Energy Conversion and Management 143 (2017) 218–226

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Human and environmental analysis of wearable thermal energy harvesting

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ARTICLE INFO

Article history:
Received 12 January 2017
Received in revised form 31 March 2017
Accepted 1 April 2017

Keywords:
Wearable technology
Energy harvesting
Thermoelectric devices
Environmental to human correlations

ABSTRACT

In considering wearable energy harvesting, one must recognize the wide array of factors that lead to variations of energy harvesting. The objective of this work is to define analytical methods to study the effect of environmental and human factors on thermal energy generator (TEG) performance in a variety of use case scenarios. A test method for evaluating the performance of a TEG in a wearable form is developed and demonstrated using both in-lab and out-of-lab procedures. The fabrication procedure of an energy harvesting wearable device demonstrates a method of integrating rigid devices into a flexible substrate. The wearable device is used in a human trial which covered a series of activities in different environmental conditions. The results of these trials demonstrate the significant effect of movement, or convection, on thermal energy harvesting. Humidity levels do not have a significant correlation to power; however, wet bulb temperature must be taken into consideration due to the additional cooling effect of evaporation on temperature. The data collected indicates that while dry-bulb temperature does not have the greatest effect on TEG power generation, wet-bulb temperature is indicative of TEG performance. Additionally, user generated movement is the main consideration when designing a wearable device with TEGs as it had the largest effects on power generation. The results of this work quantify how a wearable device will perform throughout daily activities, allowing the definition of an operational scenario of a self-powered wearable device while choosing the most appropriate design for a particular application. This work also provides a foundation for exploring how textiles can enable the design of unique wearable devices. This will lead to further investigation into quantifying the effect that the construction of a textile has on TEG performance as well as on consumer comfort.

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1. Introduction

Recent advances in low power electronics, including semiconductor on chip and radios are enabling opportunities in wearable devices that utilize sources of energy outside the use of a battery. In wearable devices, batteries add both bulk and weight to a device reducing its perceived comfort [1–4], and also require plug-in recharging that can seem burdening to the consumer. While low power electronics enable strategies in reducing the battery size or improving the operating lifetime between battery charges, the ability to use energy harvesting directly from the body has been suggested as an alternate source of power. Studies exploring mechanical and thermal energy harvesting have shown promise in guiding energy harvesting materials design, but have been limited to benchtop and short term use case studies [5–8]. The energy harvesting packaging design for on-body use has a number of complex design criteria that define the device comfort and performance. For example, the on-body location of the device identifies form factor, flexibility, materials used, etc. that need to be considered with regard to user comfort. The device performance is highly dependent on human factors that are even more influential to the performance of the energy harvester [9–11]. For a thermal energy generator (TEG), human factors include the temperature difference between the surface of the skin and ambient air, air velocity over the TEG, and the humidity of the ambient air, resulting in a complex combinatorial effect on the energy harvesting ability of the TEG. The influence of these variables is dependent on the harvester's location on the body. This work aims to explore testing strategies for determining the effect of human factors related to thermal energy harvesting, including environmental influences

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http://dx.doi.org/10.1016/j.enconman.2017.04.002
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and position, or location, of energy harvesting, which thereby enables future strategic design of the materials surrounding the energy harvesting for improving performance.

Prior research has shown that thermal energy harvesting offers a consistent supply of energy for wearable energy harvesting purposes [12–16]. Of particular note is the work conducted by Leonov et al. [12,15,17,18] that have demonstrated TEG performance in a watch-based and shirt based platforms. Their research demonstrated that the key challenge of thermal energy harvesting from the body is the temperature differential between the body and microclimate surrounding the device that ultimately limits the energy that can be harvested. The common approach to improve thermal energy harvesting is to include a heat spreader and/or a heat sink to improve power output and maintain a temperature gradient across wearable TEGs. The rigid and bulkiness of the heat sink comes at the expense the perceived comfort of the device. Settaluri et al. [19] characterized and optimized a heat sink and heat spreader system for use with a wearable TEG wristband, acquiring a power density of 28.5 $\mu W/cm^2$. Another is the fabrication of flexible or fiber-based TEGs [8,20–22] which improves the TEG-to-skin contact. Both of these methods highlight the importance of improving TEG performance on a device level in a more comfortable manner, but do not consider the variety of environmental conditions the human body is exposed to on a daily basis. Of particular interest is the observation that thermal energy harvesting has been shown to have negative effects on human comfort due to a high heat flow from the skin resulting in a chilling effect [17,23]. For the eventual success of on-body energy harvesting, the ability to understand what factors influence energy harvesting over the wide range of body placement and human factors is paramount to mitigating human discomfort without compromising the efficiency of the thermal energy harvester.

