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Thermal Performance Investigation of Thermoelectric Cooling System with Various Hot-Side Cooling Methods

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Abstract

Thermoelectric devices have been widely used in various applications, including cooling and power generation. The potential application of thermoelectric cooling systems has been studied. However, these systems still face challenges in achieving optimal performance compared with other cooling systems. Several factors, including the hot-side cooling method, influence the performance of thermoelectric systems. This study aimed to investigate the effects of different hot-side cooling methods on the thermoelectric performance and thermal behavior of thermoelectric cooling systems. The testing methods involved the combination of the thermoelectric module with five hot-side heat exchangers, including a square heatsink, a round heatsink, a two-pipe heat pipe, four-pipe heat pipe, and a liquid cooler, with variations in the operating voltage. The experimental results reveal that the different heat exchangers considerably affected the system performance. The liquid cooler consistently achieved the lowest hot- and cold-side temperatures among all heat exchangers. In the case of the ratio of the cooling capacity and temperature difference across the module, the liquid cooler attained the highest values at 12 and 9 V. In addition, the square heatsink exhibited the highest ratio at 6 V. Meanwhile, the coefficient of performance (COP) values were relatively similar in the various heat exchangers, with the liquid cooler generally showing higher COP values.

Keywords: heatsink, heat pipe, hot-side cooling method, liquid cooler, thermoelectric cooling

1. Introduction

Cooling systems are used to reduce the temperature of an object or environment. They can be utilized in various applications, such as air conditioning, industrial machinery, automobiles, computers, and other electronic devices. Thermoelectric cooling is one of the methods used in cooling systems [1, 2].

Thermoelectric technology enables direct conversion between thermal energy and electricity. This component has been widely used in various applications, including cooling and power generation, by utilizing the Seebeck and Peltier effects. Some studies have used the cooling generated by thermoelectrics to condition cabin temperature for product storage [3–5] and cooling electronic components [6–8]. In other cases, these materials are used to achieve thermal comfort [9, 10] or in water generation [11, 12].

Several factors influence the performance of thermoelectric cooling systems: thermoelectric materials [1, 13], working fluids [14], device configurations [15], and hot-side cooling methods [16, 17]. Hot-side cooling methods dissipate heat from thermoelectric devices, which increases the temperature difference between the hot and cold sides [16]. This method can improve thermal efficiency and reduce the heat's capability to spread to the cold side.

In general, thermoelectric hot-side cooling methods adopt cooling systems, such as air and liquid cooling, for electronic devices. The commonly used heat exchanger devices include heat sinks [18, 19], heat pipes [20, 21], and water blocks [6, 22].

In the development of thermoelectric systems, the thermal efficiency of the thermoelectric device affects its performance and durability [2, 14, 23]. Therefore, research and development efforts should focus on the exploration of efficient and innovative thermoelectric technologies. Studying the variations in hot-side cooling methods to enhance the thermal performance of thermoelectric systems can be a solution to improving the thermoelectric performance.

This research aimed to analyze the influence of various hot-side cooling methods on the performance of thermoelectric systems and identify the most effective one for application in thermoelectric devices. The fulfillment of these objectives will contribute to the development of efficient and environmentally friendly thermoelectric technologies. Specifically, the findings will serve as a reference for further research in this field.

2. Methods

The experiment involved a single thermoelectric module equipped with heat exchangers on both sides to facilitate heat absorption and dissipation. The thermoelectric module, which had dimensions of 40 × 40 × 4 mm^3, was constructed using a BiSn material commercially identified as TEC1-12706. The module is widely available in the market and can operate using a direct current (DC) voltage with a maximum current rating of 6.4 A. Table 1 provides the detailed specifications of the thermoelectric module.

Heat exchangers were connected to the hot and cold sides of the thermoelectric module. On the cold side, a fan less heat sink (Figure 1(a)) was installed to facilitate natural heat exchange. Various types of heat exchangers (Figures 1(b–f)) were used on the hot side to investigate their influence on the overall thermoelectric system performance. All heat exchangers on the hot side were equipped with auxiliary equipment, such as fans or pumps, to enhance the heat exchange efficiency. Improved cooling on the hot side contributed to the generation of a high thermal energy on the cold side [14].

