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A thermoelectric cooler coupled with a gravity-assisted heat pipe: An analysis from heat pipe perspective

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ABSTRACT

Thermoelectric cooler (TEC) is attractive for cooling electronic devices because of its light, compact size, quiet and vibration free characteristics. However, its cooling performance is restricted by the thermal resistance at TEC hot side. To improve the TEC cooling performance, a gravity-assisted heat pipe (GAHP) was proposed to attach on the TEC hot side. The cooling feasibility of the TEC system coupled with a GAHP was experimentally investigated in a climatic chamber, compared with a TEC system coupled with an air cooled-heat sink on its hot side. It was observed that the cooling capacity of TEC was improved by 64.8% using GAHP. A mathematical model was established to analyze the effect of refrigerant filling ratio, TEC hot side temperature and air flow rate. Optimal parameters of the proposed system were evaluated from the heat pipe perspective. Findings showed that the optimal refrigerant filling ratio was 134%, which resulted in the maximum heat transfer ability. Increasing air flow rate was able to improve the cooling capacity but with a limitation caused by the restriction of TEC.

1. Introduction

Electronics industry undergoes an exponential growth in circuit densities and heat generation in recent years [1]. The increasing miniaturization of electronic devices makes the heat dissipation more difficult, which significantly affects the reliability of electronic devices [2]. Liu et al. [3] reported that the reliability of the central processing units (CPUs) decreased by 10% for every 2 °C above the permissible operating temperature. Therefore, effective thermal management of electronic devices is of priority concern for the electronics industry development. Conventionally, air cooling-heat sink was employed widely for thermal management of electronic devices because of the ease of obtaining the cooling fluid and the simplicity, high reliability and low cost of the required equipment [2]. However, the air cooling featuring low heat transfer performance and noise problems is currently facing extreme difficulty to deal with high density cooling demand. Moreover, its applicability in the next generation electronic devices is making the problem even worse due to the space constraints [4]. Other high performance compact cooling techniques like thermoelectric cooler (TEC) have to be developed to replace direct air-cooling system [5]. In the past several decades, TEC technique is a topic of increasing interest for cooling electronic devices [6–11].

However, the cooling capacity of TEC was restricted by the thermal resistance at TEC hot side [12]. To reduce this thermal resistance, Dizaji et al. [13] cooled the TEC hot side by constant temperature water. It was observed that with the help of water, the TEC was able to provide appropriate cooling performance even for hot climate conditions. Kim et al. [14] developed a direct contact TEG to remove the thermal resistance between TEC and heat source. The TEC was cooled by coolant (water-ethylene glycol mixture) efficiently. Hu et al. [15] developed a cooling system based on water-cooled TEC for CPU. Effects of mass flow rate of water and air velocity were investigated under severe environment. The water-cooled TEC can prevent over heat under variable operating conditions as well as save energy. Ahammed et al. [16] developed a TEC system with nanofluid in a multiport minichannel heat exchanger. The temperature difference between the TEC hot and cold side was reduced by 9.15% with nanofluids (0.2 vol%), which enhanced the coefficient of performance (COP) of TEC by 40%. Russel et al. [17] used heat pipe to improve the heat transfer of TEC hot and cold sides, one for transporting the heat existing in the TEC module to an external ambient and another one for transferring the heat from chip to the base plate of the heat sink on TEC cold side. The maximum heat dissipation capacity of the system increased as the external thermal resistance decreased. Liu et al. [3,18] proposed a TEC coupled with a micro heat

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Nomenclature

A	surface area (m^2)
B	width (m)
c	thermal capacity (kJ/(kg·K))
D	hydraulic diameter (m)
G	mass flux (kg/(m^2·s))
h	heat convection coefficient (W/(m^2·K))
H	height (m)
I	electrical current (A)
k	thermal conductivity (W/(m·K))
l	length (m)
N	number
Nu	Nusselt number
P	pitch (m)
Pr	Prandtl number
Q	heat transfer rate (W)
R	thermal resistance ((m^2·K)/W)
Re	Reynold number
T	temperature (K)
v	velocity (m/s)
Z	figure of merit

