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Human Body Heat Harvesting via Wearable Biomedical Sensor Generating Renewable Energy

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ABSTRACT

A wearable thermoelectric generator is an innovative method to generate electric power from the heat of human body. This study presents an innovative design and integration of systems, including a ring, thermoelectric generator (TEG), and heat sinks used as power sources in wearable technology. An experimental setup was designed to investigate the performance of the power generation from the proposed system. In addition, the effect of the environmental temperature on the power output of the integrating system was investigated. The key results showed that the integrating system could generate closed-circuit voltage and output power values of about 22 mV and 480 µW, respectively, at an ambient temperature of 7°C. This research demonstrated that the wearable ring with TEG gives a potential route for power generation by harvesting the heat of the human body, which could be used to run the biomedical sensor in the future.

1. INTRODUCTION

Recently, the interest in renewable energy has increased due to the continuous rise in energy demand [1-5]. The wearable device was developed with the purpose of monitoring patients' conditions at any time. Some diseases necessitate continuous monitoring of medical parameters, such as heart rate, respiratory rate, and blood oxygen [6]. There is a growing interest in monitoring human health throughout the day [7, 8]. Normal body heat can be a valuable energy source during daily activities such as running, swimming, or walking. This energy can be harnessed by various devices, including thermoelectric generators (TEGs).

A TEG is a small device made from semiconductor material that converts waste heat into electricity via the Seebeck effect by using electrons as a working fluid [9-12]. A TEG produces a voltage potential when a temperature difference is applied across it [13, 14]. Therefore, a TEG can be used as a wearable device to generate electricity based on the human body's heat and the environment. The human body temperature typically ranges about 37°C [15], while the environmental temperature varies by region. For example, in winter, it can drop to (-30°C) in some countries; in summer, it can exceed (45°C) in others. As a result, a TEG can use the temperature difference between the body and the surroundings to generate electricity. Dargusch et al. [16] reviewed the application of TEG generators as power sources for wearable devices for monitoring systems.

Many researchers have developed the use of TEG in different parts of the human body [17, 18]. Bahk et al. [17] assessed wearable devices and flexible materials that harvest human body heat. Proto et al. [18] classified the development of materials that could harvest the energies generated by the human body. Also, their work discussed the development of nanogenerators based on piezoelectric, triboelectric, and thermoelectric effects to harvest energy from the human body. Amin et al. [19] concluded that the power obtained from a small area of thermoelectric generator produced higher power density than that of the larger one. For example, a device that generated 10 $\mu W/cm^2$ may be 1000X smaller than the one generated 10 nW/cm^2. In other words, the material of the semiconductor used or the number of thermoelements was less.

However, to date, there has been a lack of systematic experimental studies addressing system miniaturization, enhancement of power density from thermoelectric generators, and the influence of ambient temperature on system performance. In response to this gap, we have designed a novel system for energy body harvesting. This system integrates very small TEG (4 mm by 4 mm), heat sink, and a finger ring into a compatible system. The integrated system serves as an innovative energy source for operating various biosensor devices.

2. THEORY OF THERMOELECTRIC GENERATOR

A thermoelectric generator (TEG) is composed of semiconductor materials, specifically N-type and P-type elements. Typically, bismuth telluride is used, arranged electrically in series and thermally in parallel, as illustrated in Figure 1(a). When a temperature difference is applied across the TEG by heating one side and dissipating heat from the other, a voltage is generated through the Seebeck effect, as shown in Figure 1(b). Power output was extracted from TEG by connecting external load as shown in Figure 1(c). The maximum power output from TEG is measured when the external load is equal to the internal load of TEG.

