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Performance analysis and assessment of thermoelectric micro cooler for electronic devices

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ABSTRACT

A novel operating mode of thermoelectric module (TEM, cooling, heating, generation) is established for electronic devices cooling, based on the method of effectiveness-number of transfer units ($\varepsilon - \mathrm{NTU}$). This work mainly focused on the effect of thermoelectric properties and the scale of extender block on cooling performance under different operating conditions in order to obtain effective cooling operating mode. Based on the TEM parameters, two sets of analytical solutions for thermoelectric cooler (TEC) are derived for the chip temperature T_j at a fixed cooling power Q_c and Q_c at a fixed $T_{j,}$ respectively. The performance of TEC with/without scale of extender block is studied for the lowest chip temperature and maximum cooling capacity at fixed conditions. Analysis results show the thermoelectric properties and extender block are significant characteristics for different operating conditions. However, the coefficient of performance (COP) and temperature difference changed a little under given thermoelectric properties. The results indicate TEC system applied in electronic devices obtains effectively cooling module by controlling operating parameters, which do not changed with scale of extender block. The validation of the present analysis is also conducted compared with previous studies and through the infrared thermal imager.

1. Introduction

High power electronic devices with smaller size and higher encapsulation have resulted in the focus on the thermal management [1]. Investigations show the thermal reliability of a silicon chip decreases by about 10% for a rise of 2 °C in temperature [2], resulting in the increasing of thermal management challenges. Simultaneously, traditional passive cooling technology such as natural convection cooling, forced air cooling, liquid cooling, are reaching the limits of cooling capacity and cooling efficiency for high power electric devices [3–5]. Compared with traditional cooling, TEC is thought to be one of the preferable technologies due to its numerous advantages, such as small volume, environmentally friendly and temperature control capability [6]. Therefore, developing thermoelectric micro cooler system has potential to make important contributions to the growing thermal management challenges of electronic devices.

Most of the previous work on the TEC system has examined optimization and performance improvement to electronic devices by building various thermoelectric modules [7–16]. Zhang [13] and Zhang et al. [14] presented a generalized theoretical model in evaluating and optimizing thermoelectric coolers. Their modules did not consider the heat exchange in heat sink through heat exchange medium. Thermal design method covering with $\varepsilon - \mathrm{NTU}$ for solving the heat dissipater problem of TEC system have been investigated [17–21]. It is noted that their module expressions were not involved the temperature-difference and operating mode of effective cooling module. At present, the operating mode of thermoelectric module in practical use have not developed because of the dynamic process covering with temperature difference with current. Only Hodes [7] investigated the operating mode of TEM under the operating parameters to illustrate the application of the analysis framework. However, for a fixed hot and cold side, the energy conversion is changing with the temperature difference, and the analysis is extended to practical use, such as electronic heat dissipater.

To the best of author' knowledge, most of previous studies are heat dissipater for electronic devices focused on thermoelectric configuration and optimizing parameters. The thermal design theory ($\varepsilon - \mathrm{NTU}$) applied in thermoelectric cooling system have not been developed. This work focuses on the operating mode of TEM under the different scale of extender block for various thermoelectric properties. Based on the thermal design theory, the

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Nomenclature

A	area (m^2)
C	specific heat ($W\ K^{-1}$)
COP	coefficient of performance
I	current (A)
I_i	current at open circuit (I = 0) value ($Q_{c,open}$) (A)
I_n	neutral current at $\Delta T = 0$ (A)
I_{sat}	current at $Q_c = 0$ (A)
I_{sh}	short-circuit current (A)
K	thermal conductance ($W\ K^{-1}$)
K_{ex}	thermal conductance of extender block ($W\ K^{-1}$)
L	length (m)
Q	heat flux (W)
$Q_{c,open}$	cooling quantity with I = 0 (W)
Q_{cmax}	maximum cooling load (W)
R	resistance (Ω)
S	Seebeck coefficient ($V\ K^{-1}$)
T	temperature (K)
T_{ho}	hot side reference temperature (K)
T_j	surface temperature of chip (K)
ΔT	TEC hot side to cold side temperature difference (K)
ΔT_{max}	maximum temperature-difference(K)
U	overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
UA	heat performance parameter ($W\ K^{-1}$)
Z	figure of merit (1/K)
ZT	dimensionless figure of merit

