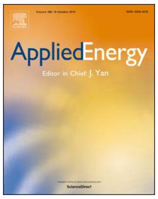
Applied Energy 218 (2018) 282–291

Contents lists available at ScienceDirect

Applied Energy

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



Personal thermal management using portable thermoelectrics for potential building energy saving

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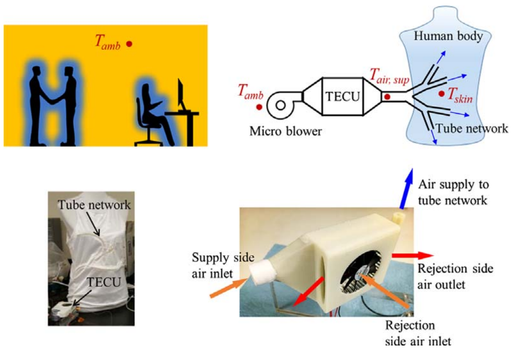
HIGHLIGHTS

- Personal thermal management can be applied for building energy saving and improving occupant thermal comfort.
- A thermoelectric unit is proposed for personal thermal management.
- Relationship established between personal energy requirement and thermoelectric energy supply.
- Weight minimization of the thermoelectric unit is achieved.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Personal thermal management
Building energy saving
Thermoelectrics

ABSTRACT

Heating and cooling of buildings consume approximately 15% of all energy used in the United States. Such a large energy demand is primarily due to heating and cooling of the entire building space to temperature setpoints usually between 21.1 °C (70 °F) and 23.9 °C (75 °F). However, even with such a narrow range of temperature setpoints, more than 20% of the occupants do not feel thermally comfortable due to individual differences (e.g. age, gender, clothing, or physiology). The personal thermal management techniques, which create a local thermal envelope around a human body instead of heating or cooling the entire building space, have the potential to greatly reduce the building energy consumption and to enhance thermal comfort of individuals. In this study, a portable thermoelectric energy conversion unit (TECU) that converts electricity into cooling and heating energy is developed. The TECU supplies cool air (in the cooling mode) or warm air (in the heating mode) to regulate the thermal comfort of a human body. The cool or warm air is supplied through a tree-like rubber tube network that is knitted into a thermoregulatory undergarment. To achieve a cooling/heating target that provides satisfactory thermal comfort, the required cooling/heating power supply from the TECU is determined first while a theoretical model is then developed to guide the design of the TECU. To minimize the TECU weight and make it suitable for portable applications, relationships between weight and thermal resistances of commercial off-the-shelf heat sinks are established first, and a method to find the minimal weight of heat sinks for the TECU is then developed. This methodology is also

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https://doi.org/10.1016/j.apenergy.2018.02.158
Received 4 December 2017; Received in revised form 13 February 2018; Accepted 23 February 2018
0306-2619/ Published by Elsevier Ltd.

applicable for other applications where heat sink weight needs to be minimized. The thermal manikin tests demonstrate that 24.6 W of personal cooling power and 18.5 W of personal heating power are achieved by using the TECU.

Nomenclature

c_p	specific heat, J/(kg K)
COP	coefficient of performance
I	electric current, A
K	thermoelectric module thermal conductance, W/K
m_c	air mass flow rate at cold side, kg/s
m_h	air mass flow rate at hot side, kg/s
q'	energy flux, W/m^2
Q	energy, W
Q_{blower}	blower energy consumption, W
Q_{fan}	fan energy consumption, W
R	thermoelectric module electric resistance, Ω
RH	relative humidity,%
T	temperature, °C
TECU	thermoelectric energy conversion unit
U	air speed, m/s
W	weight, g

Greek symbols

α	Seebeck coefficient, V/K
φ	heat sink thermal resistance, K/W

Subscripts

amb	ambient
body	human body
c	cooling mode
cl	clothing
h	heating mode
rej	air rejection side
sup	air supply side
tot	total
TE	thermoelectric

