrounding temperatures and heat is provided by different persons.

Note: The readings obtained above did not remain constant for more than 30 seconds because the electrons try to maintain the thermal equilibrium so it is necessary to couple the device with a heat sink to maintain the temperature gradient.

Table 2 : Current and voltage output of TEC1-12706

	Room temperature		Cold room	
	Voltage (mV)	Current (mA)	Voltage (mV)	Current (mA)
Person 1	185	1.6	380	3.5
Person 2	153	1.4	480	4.6
Person 3	205	1.95	430	4

3.2 Thermopile

A **thermopile** is an electronic device that converts thermal energy into electrical energy. It is composed of several thermocouples connected usually in series or, less commonly, in parallel. Thermopiles do not respond to absolute temperature, but generate an output voltage proportional to a local temperature difference or temperature gradient. Thermopiles are also used to generate electrical energy from, for instance, heat from electrical components, solar wind, radioactive materials, or combustion. The process is also an example of the Peltier Effect (electric current transferring heat energy) as the process transfers heat from the hot to the cold junctions. [6]

A **thermocouple** is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more spots, where a temperature differential is experienced by the different conductors (or semiconductors). It produces a voltage when the temperature of one of the spots differs from the reference temperature at other parts of the circuit. Thermocouples are a widely used type of temperature sensor for measurement and control, and can also convert a temperature gradient into electricity. Commercial thermocouples are inexpensive, interchangeable, are supplied with standard connectors, and can measure a wide range of temperatures. In contrast to most other methods of temperature measurement, thermocouples are self powered and require no external form of excitation. The main limitation with thermocouples is accuracy; system errors of less than one degree Celsius (°C) can be difficult to achieve.

Any junction of dissimilar metals will produce an electric potential related to temperature. Thermocouples for practical measurement of temperature are junctions of specific alloys which have a predictable and repeatable relationship between temperature and voltage. Different alloys are used for different temperature ranges. Properties such as resistance to corrosion may also be important when choosing a type of thermocouple. Where the measurement point is far from the measuring instrument, the intermediate connection can be made by extension wires which are less costly than the materials used to make the sensor. Thermocouples are usually standardized against a reference temperature of 0 degrees Celsius; practical instruments use electronic methods of cold-junction compensation to adjust for varying temperature at the instrument terminals. Electronic instruments can also compensate for the varying characteristics of the thermocouple, and so improve the precision and accuracy of measurements. The ease of availability is also an important factor while choosing the materials for making a thermocouple. [7]

We aim at making a thermocouple which uses the heat from the human body to generate electricity. First we used an aluminum wire and an iron wire of thickness 3mm to make a thermocouple but the output obtained was not sufficient to drive a booster circuit. As shown in figure 2 when one junction of the thermocouple was kept in a glass of ice for about half an hour the current measured was 4 micro ampere. The problem we encountered was that the wire was very thick and the electrons could not align and flow because the temperature difference was not sufficient. Since we aim at utilizing the heat from our bodies this arrangement could not be used further.

Figure 2 : Iron aluminum thermocouple with one junction in ice.

Next we used a paper clip and copper wires to make a thermocouple.

Figure 3 : Paper clip-Copper wire thermocouple in ice

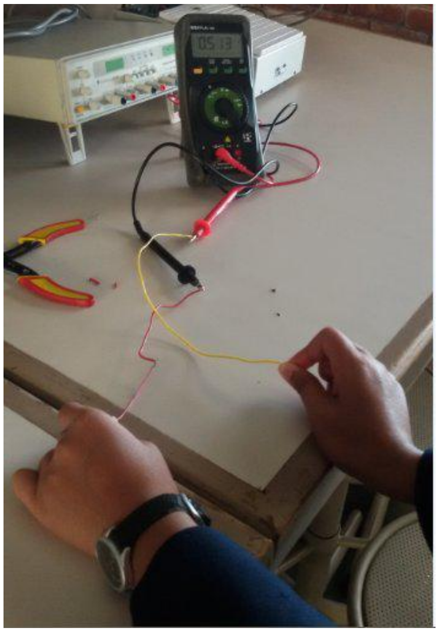

Figure 4: Paper clip-Copper wire thermocouple from human body

The output from this configuration depends on a number of factors like:

1. The body temperature varies from person to person.
2. The room temperature
3. Area of contact

Table 3: Current and voltage output from the thermocouple

	0.4 mm thickness paperclip		1.0 mm thickness paperclip	
	Voltage (mV)	Current (uA)	Volatge(mV)	Current (uA)
Ice	513	4	60	-
Person 1	452	2	49	-
Person 2	400	2	41	-

Table 3 clearly shows the dependence of voltage generated on the thickness of the wire. It is observed that the lesser the thickness, the better is the output.

