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An Experimental Investigation of Thermoelectric Air-Cooling Module

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***Abstract*—**This article experimentally investigates the thermal performance of thermoelectric air-cooling module which comprises a thermoelectric cooler (TEC) and an air-cooling heat sink. The influences of input current and heat load are determined. And performances under each situation are quantified by thermal resistance analysis. Since TEC generates Joule heat, this nature makes construction of thermal resistance network difficult. To simplify the analysis, this article emphasizes on the resistance heat load might meet when passing through the device. Therefore, the thermal resistances in this paper are to divide temperature differences by heat load. According to the result, there exists an optimum input current under every heating power. In this case, the optimum input current is around 6A or 7A. The performance of the heat sink would be improved with TEC under certain heating power and input current, especially at a low heat load. According to the result, the device can even make the heat source cooler than the ambient. However, TEC is not always effective at every heat load and input current. In some situation, the device works worse than the heat sink without TEC. To determine the availability of TEC, this study figures out the effective operating region in which the TEC air-cooling module works better than the heat sink without TEC. The result shows that TEC is more effective at a lower heat load. If heat load is too high, heat sink with TEC will perform worse than without TEC. The limit of this device is 57W. Besides, TEC is not helpful if input current is too high or too low. There is an effective range of input current, and the range becomes narrower when the heat load grows.

***Keywords*—**Thermoelectric cooler, TEC, electronic cooling, heat sink.

I. Introduction

In the past decades, heat dissipation of electronic element grows rapidly with the improvement of manufacturing technology. This growth induces serious electronic cooling problem. Air-cooling module, which composed of a heat sink and a fan, is popular for solving the heat dissipation problem. In order to satisfy the heat dissipation of modern electronic element, thermal designers have to increase fin area and fan speed to improve its cooling capacity. However, the increase of fin area is restricted by the space. Besides, the increase of fan speed would induce noise, which damages human health. Air-cooling module, therefore, is hardly to meet the requirement of modern electronic component [1], [2].

Recently, thermoelectric cooler (TEC) is applied to electronic cooling [3], [4]. With the advantages of small size, quietness and reliability, thermoelectric cooler is widely applied to military, aerospace, instrument, and industrial products for different cooling purpose [5]. A typical thermoelectric cooler consists of p-type and n-type semiconductor pellets connected electrically in series and sandwiched between two ceramic substrates. Whenever direct current passes through the circuit of heterogeneous conductors, it causes temperature differential between TEC sides. As a result, one TEC face, which is called cold side, will be cooled while its opposite face, which is called hot side, is simultaneously heated. With the above advantages, TEC might be one of the best candidates for electronic cooling and a lot of studies try to determine its utility on electronic cooling [6]-[9]. These literatures indicate that heat sink on the hot side plays an important role in the overall performance. Therefore, plenty of studies [10]-[13] integrate TEC with different heat sinks and try to improve TEC thermal performance and COP. In order to describe the thermal transport phenomenon of TEC, some studies dedicate to develop physical models electronically [14] or

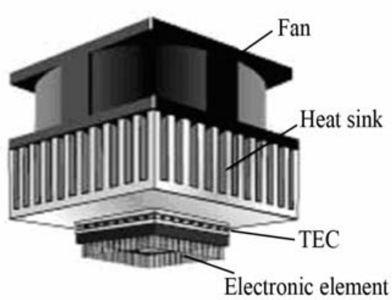

Fig. 1 The thermoelectric cooling module which comprises a thermoelectric cooler (TEC) and an air-cooling heat sink

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thermodynamically [15]. How to choose suitable TEC and heat sink to achieve a specific cooling purpose always bothers thermal designers. Huang *et al.* [16] propose a simple design method for TEC cooling modules. They measure the properties of TEC first, and then verify the thermal resistance of heat sink which can meet the thermal design temperature.