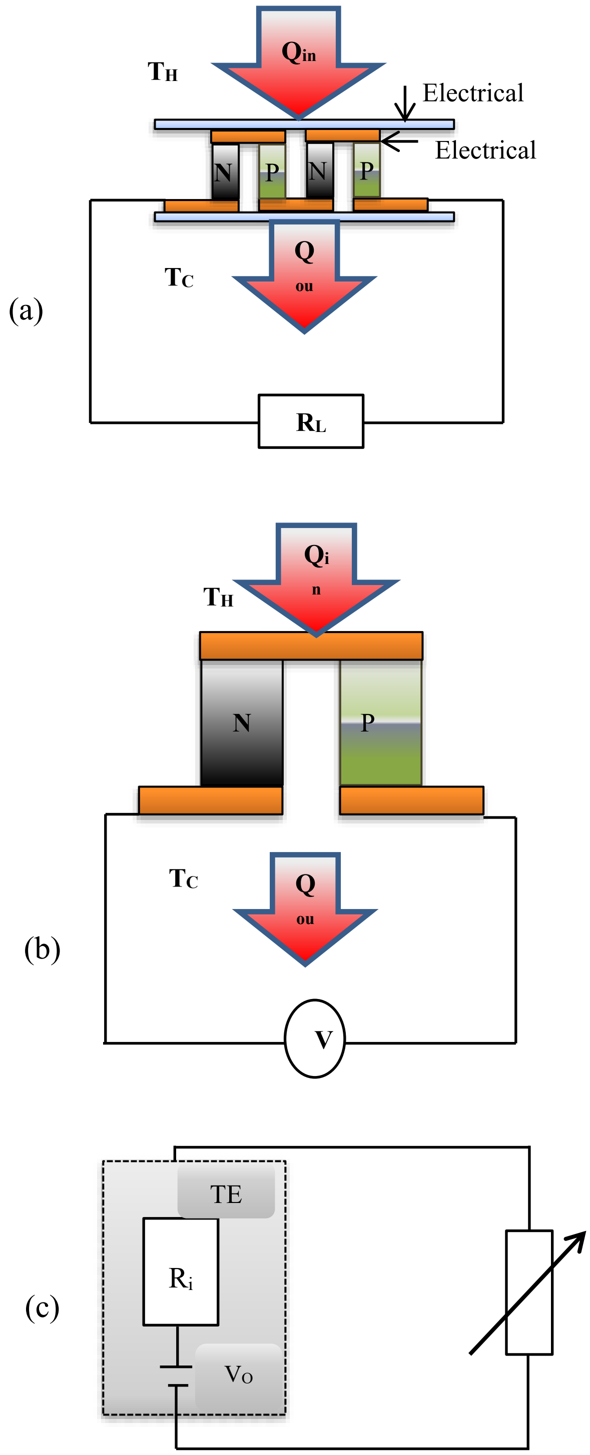

Figure 1. (a) Thermoelectric in generating mode, (b) the structure of thermoelements, (c) the electrical circuit of thermoelectric generator in case of measuring voltage and the output power

3. DESIGN AND FABRICATION OF WEARABLE SENSOR

A photograph of the experimental setup, structural design, and cross-section view of TEG is shown in Figure 2. The overall system consists of the following main parts: the ring, thermoelectric generator (TEG), and heat sink. It is interesting to mention here that both sides of the TEG were coated with a thin uniform layer of the thermal compound with a thermal conductivity of 2.9 W/m.K in order to increase the heat transfer between the heat sink and TEG in the cold side, and the ring with TEG for the hot side.

