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Theoretical study on an integrated two-stage cascaded thermoelectric module operating with dual power sources

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ABSTRACT

This paper presents an integrated two-stage cascaded thermoelectric module (TTEM) operating with dual power source. The integrated TTEM contains two stages of thermocouples with identical semiconductor cross-sectional area but different leg lengths. An analytical model for the TTEM is developed, and the influences of the key parameters are theoretically investigated. The obtained results indicate that optimum two stage currents combination can maximize both the cooling capacity and coefficient of performance (COP). Furthermore, the leg length allocation ratio for the two stages affects the maximum cooling capacity significantly. Larger leg length proportion of the colder stage may effectively contribute to the improvement in maximum cooling capacity. In addition, there exists an optimum leg length allocation ratio to obtain the corresponding optimum COP when the two stage currents are set to achieve the maximum cooling capacity of the TTEM. However, the total leg length has no effect on the corresponding optimum COP.

1. Introduction

Thermoelectric coolers (TECs), also known as Peltier coolers, are solid-state refrigeration devices that utilize the Peltier effect to provide cooling effect for all of active cooling needs. In recent years there has been increased interest in the applications of thermoelectric coolers to various fields, including the electronic cooling, thermoelectric refrigerator and air conditioner [1–8]. However, the main drawback of thermoelectric cooling is low coefficient of performance (COP) [9], particularly in larger capacity applications. This is strongly due to the inherent properties of thermoelectric materials. Thus, efforts have been focused on the development of advanced thermoelectric materials over the past decades. However, many years of efforts to increase the figure of merit of thermoelectric materials have not yet led to a fundamental breakthrough. Despite the technical difficulty, the needs for TECs mentioned above still have motivated researchers to develop thermoelectric cooling technology based on present thermoelectric materials. Significant efforts include the optimization of TEC fabrication and design, the improvement of the TEC heat exchangers, and the TEC analysis methodology [10–19].

In the current applications of TECs, the widely used thermoelectric modules (TEMs) are usually fabricated with a number of semiconductor thermocouples. Typically, in a thermocouple a p-type thermoelement and an n-type thermoelement are connected electrically in series and thermally in parallel by metal strips. This single-stage thermocouple based TEM can be directly used in the TECs for small temperature drops. To achieve a larger temperature drop with the TEM, the two or more stages integrated TECs have to be configured by externally cascading the individual TEMs. Applications of the cascaded TEMs have been proposed as the widest method for multi-stage TECs [20,21]. However, the traditional methods of externally cascading the single-stage thermocouple based TEMs to form a multistage TEC degrade the TEC performances since they have increased the overall thermal and contact resistances due to the fabrication issues [22]. Thus, development of module-level designs for TEMs is necessary to increase performance or efficiency of TEMs. Alternatively, the internal cascading of thermoelement legs, thermocouples, and modules appears to be a promising approach for improving the performances of TECs.

In this work, the research topic of thermoelectric cascades in TECs is further investigated. An integration of a two-stage TEM through the use of the two-stage cascading of semiconductor thermocouples is proposed, in which each stage contains the same number of thermocouples but different semiconductor leg length. In the fabrication approach the two-stage TEM (TTEM) can have two stages that are connected thermally in series, and electrically in both the series and parallel with two separate DC power sources.

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Nomenclature

Roman

A	area (m^2)
COP	coefficient of performance
H	thickness (m)
I	electric current (A)
K	thermal conductance ($W\,K^{-1}$)
L	length (m)
P	electric power (W)
Q	heat transfer rate (W)
R	electrical resistance (Ω)
t	Celsius temperature (°C)
T	Kelvin temperature (K)
x	length ratio

Greeks symbols

α	Seebeck coefficient ($\mu V\,K^{-1}$)
ρ	electrical resistivity (Ω m)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)

Subscripts

c	cold side
corr	corresponding
h	hot side
m	intermediate
max	maximum value
opt	optimum

The TTEM further includes an intermediate thermal conductor disposed between the first thermoelectric stage and the second thermoelectric stage and thermally coupling the first and second stages together. The objective of this work is to theoretically characterize the TTEM performance and the proper design parameters. In the present study, the maximum cooling capacity and the maximum COP of the TTEM are investigated. Main parameters that affect the TTEM performance are examined, such as the ratios of thermoelement leg length, the thermal resistance of intermediate thermal conductor and applied electric current between stages. The present study and the corresponding results are expected to provide a guide to the practical TTEMs design and their applications in TECs.