Thermal designers might be interested in whether the performance of heat sink could be promoted by applying TEC or not. However, recent studies about TEC mostly emphasize on improving the COP of TEC and developing mathematical model. Few research studies the thermal performance of a cooling module which involves TEC. In order to understand the influence of TEC on the capability of heat sink, the present study integrates a TEC and an air-cooling heat sink as a thermoelectric air-cooling module, and experimentally determines the performance of this module. The module is shown in Fig. 1. A TEC is set between electronic element and heat sink. The TEC hot side is attached on the heat sink base, while the TEC cold side is attached on the heat source. The experimental parameters are heat load of heat source and input current for TEC. This study quantifies the thermal performances under every situation by thermal resistance network. Furthermore, the present article also verifies the available operating range, in which the heat sink with TEC would work better than that without TEC.

II. Nomenclature

I	TEC input current, A
k	thermal conductivity of TEC, W/°C
Q_H	heating power from TEC hot side, W
Q_L	heating power into TEC cold side, W
R	electrical resistance of TEC, Ω
R_{HS}	heat sink thermal resistance, °C/W
R_t	overall thermal resistance, °C/W
$R_{t,w/oTEC}$	overall thermal resistance of heat sink without TEC, °C/W
R_{TEC}	TEC thermal resistance, °C/W
T_a	ambient temperature, °C
T_b	center temperature of the bottom of the heat sink, °C
T_c	cold side temperature of TEC, °C
T_d	surface temperature of the heat source, °C
T_h	hot side temperature of TEC, °C
α	Seebeck coefficient, V/°C

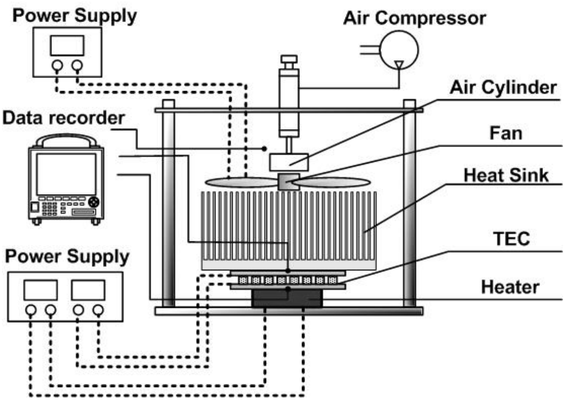

Fig. 2 The schematic graph of the experimental apparatus

III. Experimental Apparatus

A. TEC Air-Cooling Experiment Setup

Fig. 2 shows the experimental apparatus for this TEC air-cooling system. It consists of a heater, two power supplies, a data recorder, an air compressor, an air cylinder, a TEC, and a heat sink. The heater connects to a D. C. power supply which offering heating power to simulate the heat dissipation of a microchip. The heating area is 30mm×30mm. In order to diminish heat loss, thermal insulating material is wrapped on the heater besides the heating area. The heater is attached on the TEC with thermal grease. A T-type thermocouple is located at the center of the heating area for the temperature T_d. The highly effective TEC manufactured by Kryotherm is employed. The dimension of TEC is 40mm×40mm×3.2mm. The TEC is

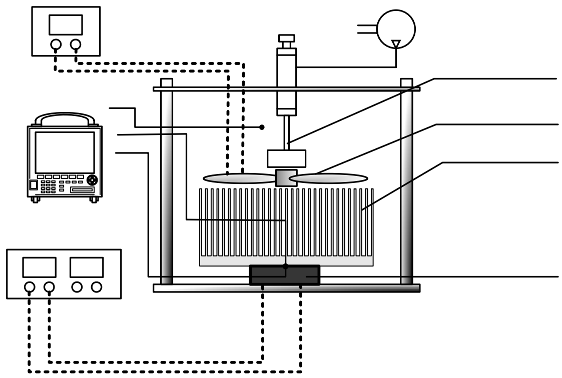

Fig. 3 The experimental apparatus for heat sink

functioned with the electricity from the power supply connecting to it. Above the TEC sets the air-cooling heat sink with proper thermal grease. The heat sink is made of aluminum. The heat sink base is in the size of 77mm×68mm×10mm, and the fins are 68mm in length, 25mm in height, and 1mm in thickness. There are 35 fins with pitch of 1.2mm on the heat sink base. A thermocouple is mounted on the center under heat sink base surface for the heat sink base temperature T_b. A fan is set above the heat sink and connected with another power supply. The fan speed is 4300 rpm, and the air flow rate is 45.48 CFM. One thermocouple is located by the experimental system for ambient temperature, T_a. The three thermocouples are connected to the data recorder. All the components are set on the test section and bound together with an air cylinder pressing on the top. The thermocouples used in the experiment have a measurement error of ±0.5°C. The data recorder manufactured by Yokogawa Ltd., Co. has a measurement error of ±0.1%. The