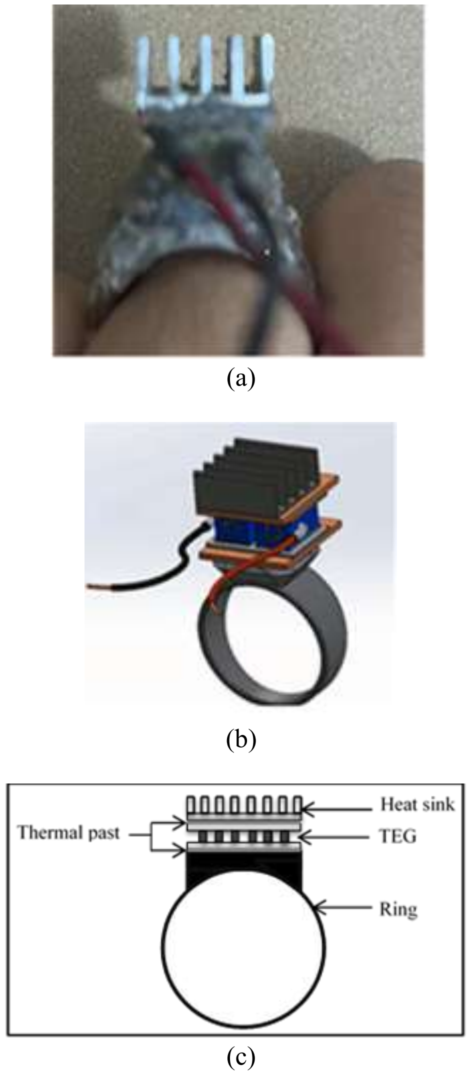

Figure 2. (a) Photograph view of wearable TEG, (b) structural design, and (c) cross-section view of TEG

A commercial-type thermoelectric generator with size (4 mm × 4 mm × 4 mm) and 14 legs made from bismuth telluride (Bi_2Te_3) with thermal conductivity of 1.20 W/m·K was used during the experimental setup.

The heat sink, made of aluminum and measuring 1.5 cm × 1.5 cm × 1 mm, functioned as a heat dissipation component. The thermoelectric generator (TEG) directly converts thermal energy into electrical energy, offering an alternative approach to generating electrical power. The efficiency of TEGs largely depends on both the material properties and design parameters, such as the number and length of thermoelectric legs. Additionally, heat transfer conditions play a critical role in determining both power output and overall efficiency. The open-circuit voltage and internal resistance were measured using an Overmeter (Ya Xun-VC9208AL). In contrast, the temperature of the hot side (T_H) and the cold side (T_C) of the thermoelectric was measured using an industrial infrared (IR) thermometer. The internal resistance of the TEG could be obtained by connecting different loads to it. Then, the value of the load when the power output is at its maximum represents the internal resistance of the TEG.

Our work is focused on developing tools for evaluating the thermoelectric power harvested from the human body. The power generated from this system has promising applications, including running a biomedical sensor and charging a small battery.

4. RESULTS AND DISCUSSION

An experimental investigation for the integrated system, including ring, TEG, and heat sink, has been conducted to harvest the output voltage from the heat of human body. The ring has been placed in direct contact with the skin of the middle finger. All measurements were carried out under conditions where the person wearing the device was stationary. The tests were accomplished at a different time during the year to evaluate the temperature difference that would be achieved and the corresponding voltage and power that could be generated. The optimization of the internal resistance of a TEG is necessary, as mentioned in many parts of the literature. Figure 3 represents the maximum power as a function of load for different ambient temperatures.

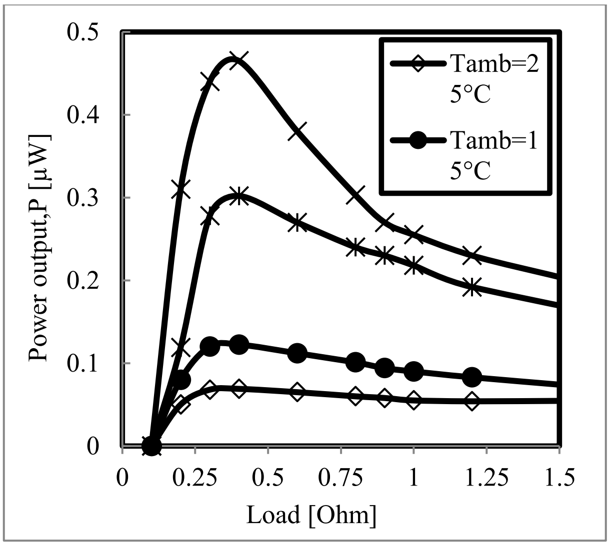

Figure 3. Effect of external loading on TEG output power

The maximum power occurred at 0.37 Ohm external load, representing the TEG's internal resistance. Figures 4-7 show the experimentally measured voltage, current and power values for TEG at the different ambient temperatures. Figure 4 shows the value of voltage, current and power when the ambient temperature (T_{amb}) was 25℃.

