Applied Thermal Engineering 109 (2016) 138–146

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Design, fabrication and feasibility analysis of a thermo-electric wearable helmet

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HIGHLIGHTS

- A thermoelectric device is studied, designed, realized, characterized, and tested.
- The related models are established, analyzed and verified by an experiment.
- The performance of system under different conditions are evaluated and predicted.
- The heat of the human body can be drive small power equipment like LEDs by TE module.

ARTICLE INFO

Article history:
Received 22 May 2016
Revised 8 August 2016
Accepted 9 August 2016
Available online 10 August 2016

Keywords:
TEG
Human body
Exercise
Wearable device
Thermoelectric

ABSTRACT

This paper presents a wearable thermoelectric generation system which is applied to a helmet. It involves the use of the relatively high temperature difference between the local effect of the head skin and the ambient to generate electricity for powering the LEDs. Meanwhile, the mathematical model of the thermoelectric generator (TEG) and the heat transfer process of the thermo-electric system are established and analyzed. The properties of the head underneath the helmet are also investigated and analyzed. Furthermore, the commercially available modules have been tested and the performance of energy conversion of it has been evaluated experimentally. And the models are verified via the experiments. Models of TEG matched with LED have been certified by the experiment results are presented to optimize the number of the TEG for maximum output and the related circuits are designed. The thermo-electric wearable helmet is manufactured. In addition, the performance of the system under different environmental conditions are evaluated and predicted. The results indicate the feasibility of the wearable thermoelectric generation system and give hints for future improvement of the wearable devices using outside under different environmental conditions.

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1. Introduction

With the high-speed development of the industrialization, the global environmental deterioration and the energy crisis are threatening the long-term steady development of mankind. Thus, governments of all countries have devoted their attentions to the research of the green environmental protection energy like the solar energy, the wind energy, the biomass energy, the geothermal energy and the ocean energy. However, the thermal energy from human body as a huge potential energy is often neglected. Compared with some other energy, the thermal energy from human body is rather unique for being common and stable.

Without the chemical reaction, gas emissions, and any moving parts, the thermoelectric generator (TEG) is environment-friendly and maintenance-free. Thus compared to conventional energy conversion systems, thermoelectric generators (TEG) theoretically offers a number of advantages and shows great potential in many field [1–6]. In particular, parts of some applications are focused on the pursuit of energy harvesting from unused sources like mechanical vibrations and wasted heat [2,4,7–10]. In more details, the thermoelectric modules are commonly used to produce electricity from heat absorption restricted to aero-spatial and automotive industries, in particular, small thermoelectric generator devices used to power localized autonomous sensors [11,12]. However, limited study focused on utilizing the thermal energy from human body for the quantity giant and without the influence by weather and geography. And with the rise of wearable devices

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.057
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Nomenclature

A_{teg}	rea of TEG, m^2
C_{fx}	local friction coefficient
C_p	specific heat, kJ/(kg K)
h_{covf}	coefficient of convection heat transfer of the thermal slug, W/(m^2 K)
h_x	heat transfer coefficient along the length of the thermal slug at the location of a convective, W/(m^2 K)
H	the height of the thermal slug, m
I	current, A
k_{teg}	thermal conductivity of TEG, W/(m K)
$K_{thermal\ slug}$	thermal conductivity of the thermal slug, W(m K)
k_{air}	thermal conductivity of air, W(m K)
l_{teg}	the length of TEG, m
L	the length of the thermal slug, m
n	number of thermocouples
Nu	Nusselt number
Pr	Prandtl number
p	the output power, W
p_{max}	the maximum output power, W
Q_{head}	energy that loss from the head, J
Q_{tegh}	energy that passed in hot side of the TEG, J
Q_{tegl}	energy that passed in cold side of the TEG, J
$R_{contact1}$	thermal contact resistance between TEG and head skin, K/W
$R_{contact2}$	thermal contact resistance between TEG and thermal slug, K/W
$R_{thermal\ slug}$	thermal resistance of the thermal slug, K/W
R_{conf}	resistance of the heat conduction in thermal slug, K/W
$R_{cov\ f}$	thermal resistance of convection heat transfer between thermal slug and ambient air, K/W
Re	Reynolds number
r_{teg}	electrical resistivity of TEG, Ω m
R_{int}	the internal resistance of the power supply, Ω
R_L	resistance of LED, Ω
S_1	the cross section area of the heat sink, m^2
S_2	the total area of the thermal slug, m^2
St	Stanton number
T_{head}	the head temperature of the skin, K
T_h	hot side temperature of TEG, K
T_c	cold side temperature of TEG, K
$T_{ambient}$	temperature of ambient air, K
u	wind speed, m/s
V_{oc}	open circuit voltage, V
α_n	Seebeck coefficients for n-type material, V/K
α_p	Seebeck coefficients for p-type material, V/K
α_{teg}	Seebeck coefficient for TEG, V/K
ρ	density of air, kg/m^3
μ	kinematic viscosity, m^2/s
α	thermal diffusivity, m^2/s
ν	dynamic viscosity, N s/m^2
ΔT	temperature difference between the thermocouple, K