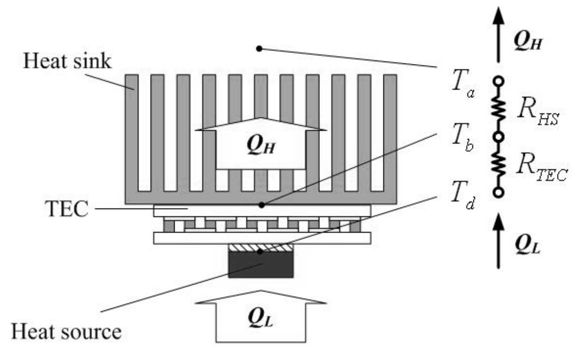

Fig. 4 Thermal resistance network of the cooling module, the thermal resistances are all to divide temperature difference by Q_L

power supply unit has a measurement error of ±0.5%. The maximum error for the thermal resistance is within ±5%

B. Heat Sink Experiment Setup

One of our objectives is to ascertain if the performance of the heat sink would be improved with TEC. Before processing the availability, the performance of the heat sink should be obtained first. Therefore, the present authors did another experiment to evaluate the thermal resistances of the heat sink. The experimental apparatus is presented in Fig. 3. The apparatus is almost the same with that for the TEC air-cooling module, besides the TEC is not employed here.

C. Experimental Parameters

The experimental parameters of TEC air-cooling module are heat load of heat source and input current into TEC. The heat load is from 20W to 100W with an increment of 20W; the input current is from 0A to 10A with an increment of 1A. Therefore, there are totally 55 experiments. The experimental parameter of air-cooling heat sink is only heating power. In order to compare with TEC air-cooling module, the heating power is from 20W to 100W with an increment of 20W as those for the TEC air-cooling module.

IV. Thermal Resistance Network

Thermal resistance network is conducted here for analysis. Since TEC generates Joule heat, it makes heat rejection, which is called Q_H, from TEC hot side larger than the heat absorption, which is called Q_L, into TEC cold side. According to literatures, the general forms of heat absorption and heat rejection are presented as bellow.

$$Q_L = \alpha I T_c - \frac{1}{2} I^2 R - k(T_h - T_c) \quad (1)$$

$$Q_H = \alpha I T_h + \frac{1}{2} I^2 R - k(T_h - T_c) \quad (2)$$

Where the first term on the right hand side is Peltier effect term, the second term is Joule effect term, and the third term is heat conduction term. Since construction of thermal resistance network is often base on the assumption of no heat generation, Joule heat generation makes construction of the thermal resistance network difficult. To make it simple, this article emphasizes on how much resistance the heat from heat source may meet when passing through the device. When heat load passes through this device, Joule heat accomplishes. But the capacity of heat sink is always limited. If TEC generates too much Joule heat, it would make heat load hard to cross the heat sink. Therefore, Joule heat of TEC can be considered as a kind of resistance for heat load. Upon the idea, the thermal resistances in this article are all to divide temperature difference by Q_L. The thermal resistance network is shown in Fig. 4. As indicated in Fig. 4, when the heat from heater passes through this cooling module, it will meet TEC resistance, R_{TEC}, and heat sink resistance, R_{HS}. The summation of these two is the overall resistance, R_t. The definitions of these resistances are described as following.

$$R_{TEC} = \frac{T_d - T_b}{Q_L} \quad (3)$$

$$R_{HS} = \frac{T_b - T_a}{Q_L} \quad (4)$$

$$R_t = \frac{T_b - T_a}{Q_L} = R_{TEC} + R_{HS} \quad (5)$$

To identify the availability of TEC for this heat sink, the present authors did an experiment for the thermal resistance of the heat sink. The thermal resistance model is illustrated in Fig. 5. The definition is described following.

