

Effects of thermal energy harvesting on the human – clothing – environment microsystem

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Abstract. The objective of this work is to perform an in depth investigation of garment-based thermal energy harvesting. The effect of human and environmental factors on the working efficiency of a thermal energy harvesting devices, or a thermoelectric generator (TEG), placed on the body is explored.. Variables that strongly effect the response of the TEG are as follows: skin temperature, human motion or speed, body location, environmental conditions, and the textile properties surrounding the TEG. In this study, the use of textiles for managing thermal comfort of wearable technology and energy harvesting are defined. By varying the stitch length and/or knit structure, one can manipulate the thermal conductivity of the garment in a specific location. Another method of improving TEG efficiency is through the use of a heat spreader, which increases the effective collection area of heat on the TEG hot side. Here we show the effect of a TEG on the thermal properties of a garment with regard to two knit stitches, jersey and 1 x 1 rib.

1. Introduction

Wearable technology is a rapidly growing consumer market that is a blend of the electronics industry and the textiles industry. Most research in wearable technology is dedicated to each industry separately. However, its success depends on the cooperation of two these well established markets. As such, it is of critical importance to understand the effect an electrical device has on a textile and vice versa. This work studies the interaction between a thermal energy harvesting device and the knit that immediately surrounds the device.

One limitation of current wearable devices is power sources and management. Batteries are bulky and heavy and a wired power supply limits the usefulness of the device. Thus, researchers and industry look to energy harvesting as the primary source of power for wearable technology. Energy harvesting appears in multiple forms, thermoelectric energy harvesting, kinetic (piezoelectric) energy harvesting, strain (triboelectric) energy harvesting, and solar (photoelectric) energy harvesting are the most widely studied energy harvesting methods for wearable applications. In this work, we focus on thermoelectric energy harvesting devices as the electronic component of a garment.

Thermoelectric materials generate current when exposed to a temperature difference, Figure 1, or generate a temperature gradient when supplied with electrical current. This is due to material



properties that result in two thermodynamic effects known as the Seebeck effect and the Joule effect. Thermoelectric materials are classified by their respective ZT values, which is a function of the inverse correlation between thermal and electrical conductivity. Optimizing a thermoelectric material results in a material paradox as thermal and electrical conductivity are generally directly correlated. Applying a thermoelectric energy generator (TEG) to the body surface utilizes the heat flux away from the body to generate power.

For a TEG to produce enough power for an electronic device, one must increase the temperature difference across the hot and cold sides of the TEG. One issue with wearable thermal energy harvesting is the small temperature difference between human skin and ambient air. Textile properties such as wicking and garment fit exaggerate this effect. Leonov et al [1–3] reported a localized sensation of skin cooling when the heat flux from the skin reached $15 - 25 \text{ mW cm}^{-2}$. This cooling sensation can be uncomfortable and adversely affect thermal power generation. Thus, the material surrounding the TEG should have insulative properties that maintain a temperature difference across the TEG without compromising the comfort of the garment.

Currently, TEGs integrated into commercial textiles as examples of wearable energy harvesting are simply added to the existing garment without taking textile factors into consideration. Much research focuses improving thermal energy harvesting by improving TEG design or materials. Rather than try to optimize a TEG to operate in a certain textile or garment, we look at manipulating the textile with regard to a specific TEG and study the thermal effects of a TEG on a textile. Due to the large and dynamic range of environmental conditions that the TEG device will be exposed to, the textile needs either to adapt to the new environment or be designed to provide comfort in a variety of ambient conditions. One method to do this is by dictating knit structure placement in garments.

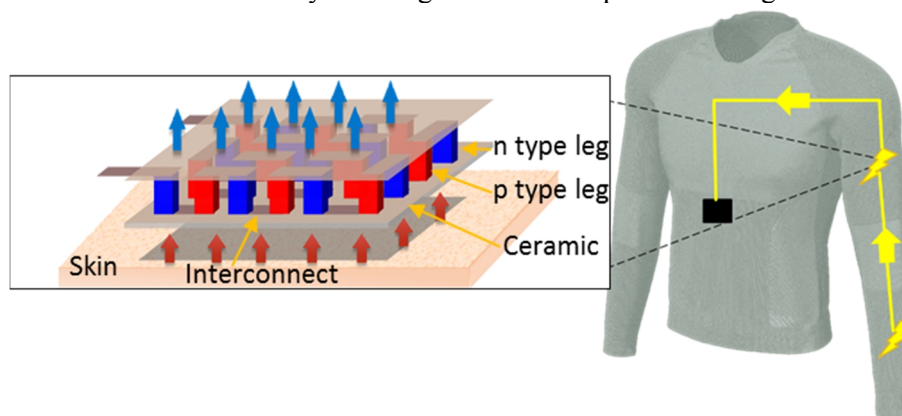


Figure 1. Schematic of a thermal energy harvesting device as worn on the body. It is shown integrated in a thermal energy harvesting shirt, where the harvested energy is used to power a wearable device.

