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Enhancing the maximum coefficient of performance of thermoelectric cooling modules using internally cascaded thermoelectric couples

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ABSTRACT

This paper presents an approach of fabricating thermoelectric cooling (TEC) module for enhancing the maximum coefficient of performance (COP) of TEC module. A significant novelty is that each stage thermoelectric couples have different leg lengths which decrease stage by stage from cold side to hot side of TEC module so that the lower stage can completely pump the heat dissipated by the upper stage. In the design configuration of the TEC module, the lower and upper stages are connected electrically in parallel and thermally in series only through intermediate copper metal strips and copper conducting wires, and thus the interstage thermal resistances and the heat leakage can be reduced compared with that of a conventional pyramid-styled configuration. A mathematical model is also developed to simulate the performances of the TEC module. The simulation results show that the enhancement in maximum COP of the TEC module can be obtained by using internally cascaded multistage thermoelectric couples.

Amélioration du coefficient de performance maximal des systèmes de refroidissement thermoélectriques faisant appel à des couples thermoélectriques en cascade interne

Mots clés : thermoélectricité ; effet Peltier ; conception ; composant ; modélisation ; simulation ; performance

1. Introduction

Thermoelectric cooling (TEC) modules have the advantages of compact structure, high reliability, and having no moving parts. They have been extensively employed as cooling devices in many applications including superconductor application, aerospace application, commercial application and electronic devices cooling. However, the main drawback

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Nomenclature

A	cross-sectional areas (m^2)
COP	coefficient of performance
I	electrical current (A)
K	thermal conductance ($W K^{-1}$)
k	thermal conductivity ($W m^{-1} K^{-1}$)
L	length (m)
P	power (W)
Q_c	heat rate at the cold junction (W)
Q_h	heat rate at the hot junction (W)
R	electrical resistance (Ω)
T_c	cold junction temperature (K)
T_h	hot junction temperature (K)
T_m	mean junction temperature (K)
U	voltage (V)
Z	figure of merit of thermoelectric couple (K^{-1})

Greek symbols

α	Seebeck coefficient ($V K^{-1}$)
β	intermediate variable
ρ	electrical resistivity(Ω m)
ϵ	the COP, tolerance

Subscripts

1	first stage
c	cold junction
h	hot junction
i	the ith stage
m	mean value
n	the nth stage, n-type semiconductor elements
p	p-type semiconductor elements
max	maximum value
min	minimum value
opt	optimum value
t	total value

of TEC modules is its poor coefficient of performance (COP), especially in wide temperature range applications. One approach to improve the COP of thermoelectric modules is to develop new materials. Over the past years, the research on improving the performance of thermoelectric materials has been developed continuously and progress has been made (Riffat and Ma, 2004). In addition to the improvement of the thermoelectric material, efforts have also been made to increase the TEC performance by improving the module design, fabrication and optimization of the thermoelectric cooling system (Yamanashi, 1996; Huang et al., 2000; Omer et al., 2001; Xuan, 2003; Chein and Chen, 2005; Chen et al., 2005; Cheng and Shih, 2006; Lineykin and Ben-Yaakov, 2007).

Usually, for single-stage thermoelectric module the maximum COP under the optimum current is determined by the temperature of the hot side and cold side as well as the figure of merit of thermoelectric material. For a fixed hot side temperature and the value of the figure of merit, the maximum COP typically decreases with a decrease in the cold side temperature, i.e. an increase in the temperature difference between the hot and cold side. As it is known, multistage modules are often used for extending operating temperature range of the thermoelectric cooling. However, some research results have indicated multistage modules may be used to improve the COP of TEC (Anatychuk et al., 1996; Lindler, 1998; Chen et al., 2002). Therefore, the application of multistage thermoelectric modules can be developed as another approach to improve the COP of thermoelectric modules.

Currently, a conventional thermoelectric cascaded module is a pyramid-styled module because keeping interstage heat balance between the lower stage and the upper stage. Another practical design configuration for cascaded module is a special cuboid-styled one, in which the number and structure of TE modules of each stage are similar and the current can be alternated (Xuan et al., 2002). Generally, for the above two design configurations of cascaded module, the heat leakage and interstage thermal resistance may degrade the cooling performance of the cascaded module. For reducing the degradation effects, a conceptual configuration for a two-stage cascaded module was proposed, in which both stages can possibly be operated under optimum current by tailoring the aspect ratio of each stage using only one pair of current injection leads (Yang et al., 2004). It is conjectured that this design has two obvious advantages that the heat leakage can possibly be avoided and the current can be introduced only at the hot side of the module.

In this paper, we propose a design configuration for the cascaded module by using internally cascaded multistage thermoelectric couples to improve the COP of TEC. A significant novelty of the presented cascaded module is that the legs of all cascaded thermoelectric couples in a fundamental unit have different length which decreases stage by stage from cold side to hot side of the cascaded module. Besides, the lower and upper stages are connected electrically in parallel and thermally in series only through intermediate copper metal strips and copper conducting wires. To validate the design configuration, a mathematical model is developed and the effects of the main design parameters on the performances of the TEC module are then investigated in this paper. The special attention will be focused on the maximum COP of the cascaded module under a condition in which the cascaded module TEC temperature range is the same as that of a single-stage thermoelectric module.

2. Cascaded module configuration and mathematical model

The basic unit of a single-stage TEC module consists of a p-type and an n-type semiconductor elements connected electrically in series and thermally in parallel by metal strips, as shown in Fig. 1. A conventional single-stage TEC module is comprised of a number of p–n thermoelectric couples connected electrically in series but thermally in parallel and sandwiched between two electrically insulating but thermally conducting ceramic plates. When the TEC module is operated between the heat reservoirs, the heat is absorbed on the cold side and the heat is released at the opposite hot side of the module, respectively, due to the Peltier effect.

Fig. 2(a) illustrates a fundamental unit of the presented internally cascaded multistage TEC module. In this unit, the p-type and n-type semiconductor elements of the lower and upper stages are placed on opposite sides, and the lower and upper stages are connected thermally in series and electrically in parallel by copper metal strips and copper conducting wires.