1. Introduction

Heating and cooling of buildings consume approximately 15% of all energy used in the United States [1]. Such large energy consumption is due to the cooling and heating of the whole building space to a narrow range of temperature setpoints between 21.1 °C (70 °F) and 23.9 °C (75 °F). In addition, the conventional heating and cooling systems aim to create a uniform thermal environment in the conditioned space. However, personal preferences on thermal comfort of the occupants cannot be 100% satisfied due to the individual differences such as age, gender, and physiology [2–4]. Personal thermal management techniques, which establish a local thermal envelope around occupants instead of cooling and heating the entire building space, have great potential for building energy saving. By using personal thermal management systems, temperature setpoints of buildings can be expanded, which results in great energy saving [5–9]. It is estimated that expanding the setpoints by 2.2 °C (4 °F) on both hot and cold sides, for example, expanding setpoint from 21.1 °C (70 °F) to 18.9 °C (66 °F) in the heating season and expanding setpoint from 23.9 °C (75 °F) to 26.1 °C (79 °F) in the cooling season, could result in at least 15% savings for building energy use or approximately 2% savings for total U.S. energy consumption [10]. Hoyt et al. [11] also showed that by increasing the cooling setpoint of 22.2 °C (72 °F) to 25 °C (77 °F), an average of 29% of cooling energy can be saved, and reducing the heating setpoint of 21.1 °C (70 °F) to 20 °C (68 °F) saves an average of 34% of terminal heating energy. Ghahramani et al. [12] reported that compared to the baseline setpoint of 22.5 °C, selecting the daily optimal setpoint in the range of 22.5 ± 1 °C, 22.5 ± 2 °C, and 22.5 ± 3 °C would result in an average savings of 7.5%, 12.7%, and 16.4%, respectively. In addition, personal thermal management techniques enable occupants to control their immediate thermal environment individually, which could significantly enhance personal thermal comfort [13,14]. Pasut et al. [15] reported a 92% thermal satisfaction rate by employing a heated/cooled chair in human subject tests.

The state-of-the-art personal thermal management techniques can be categorized into near-range energy transfer technologies and thermoregulatory clothing systems. The near-range energy transfer technologies, such as personal ventilation (PVent) [16–18], personal air conditioning [19–21], thermal chair [15,22], bedroom task/ambient air conditioning (TAC) system [23], and personal evaporative coolers [24], are facing challenges including high cost, and system complexity. For example, both the PVent and personalized air conditioning systems use an additional air distribution system that is connected to the building air conditioning system. This makes the whole system more complicated and costly, even for furniture-integrated PVent systems [25]. In contrast, the thermoregulatory clothing system is more promising because it is a wearable technology with low complexity. Research efforts have been devoted to incorporate active cooling/heating elements (fan [26,27], water circulation system [28]), phase change materials [29], and other innovative materials [30–33] in clothing systems, but most existing thermoregulatory clothing systems have significant drawbacks in aesthetics, size and weight. Many thermoregulatory clothing systems have been developed for special use such as spacesuits, armory for firefighters or for motorcyclists, but are not appropriate for use in the general indoor environment [34]. Among those, some thermoregulatory clothing systems can provide only cooling or heating, instead of both [22,35–38].

Solid-state thermoelectric modules that can convert electricity into both cooling and heating are of interests for developing portable systems, as they are compact in size, light in weight, and highly reliable and environmentally friendly with no refrigerants [39]. They have been used to fabricate wearable thermal energy harvesting devices [40]. However, in terms of cooling and heating, earlier thermoelectric systems are usually bulky [41–45] and not appropriate for portable applications. For example, Choi et al. [44] developed a thermoelectric device to control the temperature of the car-seat surface, but the size of the heat sink employed (350 × 38 × 10 mm^3) makes it unsuitable for portable applications. Therefore, there is a strong need to design thermoelectric systems with weight and size targets for integration into a portable thermoregulatory clothing system.

This study introduces a portable thermoelectric energy conversion unit (TECU) that can provide both cooling and heating for personal thermal management, aiming at significantly reducing building energy consumption and improving personal satisfaction of thermal comfort. The TECU supplies cool air (in the cooling mode) and warm air (in the heating mode) to a human body through a tree-like rubber tube network that is knitted into a thermoregulatory undergarment. To achieve a cooling/heating power target that provides satisfactory thermal comfort, the required cooling/heating power supply from the TECU is determined first. A theoretical model is then developed to guide the