Optimum Thermoelectric Energy Harvesting for Wearable System Applications

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ABSTRACT

The limitations in wearable devices are the battery size, weight, and its limited life time. By placing thermoelectric generator (TEG) on human body, wearable devices with micro-power operations can be powered continuously. In this paper, a thermoelectric energy harvesting technique is presented to power a micro-power wearable watch. The output voltage of TEGs is required to be higher than a certain voltage level (e.g. 28.5mV) for efficient operations. The required input and output voltages of the TEG are maintained during different activities, environmental conditions, and load conditions. The experimental result shows an output voltage of 5 V at open circuit, and 4.15V when it produces output power of 86.8μW at optimum load resistance of 200 kΩ. Experimental results are also extended for hybrid energy harvesting using both TEG and solar which provides fast and efficient energy harvesting both indoor and outdoor.

Keywords

Human Power; Energy Harvesting; Wearable; Thermoelectric.

1. INTRODUCTION

Energy harvesting techniques, which are small power generators, are becoming popular to be integrated with self-powered wearable devices. The energy harvesting techniques, such as mechanical vibration, solar or electromagnetic energy, and heat flow, are used for self-powered wearable devices. Though the energy from heat flow is relatively lower than other techniques, wearable devices powered by thermoelectric energy are particularly useful for elderly and mobility impaired people [1].

The thermoelectric generator (TEG) is based on Seebeck effect which produces voltage depending on temperature differences between each side of p-type and n-type semiconductors. Although the human body can continuously generate about 100W of heat energy on average, TEG placed on human body can convert only 0.2-0.4% of heat energy into electricity due to high thermal and contact resistances [2, 3]. Some efforts have been made to design and fabricate for higher output power of TEG and improved thermal and contact conductance [3-8]. The performance of TEG is also explored for wearable applications, such as electrocardiography, electroencephalogram, and pulse oximeter, which require lower power compared to the power generated by TEG [2, 8-11]. Considerable efforts have also been made to design better radiators with lower contact resistance to improve heat flow as well as output power per unit area.

The open circuit voltage generated by TEG (V_{TEG_OC}), as shown in (1), is directly proportional to the temperature difference (ΔT), the number of thermoelectric element (N), and the material of the thermoelectric element or Seebeck Coefficient (S).

$$V_{TEG\_OC} = \mathrm{N} \times S \times \Delta T \qquad (1)$$

The maximum power produced by TEG (P_{load}) can be achieved by matching the internal resistance of the TEG, R_{TEG} with load resistance, R_L. The maximum power produced by wearable TEG is recorded in [11] to be 1.65mW for ΔT of 13.1℃ during running outdoor condition.

This paper investigates an energy harvesting technique using TEG to achieve higher output voltage and power under different activities, environmental conditions, and load conditions. The performance of this technique with a boost converter circuit is also verified for charging up a super-capacitor as well as a wearable watch. The operating time and efficiency of the TEG is improved by adopting a hybrid TEG and solar cell for ultra-low power wearable devices.

2. THERMAL ENERGY HARVESTER

2.1 Design of TEG

Two commercial TEGs, Tellurex (TXL-287-03Z) and ZP9104, having dimensions of 6.2x6.2cm and 4x4cm, and internal resistances (RTEG) of 8.3Ω and 1.5Ω, respectively, are chosen for the experiments. The TEG comes with ceramic plates mounted on both sides, as shown on Fig. 1(a). The TEG is placed on human forearm, and thus heat is applied on one side. On the other side of the TEG, a heatsink is attached to maximize the temperature difference. A flat aluminum 2mm thickness heatsink is placed on TXL-287-03Z (big TEG), and a 6.2mm thick pinned aluminum heatsink is placed on ZP9104 (small TEG).