From Figure 4, it is clear that the maximum power output was about 70 µW. The value of power output slightly increased when the ambient temperature decreased due to increase in the temperature difference across the thermoelectric generator. For example, the maximum power output reached 120 µW when the ambient temperature decreased to 14℃, as shown in Figure 5.

It's worth noting that the heat sink plays a significant role of the heat sink in enhancing the TEG performance. As the ambient temperature decreases, the power output increases, reaching 395 µW and 480 µW, as shown in Figures 6 and 7, respectively. As long as the heat sink efficient to transfer the heat the temperature difference and the voltage output become high. The observed increase in output power is directly attributed to the drop in outdoor temperature, which lowers the temperature of the heat sink and, in turn, the cold side of the TEG. In contrast, the hot side, representing body heat, remains relatively stable. This enhanced temperature gradient across the TEG is crucial for generating a greater temperature difference, which in turn boosts the voltage and overall power output.

The maximum power, voltage and current occurred at the lowest ambient temperature as shown in Figure 7. The lowest ambient temperature fulfills the maximum temperature difference across thermoelectric generators. Thereby, the voltage and power generated from TEG will be higher. On the other hand, the lowest power, voltage and current happened at the highest ambient temperature, as shown in Figure 4 due to the lowest temperature difference. Torfs et al. [20] mentioned that 100 µW was engouth to operate a boimedical sensor such as puls oximeter. In summary, the 22 mV is enough to charge a battery or operate a biomedical sensor. Another word the power density generated from this word achieve the goal.

Table 1 shows the number of TEG couples, open circuit voltage and different power density values. The power density was calculated by dividing the power output to the total area of heat dissipation and the number of thermoelectric couples. It is interesting to mention that the voltage was increased up to (22 mV) because the temperature difference across thermoelectric generator was high due to Seeback effect ($V = \alpha.\Delta T$) [21]. Also, the heat flow by conduction from the hot side (the body skin) to the cold side (heat sink) was also, high according Fourier's law ($Q = -k.A.\Delta T/L$) [22]. Table 1 presents the open circuit voltage and output power density generated from this work and some references in the literature [23-30]. The results showed that the highest power density (200 µW. cm^{-2}) could be achieved due to the big temperature difference across TEG, about 30℃. As a result of using materials with high thermal conductivity and a reduced number of thermoelectric elements, heat flow through the TEG slowed down significantly. This led to an increased temperature difference across the device, thereby enhancing the generated voltage and power density.

Table 1. A comparison between experimental results of the powers output density from different works in the literature

No.	Number of TEG Couples	Out Put Power Density µW. cm^{-2}	Open Circuit Voltage (mV)	References
1	5	3.44	151	Wen et al. [23]
2	25	4.6	12	Hyland et al. [24]
3	25	6.1	14.8	Hyland et al. [24]
4	52	16.8	37.2	Wang et al. [25]
5	12	4.75	10.5	Shi et al. [26]
6	32	7.25	11	Suarez et al. [27]
7	15	5.6	8.8	Park et al. [28]
8	8	3800	90	Kim et al. [29]
9	15	126	---	Lee et al. [30]
10	7	200	22	Current work