Abbreviations

TEC	thermoelectric cooler
GAHP	gravity-assisted heat pipe

Greeks

α	seebeck coefficient (V/K)
δ	thickness (m)
η	efficiency (%)
μ	dynamic viscosity (Pa·s)
θ	louver angle (°)
ρ	density (kg/m^3)
σ	electrical conductivity (s/m)

Subscripts

a	air
Al	aluminum
b	fin base
c	cold
$cond$	condensation
$evap$	evaporation
fin	fin
h	hot
i	inner
in	inlet
out	outlet
o	outer
ref	refrigerant

pipe system for cooling CPUs. It was found that an operating voltage of 12 V could achieve the maximum cooling capacity. Sun et al. [19,20] proposed a thermoelectric cooling system coupled with a gravity-assisted heat pipe to regulate the heat buildup within electronic devices. Experimental research was conducted by comparing the cooling performance with a TEC system with an air cooling heat sink. An improvement of 64.8% in cooling capacity was observed. He et al. [21] used a heat pipe to assist the heat transfer between thermoelectric generator and solar panel. The TEC and solar panel were connected via heat pipes to get the maximum power conversion efficiency. Remeli et al. [22] proposed a thermoelectric generator using heat pipe for waste heat recovery. Heat pipe was attached on the cold and hot side of thermoelectric generator, respectively. A higher mass flow rate ratio results in a higher amount of heat transfer and greater power output.

Summarizing the above techniques, heat pipe was more attractive to improve the heat dissipation of TEC as its high heat transfer capability, which can be 500 times larger, compared to the best available thermal conductors [23]. The studies on the performance of TEC coupled with heat pipes mainly focused on the variations of cooling capacity caused by factors related to TEC [24–26], like operating voltage, cold side temperature, temperature difference between hot and cold sides and so on. However, for this coupled TEC system, its performance was also affected by the factors related to heat pipe. This paper seeks to find the optimal parameter of a TEC system coupled with a gravity-assisted heat pipe (GAHP) from the perspective of heat pipe under different climate conditions. A prototype was developed and tested in a climatic chamber, compared with a TEC system with an air-cooled heat sink. In addition, a mathematical model was developed to predict the operation of the proposed TEC system with different refrigerant filling ratios, TEC hot side temperature and air flow rates under various climate conditions.

2. Experiments

2.1. Experimental apparatus

A TEC system coupled with GAHP was designed with a cooling capacity of 200 W. The dimensions of the prototype were 310 mm × 100 mm × 440 mm (W × D × H). The constructed system consisted of four thermoelectric modules, one air-cooled heat sink, one gravity-assisted heat pipe, two axial fans and other ancillary components (Fig. 1). The technical specifications of the thermoelectric module are shown in Table 1.

In the table, Z represents the figure of merit (FOM) of the TEC, which was calculated by Eq. (1).

$$Z = \frac{\alpha^2\sigma}{k} \tag{1}$$

where α was the Seebeck coefficient; σ was electrical conductivity; and k was the thermal conductivity of TEC.

A TEC system coupled with air-cooled heat sink was also designed, which consisted of same components with the proposed TEC system except for the GAHP. An air-cooled heat sink was attached on the TEC hot side instead of GAHP. The two TEC systems were installed in a cabinet, which consisted of two same parts and was thermally insulted with rubber. The cabinet was located in a climatic chamber that was isolated from the external environment. The climatic chamber replicated outdoor conditions (T_{air} and RH_{air}).

An AC/DC inverter was used to change the AC electric flow (220 V) to a constant level of 48 V DC, which supplied 12 V DC to each thermoelectric module. Two heaters were installed in the cabinet to simulate the heat generated by electronic devices. Two T-type thermocouples were mounted on the base plate to monitor the temperature of heat sink at TEC cold side. One thermocouple was fixed on the outlet of vapor ascending tubes. Two thermocouples were fixed on the condensation zone and one more thermocouple measured the outlet temperature of condensate descending tube. The ambient temperature was measured by thermocouples exposed to ambient. The accuracy and