2.2 Characterization of TEG

By connecting both TEGs directly to a resistive load under outdoor and indoor conditions, as shown in Fig. 1(b), the maximum power generated by both TEGs is measured using $P_{load} = \left(V_{TEG\_OC}\right)^2 \times R_L/(R_L + R_{TEG})^2$, where V_{TEG_OC} is measured by averaging 1-hour of voltage data at ambient temperature of 17℃. The energy

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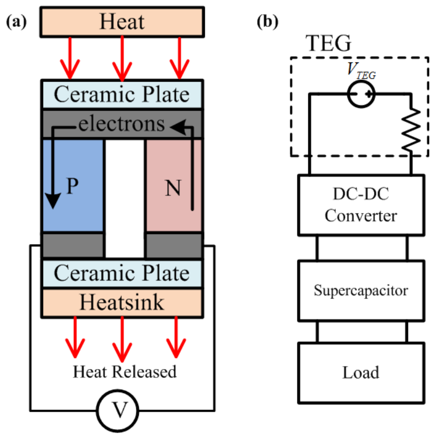

Figure 1. (a) Structure of a thermoelectric generator (TEG). (b) Block diagram of the energy harvesting system using TEG.

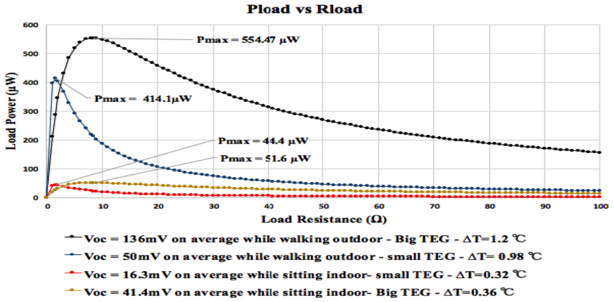

Figure 2. Load power of 6.2x6.2cm Big TEG and 4x4cm Small TEG under different activities, environmental conditions, and load conditions.

harvesting system uses a DC-DC boost converter circuit to deliver power to a supercapacitor and a load. The output voltage of the DC-DC boost converter (LTC3109) can provide a constant output voltage of 4.97 V if the input voltage is higher than 28.5mV. Therefore, the TEGs are optimized to provide higher output voltage under different activities, environmental conditions, and load conditions.

The output power calculated at different load resistances for both TEGs with heatsinks are shown in Fig. 2. For big TEG with flat heatsink at matching load, the maximum output power of 554.47 μW, which corresponds to power density of 14.42 μW/cm^2, is achieved under walking outdoor condition with V_{TEG_OC} of 136 mV and ΔT of 1.20^o C. While walking outdoor condition yields higher output power, sitting indoor condition produces a maximum output power of 51.6 μW with V_{TEG_OC} of 41.4 mV and ΔT of 0.36^o C. For small TEG with pinned heatsink at matching load, the maximum output power of 414.10 μW is achieved under walking outdoor condition with V_{TEG_OC} of 50 mV and ΔT of 0.98^o C. Under sitting indoor condition, this TEG produces output power of 44.40 μW with V_{TEG_OC} of 16.3 mV and ΔT of 0.32^o C. The internal resistances of the big and small TEG are 8.3Ω and 1.5Ω, respectively.

Though both TEGs produces enough power for ultra-low power wearable devices, it is required to provide a regulated and higher voltage for varying open circuit voltage output obtained from TEGs. A DC-DC boost converter (LTC3109) is used, as shown in Fig. 1(b), which can provide a constant output voltage of 4.97 V for more than 28.5 mV of input voltage from TEGs. The input voltage of the boost converter generated by both TEGs and the output voltage of the boost converter under different activities and environmental conditions are shown in Fig. 3. From the figure, walking outdoor and walking indoor conditions yield a stable output voltage from boost converter as both TEGs produces voltage higher than 28.5 mV due to higher temperature gradient from higher induced and natural convection of air. Since sitting outdoor condition is only influenced by natural air convection, the big TEG produces output voltages around 28.5 mV, which in turn yields fluctuating output voltage from boost converter. Due to smaller area of small TEG, the temperature difference as well as output voltage from TEG is smaller than big TEG under sitting outdoor condition. Both TEGs cannot produce enough voltage to produce a stable output voltage from boost converter under sitting indoor condition due to very limited natural air convection.

The average output power for both big and small TEGs, which are measured under walking outdoor condition with load resistance of 200 kΩ connected at the output of boost converter, are 86.8 μW and 66.5 μW, respectively. Though the output power from boost converter under sitting indoor and outdoor is lower, a supercapacitor can be used, as shown in Fig. 1, to store the energy.