2. Experimental Methods

In this work, the thermal distribution in a garment induced by the addition a TEG is verified using finite element simulation and experimental data. For the finite element simulation, a CAD model of both a jersey and a 1x1 rib knit structure are imported into ANSYS FLUENT, a finite element analysis software for fluid flow and heat transfer, to model heat flux as it moves away from the body and through the textile. Experimental data is generated by a controlled laboratory experiment using thermal imaging measurements and a human trial experiment. The computational results match the results thermal imaging experiments verifying the accuracy of the model and enabling the design of a TEG shirt, Figure 1, to be used in the human trials.

The controlled experiment consists of placing a 120 mm by 60 mm swatch of knit fabric on a hot plate set to average skin temperature, 37°C . [4] Two knit stitches, jersey and rib, are compared by knitting swatches, cutting a hole for TEG insertion into the swatch, and using a FLIR thermal imaging camera to monitor the surface temperature change over time. The samples are placed on a room

temperature surface that then heats to 37 °C. The sample remains with 37 °C input for 5 min before removal. The hot plate is allowed to cool between each trial.

The knit swatches are modelled in detail using Solidworks software, Figure 2a. However, after importing the model to ANSYS for analysis, processing time increased significantly. So for the computational analysis, the swatches are considered porous substrates with thermal and geometric data acquired from the fabricated swatches. The heat transfer simulation constraints and boundaries are set to mimic those specified in the experimental trials. In the simulations, we assume the TEG to be a solid material component of bismuth-telluride. A heat source is modelled with a total heat generation of 1 W m⁻³. Stagnant air at room temperature defines the simulation environment.

The information from the previous experiments guides the knit design of the shirt. To reduce knitting production errors, only jersey and rib, structures are used in the design. For example, the sleeves of the shirt are constructed with a 1x1 rib knit that provides more insulation surrounding the TEG and supplies increased mechanical support via compression. The knit structure of the shirt is designed in Apex3 software and knit on a 15G Shima Seiki Mach 2XS Whole Garment machine. The shirt is knit with 3 ends of 2-ply 140 den. polyester Repreve yarn. Then, a TEG is integrated into the knit so that the body serves as the heat source and heat flux is normal to the skin. At the site of each TEG is a circuit board to measure movement and temperature conditions immediately surrounding the TEG.

The addition of the TEG and electronic components disturb the traditional heat transfer model away from the skin by adding additional sources of heat (electronic components) and thermal resistances. A new heat flux model that accounts for these differences is calculated so the knit shirt may be designed to mitigate any thermal disruption via changes in knit structure or stitch length.

3. Results and Discussion

The renderings of each knit structure are seen in Figures 2a and 2d. ANSYS was unable to mesh the detailed geometries due to processing constraints. The knit swatches for the thermal imaging experiment define the material properties for the simulation. The simplified porous model for the jersey knit is imported with a thickness of 1 mm and of 2.75 mm for the rib knit. The density of the jersey sample is 0.2016 g cm⁻³ as found by weighing a 1 cm by 1 cm square and then dividing by the thickness. The density of the rib sample is 0.0826 g cm⁻³. The thermal conductivity of polyester is defined as 0.24 W m⁻¹ K⁻¹ where the effective thermal conductivity due to the porous structure is accounted for by stating the porosity. The porosity of the knits are 0.16 and 0.27 for the jersey and rib structures, respectively. The TEG is included in the analysis as a solid thermal resistance block. An equivalent hole is cut in the textile model to accommodate the TEG block. The ANSYS simulation models the temperature distribution throughout the textile with a 1 W m⁻³ heat generation input at the base of the textile to simulate heat flux away from the skin.

The results of the heat transfer modelling are seen in Figures 2c and 2f as compared to the same temperature color scale. There is a significant difference in temperature distribution noted between the two knit simulations. The jersey knit, Figure 2c, has an even temperature across the textile with no apparent disturbance induced by the addition of the TEG. However, the rib knit, Figure 2f, shows a thermal gradient both across and through the textile as well as a lower surface temperature. There is additional thermal disturbance surrounding the TEG that indicates the creation of a thermal interface.

The temperature distribution seen in the simulation is verified via experimental thermal imaging data, seen in Figures 2b and 2e. A 9 mm by 9 mm square is cut in the knit swatches for TEG insertion. After the heat source reaches 37 °C, the system is allowed reach a thermal steady state. The thermal images confirm the results of the ANSYS simulation. There is a uniform temperature distribution across the jersey knit, while the rib knit shows more variation. As before, the surface temperature of the rib knit is lower than that of the jersey knit due to differences in density and porosity.