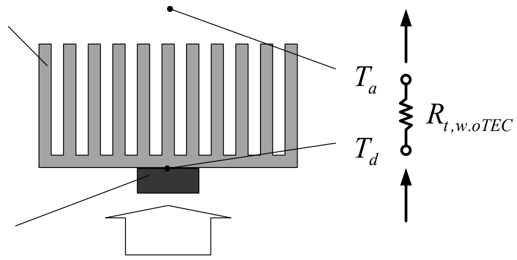

Fig. 5 Thermal resistance of the heat sink, this is determined for the comparison with the TEC air-cooling module

$$R_{t,w/oTEC} = \frac{T_d - T_a}{Q_L} \quad (6)$$

V. Results and Discussions

A. TEC Resistance, R_{TEC}

Fig. 6 shows TEC resistances under different heating power and input current. In the figure, x-axis show the input current, y-axis shows the TEC resistance R_{TEC}, and each curve means different heat load. As indicated in Fig. 6, TEC resistance increases with increasing heat load at a fixed input current. When heat load is large, TEC should raise the temperatures on the both side to keep the energy balance. However, this move drops the TEC performance. Fig. 6 also shows that TEC resistance decreases with increasing input current under fixed heating power. This is caused by Peltier effect. The heat

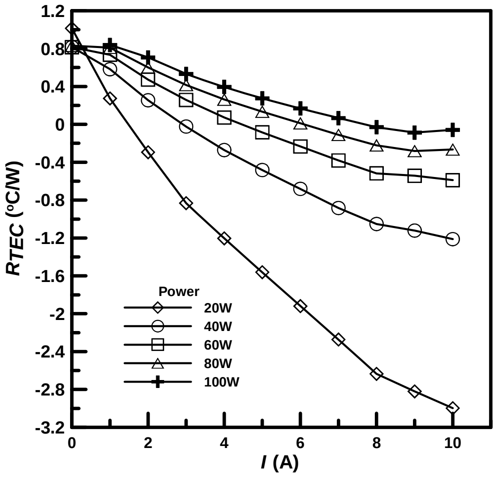

Fig. 6 TEC resistance under every heating power and input current, R_{TEC} increases with heat load and decreases with input current

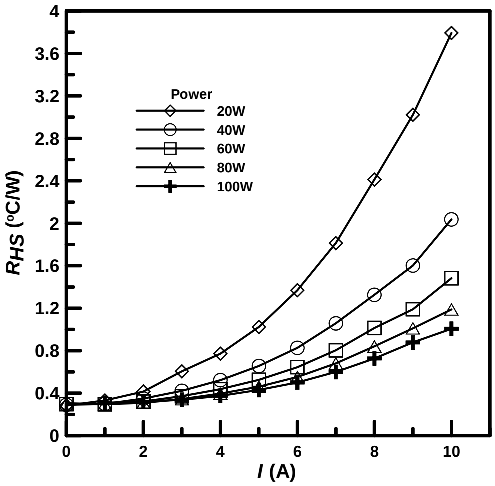

Fig. 7 Heat sink resistance under every heating power and input current, R_{HS} increases with input current and decreases with heat load

transfer rate by Peltier effect is propotional to the magnitude of input current. When input current grows, the heat tranfer rate by Peltier effect also grows. Since a lower thermal resistance means a better performance, it is positve for the performance of TEC. Note that some TEC resistances are negative, especially at low heating power and high input current. According equation (3), R_{TEC} becomes negative if T_d is lower than T_b. This happens when TEC is well-functioned. Readers should note that the temperature on the cold side is lower than hot side when input current is large enough. But the area of TEC is larger than the heating area. The difference induces a spreading resistance on the cold side. This makes some TEC resistances positve at high heating power. Summarily, a high input current is positve for TEC performance in our results.