microelectronic devices, how to provide long-term, stable and efficient power for them is a key promising technology. In 1999, Kishi et al. [13] put forward a wrist-watch with thermoelectric generators (TEGs) that used the heat released from the human body. Similarly, Leonov et al. [14] designed a wireless sensor nodes with fabricated TEGs powered by human warmth in 2007. Wang et al. [15] made a wearable miniaturized thermoelectric generator for human body applications based on a surface micro-machined poly-SiGe thermopile. Being worn on human body, the TEG delivers an open-circuit output voltage of about 0.15 V. Huesgen et al. [16] fabricated thermoelectric generators to supply Micro-Electro-Mechanical system (MEMS) by harvesting thermal energy from human body. However, those studies applied for indoor applications and focused on the temperature difference between the human skin surface and the indoor environment. The temperature difference used by the thermoelectric generator is really low, perhaps only 4 or 5 K [17], the power output of thermoelectric devices is relatively low due to the performance of TEGs is significantly affected by the temperature and heat exchanger on it [18–20].

In this context, the novelty of our work is that, comparing to the previously mentioned devices and the known applications discussed above, it provide relatively large output particular by its novel structure and different application situations. It not only provides efficient method for the application of TEG on human body, but also provides a new and effective way for utilizing low thermal potential energy with low temperature. In order to make better use of the TEG without structural changes, the relatively large temperature difference is requisite for a specific TE (thermoelectric) material in view of the specific thermal environment of human body [21]. In fact, aerobic exercise could increase heat generation and loss from the human body. And the coverages on human will reduce the thermal losses to provide a relatively higher temperature by the local effect such as a headgear or helmet [22]. In addition, the human motion can also speed up the flow of the surrounding air, which can enhance the heat transfer coefficient on the cold side of TE with the ambient environment. Thus, the thermal efficiencies and the performance of the TEG will be improved greatly. Based on the ideas, the heat transfer model and the power generation model of the wearable thermoelectric generation system are established. Furthermore, the accuracy of the model is verified via a simple numerical simulation and an experiment. Then, based on the feasibility of the LEDs and the function of the thermoelectric generation system, the LEDs are matched with the TEG modules. What's more, the structure of the system is designed, and the wearable thermoelectric generation system is fabricated. In addition, the performance under different seasons with different outdoor temperatures and different riding speeds were evaluated and predicted, which indicated the feasibility of the wearable thermoelectric generation system.

2. Models

2.1. TEG generation model

The TEG have a specified capability of delivering electrical output power by the temperature difference between the two ends due to Seebeck effect. Typical TEG module are composed by a set of semiconductor components consisted of two different materials which mixed with two thermally conducting plates.

The basic equation for the output voltage of a thermoelectric generator is as follows [2]:

$$V_{oc} = n \cdot (\alpha_p - \alpha_n) \cdot \Delta T \quad (1)$$

2.2. The heat transfer models of the system

The heat transfer models of the thermo-electric wearable helmet deployed on head can be discussed by the equivalent thermal circuit illustrated in Fig. 1. Typically, in case of wearable devices, the heat source is the human head, and the heat is dissipated to the ambient air outside of the devices. The hot side gains the heat

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