2. TTEM configuration and modeling

An integrated thermoelectric module with the two-stage cascading of semiconductor thermocouples is illustrated schematically in Fig. 1. The TTEM comprises a specified number of basic thermocouple units that are connected thermally in parallel and electrically in series with two separate DC power sources, as shown in Fig. 1a. In the basic thermocouple unit (Fig. 1b), two pairs of p-type and n-type thermoelements are assembled together through the metal strips and the intermediate thermal conductors (i.e. ceramic plate) to form the cascaded two stages. The thermoelements are connected thermally and electrically in both the series and parallel. When electric currents from the two separate DC power sources are applied to the basic thermocouple unit, the first stage thermocouple (colder stage) performs the heat absorption and heat rejection at the cold end and intermediate thermal conductor, respectively, as shown in Fig. 1b. Simultaneously, the second stage thermocouple (hotter stage) absorbs the heat from the intermediate thermal conductor and rejects the heat at the hot end, respectively. Note that the heat balance at intermediate thermal conductor can be achieved by properly configuring the applied electric currents and the thermoelement leg lengths for each stage thermocouple. Based on such basic thermocouple unit, the TTEM can pump heat from the cold end to the hot end when DC currents are applied. As known, a typical two-stage pyramid-styled TEM is usually fabricated by a pyramid stack of two individual single-stage TEMs. In the regular pyramid type, the two separate single-stage TEMs with different areas are attached with each other. In this case, the contact and spreading thermal resistances naturally exist between the interfaces of two objects.

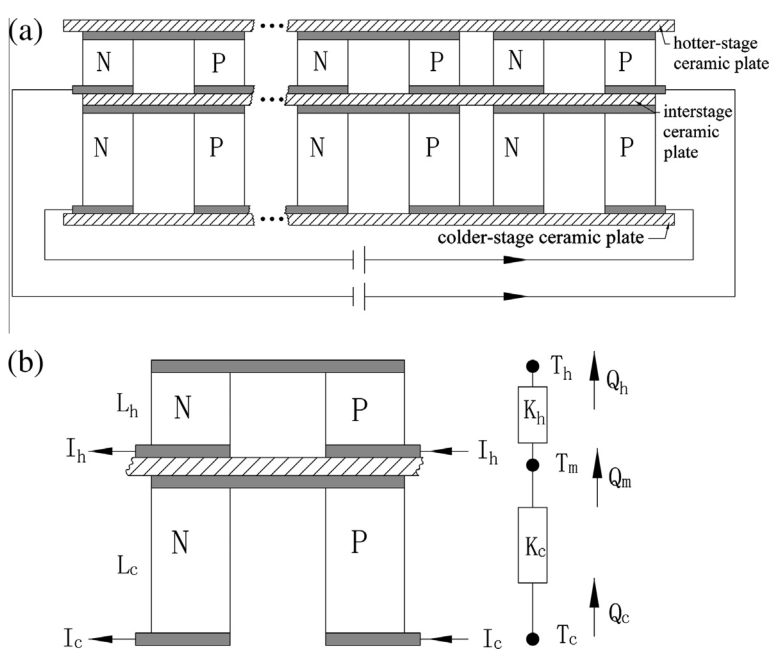

Fig. 1. Schematic diagrams: thermoelectric module (a); schematic diagrams: basic thermocouple unit (b).