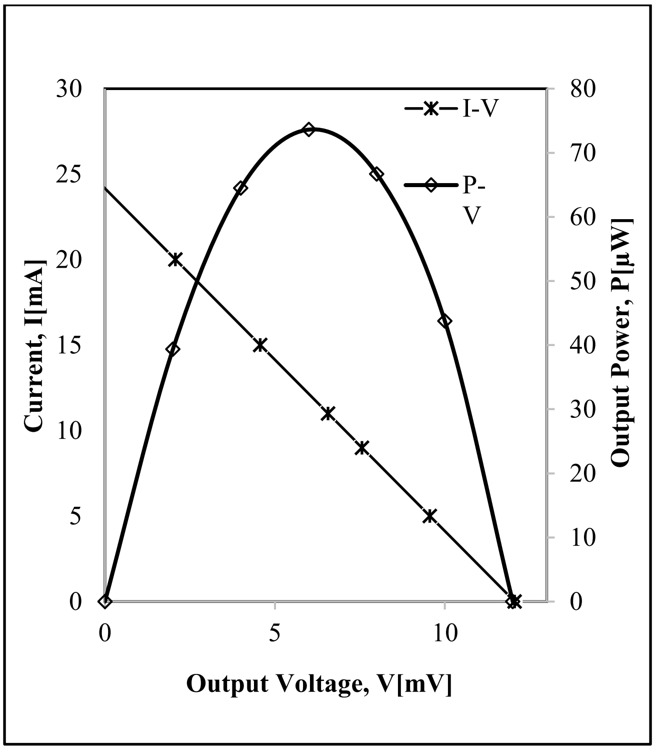

Figure 4. Voltage, current and power when T_{amb} was 25°C

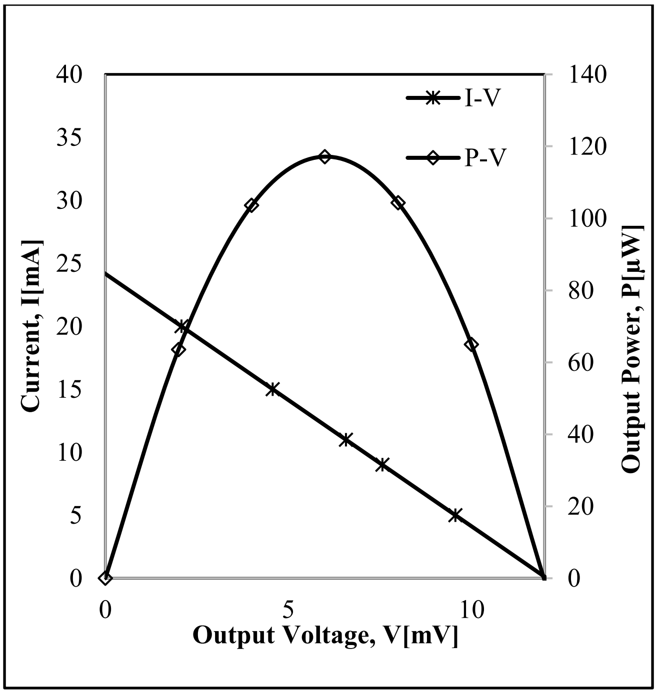

Figure 5. Voltage, current and power when T_{amb} was 14°C

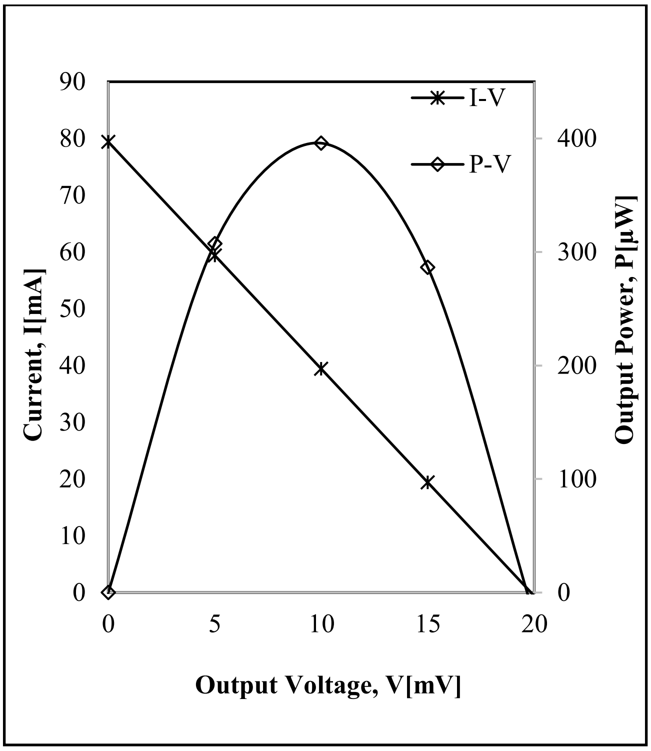

Figure 6. Voltage, current and power when T_{amb} was 10°C

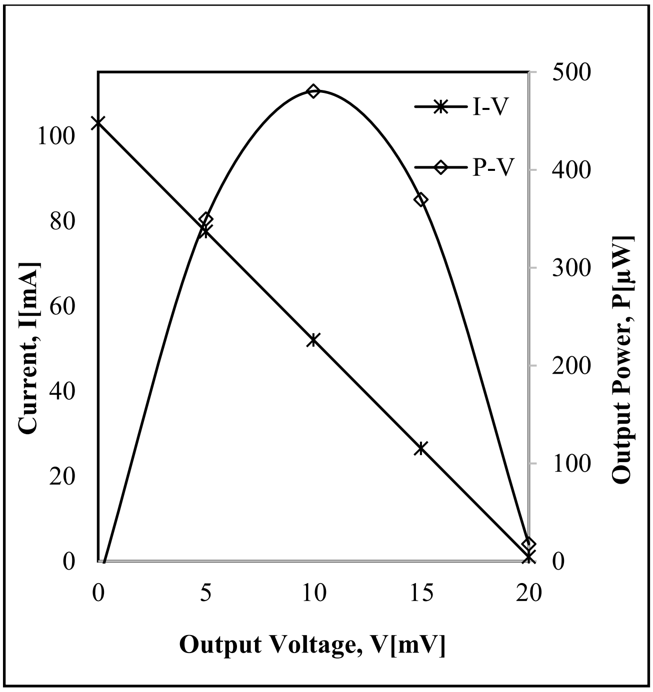

Figure 7. Voltage, current and power when T_{amb} was 7°C

5. UNCERTAINTY ANALYSIS

An uncertainty calculation was performed to assist the accuracy of the presented results. The stander deviation and uncertainty were calculated by using the following formulas [31].

$$X_m = \frac{1}{N}\sum_{i=1}^{N} X_i \tag{1}$$

$$V = \frac{1}{(N-1)}\sum_{i=1}^{N}(X_i^N - X_m^2) \tag{2}$$

$$S = \sqrt{V} \tag{3}$$

$$\mathrm{U} = \sqrt{\sum_{i=1}^{R} a_i^2\, X\, S^2} \tag{4}$$

where, X_m, X_i represents the mean of the observations and the specific observations, respectively. The total number of observations characterized by N while a is the precision. The standard deviation and uncertainty represented by S and U, respectively.

Uncertainty calculation data obtained from the measurements parameters which are voltage, hot side and cold side temperature are presented in Table 2.

Table 2. The standard deviation and uncertainty calculations

Parameters	V	S	U
Voltage	2.8E-08	0.000167	7.48E-05
Hot side Temperature (T_H)	0.599	0.774	0.346
Hot side Temperature (T_C)	0.116	0.341	0.152

6. CONCLUSIONS