A supercapacitor (ELNA 47mF, ESR = 120Ω, 5.5V) is used to store energy from the output voltage of boost converter while walking outdoor. The rate of voltage change during charging phase is 41.5 mV/minute using big TEG, as shown in Fig. 4. For small TEG, the rate of voltage change during charging phase is 39.3mV/minute. The current through the capacitor for big TEG and small TEG is 32.43μA and 29.61μA, respectively.

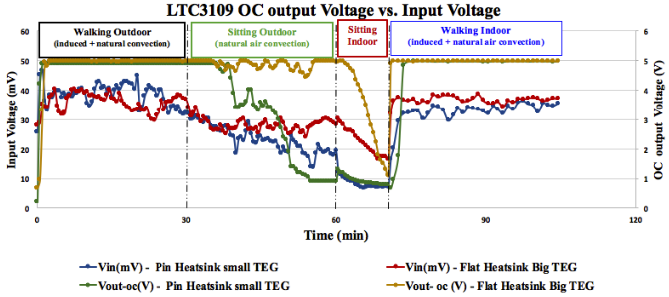

Figure 3. The input voltage of the boost converter generated by both TEGs and the output voltage of the boost converter under different activities and environmental conditions.

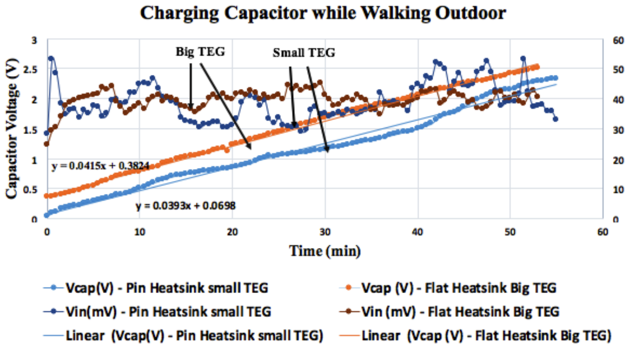

Figure 4. Charging characteristics of a 47mF supercapacitor for both big and small TEG.

2.3 Wearable Watch with TEG

A Casio watch (W-59-1VQES), which is used as a load for the circuit, is powered using the small TEG with pinned heatsink and the boost converter with output voltage regulated at 3V. Figure 5 shows the experimental setup to deliver power to a watch from TEG. The load current and the voltage has been recorded when walking outdoor and indoor, and sitting indoor. The load voltage and power of the watch during walking outdoor, sitting indoor, and walking indoor conditions are shown in Fig. 6. The watch remains operational as long as the load voltage (blue line) is above 1V or the power (orange line) is above 1.5μW. Under sitting indoor condition, the TEG can deliver power to the watch for 6 minutes. Under walking indoor or outdoor conditions, the TEG can deliver power to the watch.

To increase the duration of operating time under sitting condition, a capacitor is also connected in parallel with the watch. The output voltages of TEG and load with supercapacitor during walking outdoor, sitting indoor, and walking indoor conditions are shown in Fig. 7. This configuration can extend the operating time considerably for low-power wearable devices.

3. HYBRID THERMAL AND SOLAR ENERGY HARVESTER

3.1 Design of Hybrid TEG and Solar

To further extend the operating time, a hybrid TEG and solar cell is designed, as shown in Fig. 8. In this circuit configuration, the small TEG with pinned heatsink and a flexible solar cell is used. The Schottky diodes are used to control the power flow from TEG and solar cell to either capacitor or load. When solar cell is producing higher power than TEG under sunny outdoor condition, solar cell can deliver power to the load, R_{Load} while TEG can store energy in capacitor C_1. During dark or cloudy condition, TEG or stored energy from C_1 can deliver power to the load while solar cell can store energy in capacitor C_2. In this process, the energy harvested from thermal and solar can be used for low-power wearable devices. Figure 9 shows the experimental setup of hybrid TEG and flexible solar cell for efficient power management. The values of C_1, R_{Load}, and C_2 used during the experiments are 47mF, 200kΩ , and 1F, respectively.