B. Heat Sink Resistance, R_{HS}

Fig. 7 shows heat sink resistances under different heat load and input current. Heat sink resistance increases with increasing input current under each heat load. Theoretically speaking, the thermal resistance of the air-cooling heat sink is constant when dividing the temperature difference by the total amount of heat passing through the heat sink. However, the thermal resistance in this article is only to divide temperature by the heating power of heater. The amount of heat actually passes through heat sink is more than the heat from heater. This can be proved by subtracting euqation (1) from (2).

$$Q_H - Q_L = \alpha I(T_h - T_c) + I^2 R \tag{7}$$

Since T_h will be higher than T_c when supply enough electricity to TEC, the summation on the right hand side of euqation (7) is always positive. Therefore, if Joule heat exists, the heat sink resistance by Q_L would be larger than ordinary thermal resistance definition. When input current grows, Joule heat of TEC grows, too. It makes the percentage of Q_L in Q_H becomes smaller. Hence, heat sink resistance is larger at a high input current than a low one. Fig. 7 also shows that heat sink resistance decreases with increasing heating power at a fixed input current. When input current is fixed, Joule heat generation is the same. With a constant Joule heat generation, the percentage of Q_L in Q_H increases with increasing heating power. Therefore, heat sink resistance reduces with growing heat load under a fixed input current. Because the capability of heat sink is limited, a large Joule heat would make the heat transfer of Q_L

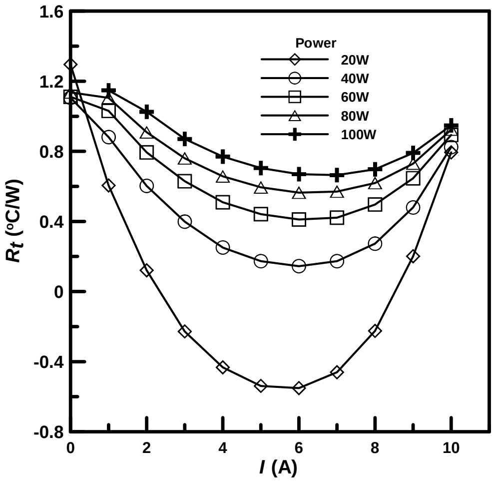

Fig. 8 overall resistance under every heating power and input current, R_t increases with heat load. Due to the contrary trends of R_{TEC} and R_{HS} for input current, an optimal input current exists in R_T

difficult. According to the above discussions, Joule heat generation of TEC has a significant influence on heat sink resistance. Thermal resistance of a normal air-cooling heat sink is around 0.25°C/W, but the heat sink resistance in this module achieves 3.79°C/W. Hence, Joule heat generation is vital for the cooling module.

C. Overall Resistance, R_t

Fig. 8 shows the overall resistances under different heat load

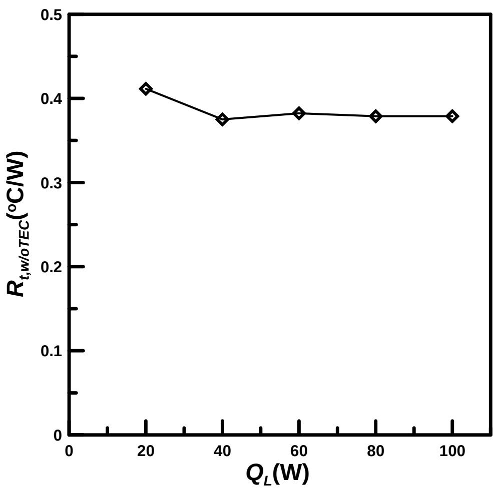

Fig. 9 overall resistance of the heat sink without TEC under every heating power, generally the thermal resistance is constant, the average is 0.385 °C/W

and input current. Under each heat load, overall resistance decreases with increasing input current until the current reaches 6A. When the input current exceeds 6A, overall resistance increases with the growth of input current. The optimal input current is 6A or 7A. The minimal overall resistance of 20W and 100W are -0.551 and 0.664°C/W respectively. Whereas overall resistance is the combination of TEC resistance and heat sink resistance, overall resistance includes the effects on the two resistances. Recall that TEC resistance decreases with increasing input current, while heat sink resistance increases with increasing input current. Their trends for input current are opposite, therefore, an optimal input current comes to overall resistance. Fig. 8 also shows that overall resistance grows with the increase of heating power. At the heating power of 20W, overall resistance even reaches negative value while input current is from 3A to 8A. A negative value of overall resistance means this cooling module can makes the heater cooler than the ambient. According to the above results, Joule heat generation plays an important role in this module. Even TEC works, Joule heat of TEC increase the burden of the heat sink and damage the overall performance.