The purpose of this work is to quantify the effects of transient environmental conditions and human scenarios on the efficiency of a body-worn TEG via controlled laboratory experiments and human trial studies. The controlled tests presented in this work characterize the TEG with defined heat loads, air velocities, and heat sinks to define TEG integration strategies. Using these design strategies, a wearable platform is used to collect experimental data directly from a human in true indoor and outdoor conditions. As part of the device design, a novel printed circuit board (PCB) design was constructed to simultaneously monitor the environmental conditions, activity level of the human, and the instantaneous power generated by the TEG device. Data was collected using this platform in real time with human subjects performing different activities that changed motion and environmental conditions. The results of this work identify specific environmental variables that show the largest effect on the energy harvested and analysis is performed to define correlations between motion intensity and power generation. Finally, a power map based on activity and external environment is defined that can be used to estimate TEG efficiency in future studies.

2. Methods for TEG characterization and human trials

2.1. In-Lab TEG characterization

Several tests were performed in a controlled laboratory setting to characterize the response of the TEGs (Laird Technologies: OT08, 18, F0, 0505, 11) used in this study. In a benchtop analysis, finned heat sinks with values of 10 °C/W, 4.6 °C/W, and 1.9 °C/W (CTS Electronics Components) were each applied to the TEG with matched load (4.4 Ω) and the power output recorded. The TEG was placed in contact with a thin layer of polydimethylsiloxane (PDMS) situated in contact with a hot plate. The PDMS served as a thermal simulant to skin (the thermal conductivity of PDMS is 0.15 W/mK [24] while the thermal conductivity of the epidermis layer of skin ranges from 0.2 to 0.5 W/mK [25]) and the PDMS was able to dampen the effects of the temperature fluctuations of the hot plate with minor spatial variability. A hot plate temperature of 37 °C resulted in a PDMS exposed surface temperature of 35 °C, which is an average temperature of human skin [26]. During all experiments, the ambient air temperature remained between 21 and 22 °C. After the TEG power output reached steady state in stagnant air (~30 min), an air flow of 1.2 m/s was provided using a small fan placed 15 cm away from the heat sink edge to simulate the airflow induced by a human walking pace [27]. This setup is similar to that demonstrated previously in testing for a material's Seebeck coefficient for a TEG placed on the body [28].

The effect of spacing between TEGs was evaluated by placing two TEGs in series at increasing spaces. The spacing between the TEGs ranged from 0 mm to 6 mm as measured between the neighboring edge of each device, and held in place with in a structural mold. The TEGs were placed on the heated PDMS with a matched resistive load (8.8 Ω) and the experiment outlined previously was repeated.

2.2. On-Body TEG evaluation

The construction of the wearable TEG devices is outlined below in terms of the formation of the flexible TEG integration into a textile assembly and the construction of a novel evaluation platform for communicating the data wirelessly from the body to an Android tablet. Finally, the experimental design for the human trial study is described.

The design for integrating a series of TEGs into a flexible package is outlined in Fig. 1a. Pyralux® (Dupont), a flexible Kapton substrate that is coated in Cu on one side, serves as the flexible substrate which connects the TEGs. Pyralux® substrate is prepared

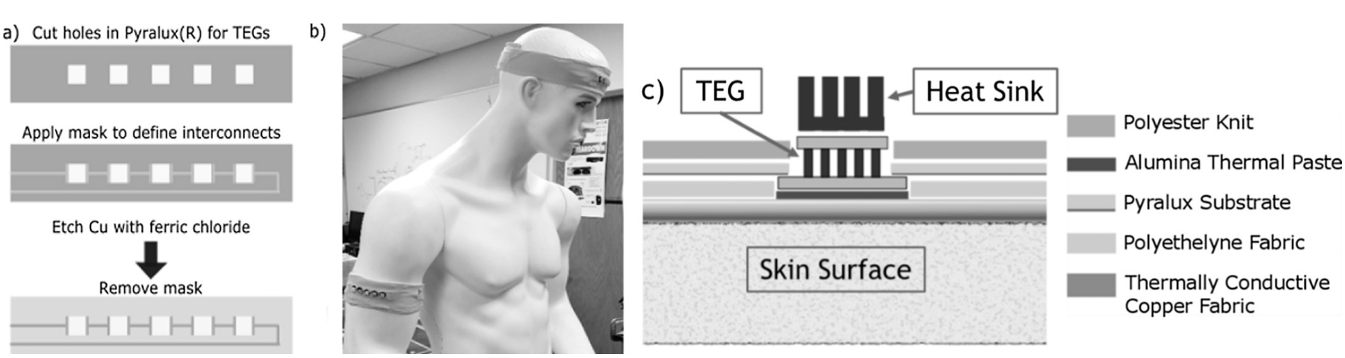

Fig. 1. (a) Overview of flexible circuit fabrication process. (b) Fabricated headband and armband. (c) Profile view of device assembly.

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