An integrated system of miniaturized thermoelectric generators with the ring and heat sink was designed and fabricated to investigate the effect of ambient temperature on generating voltage and power from TEG. Different range of temperature differences characterized the open and closed-circuit voltage and power were investigated in this study. The following conclusions can be drawn from this research:

- The TEG's output voltage in the integrated system has a significant future potential.
- The maximum power is generated at approximately 0.37 Ohm when connecting different loads to the TEG at various temperature differences in a closed circuit, representing the TEG's internal resistance.
- The results indicated that decreasing the ambient temperature increases the temperature difference across thermoelectric generators, which increases the voltage and power generated, thereby achieving the maximum values of V_{out} = 22 mV, P_{max} = 480 μW and power density 200 μW. cm^{-2} at T_{amb} = 7°C.

7. FUTURE WORK

A significant development in performance can be achieved by introducing an amplifier system, which can almost double the power output. Additionally, the power generated could be investigated to run a biomedical sensor, such as a body heat sensor or an oxygen sensor.

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NOMENCLATURE

I	current, mA
k	thermal conductivity, W.m $^{-1}$. K $^{-1}$
P	power, W
Q_{in}	inlet heat transfer, W
Q_{out}	outlet heat transfer, W
R_L	external load, Ohm
R_{in}	internal load, Ohm
S	standard deviation
T_C	cold side temperature, ℃
T_H	hot side temperature
T_{amb}	ambient temperature
U	uncertainty
V_{OC}	open circuit voltage, V

Greek symbols

α	Seeback coefficient, V/K