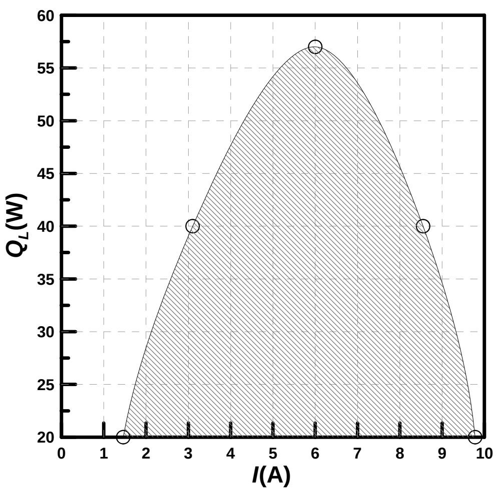

Fig. 10 available operating region of TEC for the heat sink, when operate in the shadow area, this device would works better than the heat sink only

D. Availability of TEC for the Heat Sink

This section is to verify the operating situations in which the TEC air-cooling would works better than the air-cooling heat sink only. First, the thermal performance of the heat sink without TEC is determined. And the result is illustrated in Fig. 9. The result shows that heat sink without TEC is almost constant under different heating power. The average $R_{t,w/oTEC}$ is 0.385 °C/W. This average is taken as a criterion, if the overall resistance is smaller than this value, TEC is available under the heating power and input current.

Fig. 10. illustrates the availability of the TEC for this air-cooling heat sink. The x-axis shows the input current of TEC, and the y-axis shows the heat load of heater. The border of the shade means the overall resistance R_t is identical to the thermal resistance of the heat sink without TEC $R_{t,w/oTEC}$. If the operating point is inside the shade, the cooling capacity of the TEC air-cooling module is better than that of the air-cooling heat sink. As shown in Fig. 10, the maximal available heating power is 57W which is at the input current of 6A, but the performance of the cooling module is the same with the heat sink at the operating point. Inside the shade, the TEC air-cooling module performs better at low heat loads. Readers can observe this in Fig. 8, the overall resistances of 20W are lower than those of 40W, it means the TEC cooling module can reach a better performance at 20W than 40W. Besides, the available range of input current is wider at low heating power. In conclusion, the TEC air-cooling module is available for low heat dissipation applications, if heat dissipation is larger than 57W, the air-cooling heat sink is prefered rather than integrating it with TEC.

VI. Conclusion

This study experimentally investigates the performance of the TEC air-cooling module. The influences of heating power and input current are determined. Thermal resistance network for analysis is employed. According to the measurement of temperatures, the cooling module includes TEC resistance and heat sink resistance. TEC resistance stands for the thermal capacity of the thermoelectric cooler, and heat sink resistance for the capacity of the air-cooling heat sink. Overall resistance is the summation of these two. With increasing input current, TEC resistance decreases and heat sink resistance increases. The opposite trends on input current result in an optimal value in the overall resistance. The optimum is 6A in this article under each heating power. With increasing heating power of heat source, TEC resistance increases and heat sink resistance decreases. Including these two effects, the overall resistance grows with the increase of heating power. The minimal overall resistance of 20W and 100W are -0.551 and 0.664°C/W respectively. In our experimental results, thermoelectric cooler does work, it even makes heat source cooler than the ambient at low heating power. However, the Joule heat generation causes an extra load for heat sink. Since the cooling capacity of heat sink is limited, the Joule heat generation becomes another resistance and damages the overall performance. By comparing with the thermal resistance of the heat sink without TEC, this article verifies the effective range in which TEC is effective to enhance the heat sink. The result shows that the maximal available heating power is 57W. As heating power is lower, the available range of input current is wider.

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