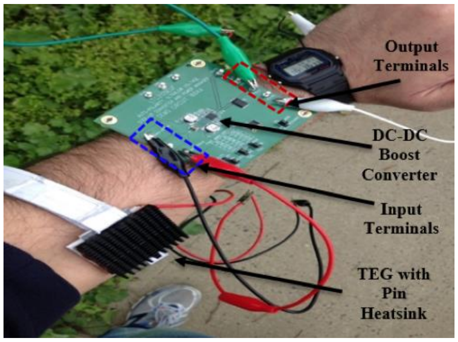

Figure 5. Experimental setup to power on a watch using TEG.

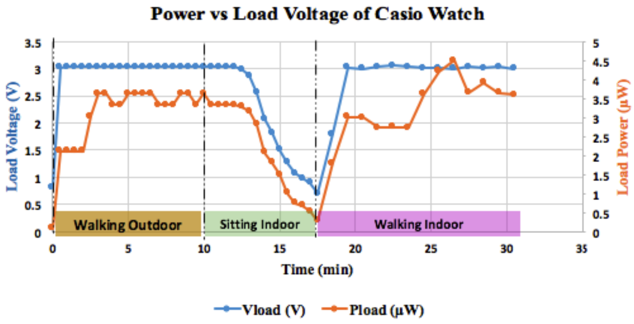

Figure 6. Load voltage and power of a watch during walking outdoor, sitting indoor, and walking indoor conditions.

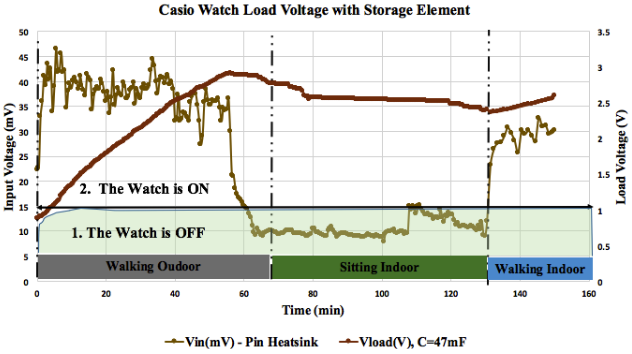

Figure 7. The output voltage of TEG and load with supercapacitor during walking outdoor, sitting indoor, and walking indoor conditions.

3.2 Experimental Results

The output voltages at five nodes of hybrid energy harvester of TEG and solar cell circuit in Fig. 8 under different activities and environmental conditions are shown in Fig. 10. During walking outdoor under the shade (or dark) condition, output voltages at node A and B (V_A and V_B on TEG side) are increasing while output voltages at node D and E (V_D and V_E on solar side) remains constant. Since the output voltage at node B is higher than node D, the load voltage at node C follows the TEG side. Therefore, TEG

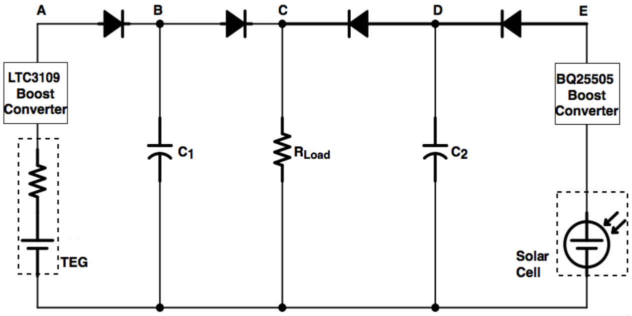

Figure 8. The hybrid energy harvester of TEG and solar cell.

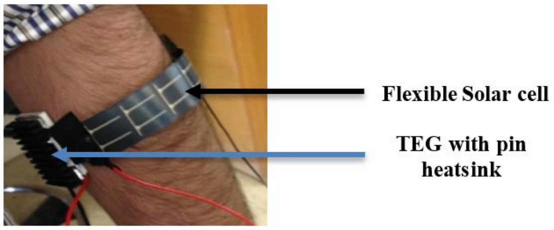

Figure 9. Experimental setup of hybrid TEG and solar cell.

delivers power to the load and C_1 and solar cell is storing energy in C_2 during walking outdoor conditions.