Greek symbols

σ	heat loss efficient
$\sigma_{he,h}$	heat loss efficient of heat exchanger
σ_{te}	heat loss efficient of thermoelectric cooler
ε	heat exchanger efficient
φ	equivalent thermal efficiency

Subscript

c	TEC cold side
ejc	equivalent cold side junction to TEC
ex	extender block
h	TEC hot side
he	hot-side heat exchanger
in	inlet
jc	junction to TEC
jc,c	cold side junction to TEC
jc,h	hot side junction to TEC
max	Maximum
n	Neutral
sh	short-circuit
te	thermoelectric cooler

expression of cooling power and chip temperature are obtained for considering various operating mode. Two sets of analytical solutions for thermoelectric cooler are derived for the chip temperature at a fixed cooling power and cooling power at a fixed chip temperature, respectively. The objective of operating mode of TEM is to establish effective cooling module to predict the efficiency of TEC system and set up references for TEC system. Comparison with previous work and the full-scale experimental are also conducted for verification of the present analysis method.

2. Schematic diagram of TEC system

As shown in Fig. 1, the schematic of TEC system consists of TEM, hot side heat exchanger, extender block, and heater block. The TEM comprises many pairs of P-N type semiconductor columns, metallic connectors, and two electrically insulting ceramic plates [22]. The interface face contacted with electrical device by extender block is the cold side of thermoelectric cooler. Inversely, the interface face connected with heat sink is the hot side of thermoelectric cooler, and in this paper the heat sink with fins is called as hot side heat exchanger. The extender block, which could avert decreasing the cooling capacity and COP, has been considered as a buffer plate. A hot side heat exchanger with fin is used to take away the heat from heat source in the hot-side of TEC. The design task is to minimize the chip temperature or maximum cooling thermoelectric cooling load through TEC enhanced air cooling or others cooling ways. It is noted that the hot or cold side of TEC is not dependent on the temperature level. The contact of thermoelectric two side and aluminum extender is coated with thermal grease for decreasing thermal resistance. An axial fan connected to the far end of the air duct entrained the ambient air to enhance heat dissipater.

2.1. Thermoelectric module

It is noted that the effects of ceramic plated and joining copper traces and electrical contact resistances, which is small compared with the P-N type, are not considered at the back of the thermal balance equation. Thus, the theoretical equation for the TEM can be given as follows [23,24],

$$Q_c = ST_cI - \frac{1}{2}I^2R - K(T_h - T_C) \tag{1}$$

$$Q_h = ST_hI + \frac{1}{2}I^2R - K(T_h - T_C) \tag{2}$$

$$P = Q_h - Q_c = SI(T_h - T_c) + I^2R \tag{3}$$

where I is the electric current, T_h and T_c are the junction temperature of thermoelectric cooler. The Seekbeck coefficient S, thermal conductivity K and the total electrical resistance R are the physical properties of a TEM, which is important for the thermoelectric module.

Thermoelectric cooler COP is defined as

$$COP = \frac{Q_c}{P} \tag{4}$$

Setting $dQ_c/dI = 0$ yields I_{max} as

$$I_{max} = \frac{ST_c}{R} \tag{5}$$

The corresponding rate of maximum cooling (Q_{cmax}) at the cold side is

$$Q_{cmax} = \frac{S^2T_C^2}{2R} - K(T_h - T_C) \tag{6}$$

The value of T_h-T_c at which Q_c equal zero is defined as $\Delta T_{max.}$ It can be derived from Eq. (6).

$$\Delta T_{max} = \frac{S^2T_C^2}{2RK} \tag{7}$$

In fact, the parameters of physical properties of a TEM are dependent on temperature. However, effect of temperature on the physical property is not in our consideration for simplifying assumption.