The challenge now is to step up the current so that it is sufficient to drive our charging circuit. One solution is to put a number of such thermocouple units in parallel to obtain a higher value of current which could be step up further by using a booster circuit

4. DC-DC Converters

DC-DC converter is a class of power converters. It converts a DC source of a certain voltage level to another voltage level. In modern electronic systems, DC-DC converters are needed to convert the voltage supply from the power source to the voltage level required by the target function block. Beside, DC-DC converter can also regulate the output voltage. For TEG utilizations in body heat powering devices, DC-DC converter is commonly used for boosting up voltage supplied by the TEG converted power source, so as to reach the voltage levels required by different applications.

We have discussed one of the many circuits used as voltage boosters.

4.1 Micro voltage booster

We present a voltage booster circuit which takes on very low input values (in the range of mV) and gives a boosted up output which can drive low power devices.

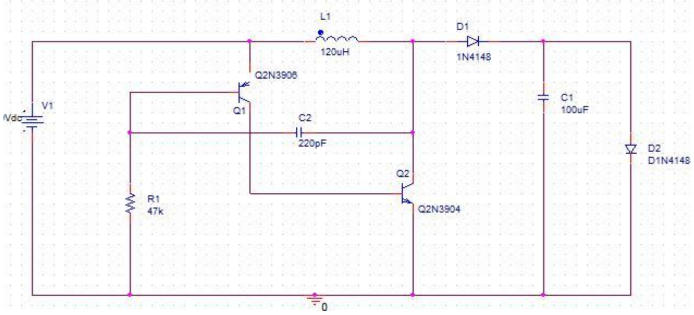

Figure 5 : Circuit of micro-voltage booster.

This Circuit employs a Sziklai Darlington Pair. The **Sziklai Darlington Pair**, named after its Hungarian inventor George Sziklai, is a complementary or compound Darlington device that consists of separate NPN and PNP complementary transistors connected together as shown below. This cascaded combination of NPN and PNP transistors has the advantage that the Sziklai pair performs the same basic function of a Darlington pair except that it only requires 0.6V for it to turn-ON and like the standard Darlington configuration, the current gain is equal to β^2 for equally matched transistors or is given by the product of the two current gains for unmatched individual transistors. [8]

The circuit takes very low input values, which are stepped up to a value that is sufficiently higher than the input. To demonstrate the working of the circuit, an LED is connected across the output. Input voltage in the range of 0.6 to 1V is given. The input is boosted up and is used to glow the LED.

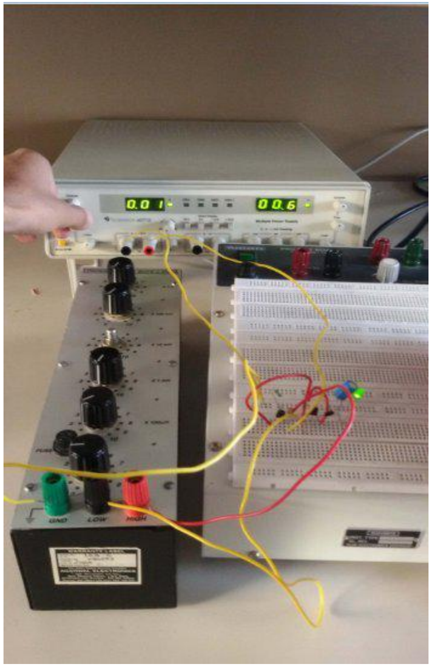

Figure 6: Micro voltage booster powering the LED

As it is clear from figure 6 above that the circuit boosts up the input voltage to a level which is sufficient to glow an LED. The current values obtained from the circuit are tabulated below:

Table 4 : Voltage vs. Current of micro voltage booster.

Input Voltage(V)	Current across the LED (mA)
1	0.9
1.1	1.2
1.2	1.5
1.3	2.2
1.4	2.4
1.5	2.7
1.6	4.5
1.7	5.3
1.8	5.9
1.9	6.6
2.0	8.3

Conclusion :

The TEG based energy harvesting circuit presents an easy and efficient method of generating electricity from the human body heat. The source of powering the device is inexhaustible and the energy harvested from this circuit will be helpful in supplementing the increasing demand for electricity. The TEC1-12706 gave promising output in the range of 100mv to 500 mV which is then fed to the booster circuits. The thermocouple of paperclip and copper wire also gave output in the same range but a comparatively weak current. We are looking for methods to step up the current from the thermocouple.

Apart from the commercially available TEG we plan to come up with a wearable device using the paper clips and copper wires. The thermocouple of paper clip and copper wire has a very promising future since the investment in it is negligible as compared to the potential benefits it offers.

We further propose to come up with a circuit which stores the energy output from the step up converter to be used later.

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