During sitting outdoor in partially cloudy environment, solar cell produces higher power compared to TEG which in turn increases output voltage from solar cell significantly. When output voltage at node D is higher than node B, the load voltage at node C follows the solar side. Therefore, solar cell delivers power to the load and C_2 and TEG is storing energy in C_1 during sitting outdoor in partially cloudy conditions.

During sitting indoor condition, the load voltage at node C continues to follow voltage at node D or solar side due to its higher voltage than node B. At this condition, the energy stored in C1 at node B can deliver power to load if the voltage at node D becomes lower. Therefore, the hybrid TEG and solar cell can improve the operating time for low-power wearable devices.

4. PERFORMANCE SUMMARY

A performance comparison of the energy harvesting technique using TEG with previous wearable TEGs in the literature is shown in Table 1. The big TEG (without boost converter) placed on human forearm is capable of producing 554.47 µW with power density of 14.42 µW/cm^2 which is higher than that in [10]. The maximum power density is 25.9 µW/cm^2 using the small TEG (without boost converter) which is higher than the power densities in [8-10]. Though the maximum power density of 120 µW/cm^2 is reported in [3], the use of a fan with adjustable speed for forced air convection can consume higher power. In this work, the measurements are performed for natural and induced air convection.

5. CONCLUSION

An energy harvesting system consisting of thermoelectric generator and boost converter is designed. The experimental results also validate the applicability of this system for ultra-low power wearable devices. The operating time of the system is improved by connecting a supercapacitor in parallel with the load. A hybrid thermal and solar cell system is explored to further improve the operating time of the system which is suitable to deliver power to wearable devices under different activities, environmental conditions, and load conditions.

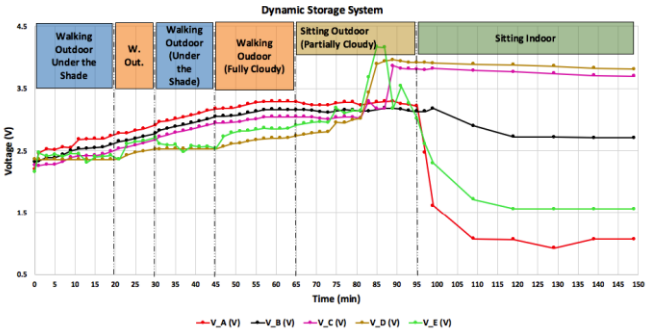

Figure 10. The output voltage at 5 nodes of hybrid energy harvester of TEG and solar cell circuit in Fig. 8 under different activities and environmental conditions.

6. ACKNOWLEDGMENT

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7. REFERENCES

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Table 1: State-of-the- Art of wearable thermoelectric generator.

Reference	**This Work**		**This Work**		**[3]**	**[8]**	**[10]**	**[9]**
Year	2016		2016		2016	2016	2014	2012
TEG Name	ZP9104 (small TEG)		TXL-287-03Z (big TEG)		Custom TEG	TEG with PDMS	G230–0313	wearable wristband
R_{TEG}	1.5 Ω		8.3 Ω		9 Ω	1.8Ω	7.6 Ω	10 Ω
Walking Outdoor Average Power or Power Density	414.10 µW or 25.9 µW/ cm^2		554.47 µW or 14.42 µW/ cm^2		120 µW/ cm^2 at 0.9 m/s of air speed	20 µW/ cm^2	20µW or 2.2µW/cm^2	280µW or 25µW/cm^2
Sitting Indoor Average Power or Power Density	44.40 µW or 2.8 µW/ cm^2		51.60 µW or 1.34 µW/ cm^2		20 µW/ cm^2 with no air flow	6 µW/ cm^2	-	-
TEG Location	Forearm		Forearm		Wrist	Forearm	Wrist	Forearm
Ambient Temp.	**Indoor**	**Outdoor**	**Indoor**	**Outdoor**	27°C	-	22°C	-
	22.5°C	17°C	22.5°C	17°C				
ΔT	0.32°C	0.98°C	0.36°C	1.20°C	<1°C	2.0°C	0.5°C	3.5°C
Heatsink Type	Pin Radiator		Plane Aluminum		Pin Radiator	Copper	Aluminum block	Checker-board

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