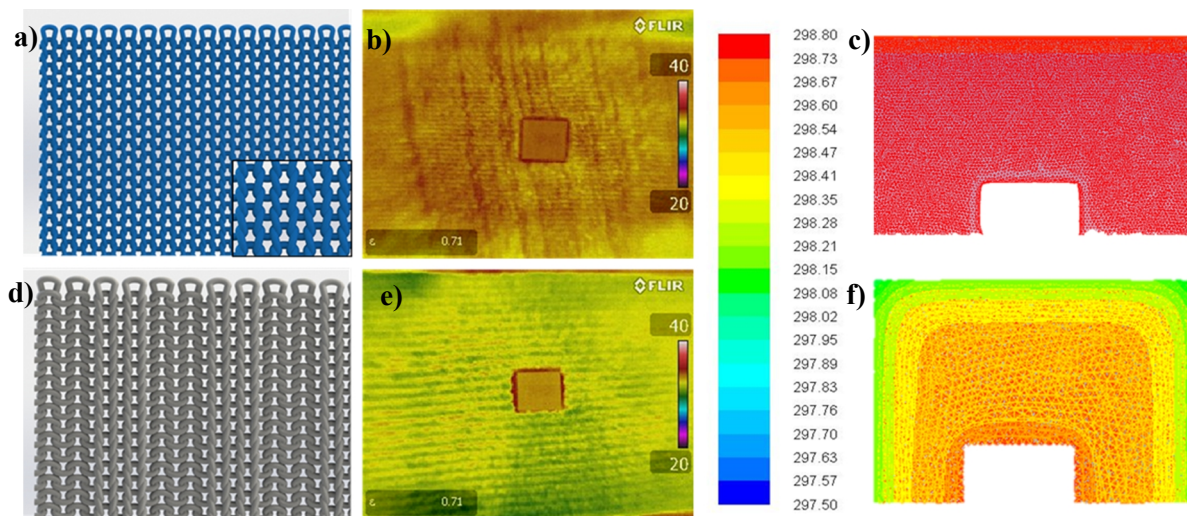


Figure 2. a) Solidworks rendering of a jersey knit structure b) Steady state infrared image of the jersey knit surface with an integrated TEG c) Predicted temperature distribution across the jersey textile surface from the ANSYS model d) Solidworks rendering of a rib knit structure e) Steady state infrared image of the rib knit surface with an integrated TEG f) Predicted temperature distribution across the rib textile surface from the ANSYS model

The results of the simulation and thermal imaging experiments dictate the design of the thermal energy harvesting shirt. The shirt, seen in Figure 3, has four TEGs integrated at the following locations: wrist, upper arm, chest and back. At each of these locations, the knit properties need to be specified to help maintain the temperature difference across the TEG. For this shirt, the rib structure is used as the insulating knit surrounding the TEG and the jersey structure makes up the remainder of the shirt. A heat spreader is added to the interface between the TEG and skin. Its purpose is to increase the heat flow from the body to the TEG. The heat spreader is a Ni/Cu coated taffeta that is laminated onto the knit using thermoplastic polyurethane (TPU).

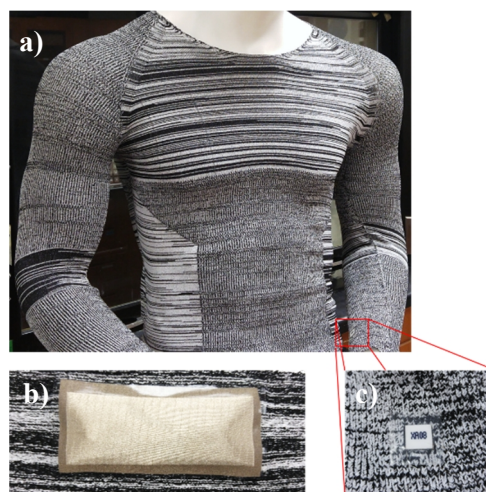


Figure 3. a) The TEG shirt as knit with specified structures b) The heat spreader after lamination onto the shirt where the TEG will be located c) The surface of the integrated TEG surrounded by the 1 x 1 rib knit.

4. Conclusion

To maintain a temperature difference across a TEG for energy harvesting purposes, the textile must act as a thermal insulator. This can be achieved by changing the knit structure surrounding the TEG or by

using a different yarn. The goal of this textile manipulation is to lower the thermal conductivity by changing the knit density and porosity. When comparing a jersey knit and a 1 x 1 rib knit, the difference in porosity and density show a significant effect on the temperature distribution across the surface of the textile. The 1 x 1 rib knit has a higher porosity and thus is better suited for insulating purposes. This is confirmed by using ANSYS simulations and thermal imaging data to study the thermal disturbance in the textile with a heat generation input of 1 W m^{-3} at the base of the textile-TEG system. The addition of a heat spreader increases the heat flux through the TEG, improving the power output. In future studies, conductive yarn will be integrated directly into the shirt to act as the heat spreader.

Acknowledgments

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References

- [1] Leonov V 2011 Energy Harvesting for Self-Powered Wearable Devices *Wearable Monitoring Systems* ed A Bonfiglio and D De Rossi (Boston, MA: Springer US) pp 27–49
- [2] Leonov V, Hoof C Van and Vullers R J M 2009 Thermoelectric and Hybrid Generators in Wearable Devices and Clothes *2009 Sixth International Workshop on Wearable and Implantable Body Sensor Networks* (IEEE) pp 195–200
- [3] Leonov V and Vullers R J M 2009 Wearable electronics self-powered by using human body heat: The state of the art and the perspective *J. Renew. Sustain. Energy* **1** 62701
- [4] Suarez F, Nozariasbmarz A, Vashae D and Ozturk M C 2016 Designing Thermoelectric Generators for Self-Powered Wearable Electronics *Energy Environ. Sci.* **9**