Table 1. Specifications of the Thermoelectric Module

Item	Remark
Model	TEC1-12706
Dimension	40 × 40 × 4 mm^3
Material	BiSn
I_{max} (A)	6.4
V_{max} (V)	16.4
Q_{cmax} (W)	57
ΔT_{max} (K)	75

However, precise and accurate connections must be ensured between the heat exchangers and thermoelectric module. Tiny gaps can increase thermal resistance. Therefore, during the experiment, such effect was minimized by a applying a thermal paste with a thermal conductivity rating of 10.5 W/mK between the heat exchangers and thermoelectric module. Figure 1 provides a visual representation of the heat exchangers used in this study. Table 2 presents in detail the specifications of each heat exchanger.

The experiments involved testing five types of hot-side heat exchangers, namely, (1) square heat sink, (2) round heat sink, (3) two-pipe heat pipe, (4) four-pipe heat pipe, and (5) liquid cooler with a thermoelectric module. In addition, the input voltage was adjusted to specific values to examine the performance of the combined module and heat exchangers when applied at variable capacities. The air temperature in the room was maintained at a constant value during the experiment. Table 3 provides a summary of the test variables.

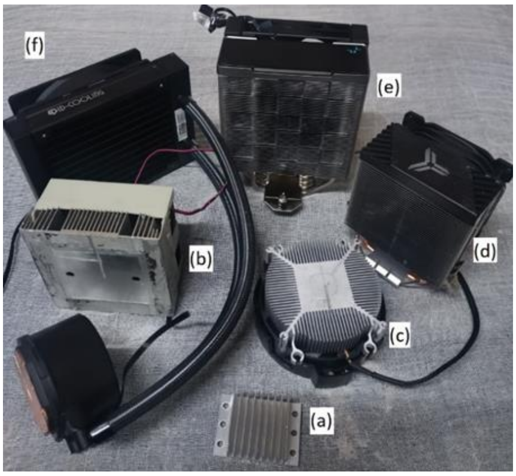


Figure 1. Various Heat Exchangers: (a) Cold-side Heatsink, (b) Square Heatsink, (c) Round Heatsink, (d) Two-pipe Heat Pipe, (e) Four-pipe Heat Pipe, and (f) Liquid Cooler

Table 2. Specifications of the Heat Exchangers

Code	Types	Dimension	Material	Rated Voltage
(a)	Heatsink	58 × 40 × 17 mm^3	Aluminum	-
(b)	Heatsink	Heatsink: 98 × 100 × 24 mm^3 Fan: 90 × 90 × 25 mm^3	Aluminum	12 V
(c)	Heatsink	Heatsink: Ø87 × 20 mm Fan: Ø94 × 25 mm	Aluminum	12 V
(d)	Heat pipe	Heat pipe: 2 × Ø6 mm Fan: 93 × 92 × 25 mm^3 Total: 93 × 128 × 67 mm^3	Heatsink: Aluminum Heat pipe: Copper	12 V
(e)	Heat pipe	Heat pipe: 4 × Ø6 mm Fan: 120 × 120 × 25 mm^3 Total: 127 × 97 × 155 mm^3	Heatsink: aluminum Heat pipe: Copper	12 V
(f)	Liquid cooler	Radiator: 154 × 120 × 27 mm^3 Fan: 120 × 120 × 25 mm^3 Water block: 72 × 72 × 447.3 mm^3	Radiator: aluminum Water bock: Copper	Fan: 12 V Pump: 12 V

During the experiment, the temperatures on both sides of the thermoelectric module were recorded using type K thermocouples to observe the thermal behavior and evaluate the system's performance in each test variation. The cross-section of the heat exchangers was given a gap equal to the sensor diameter (Figure 2). In addition, the current values of the thermoelectric module and heat exchangers were recorded to evaluate their changes in each test variation. Table 4 shows the specifications of the measuring instruments used in the experiment.

The characteristics compared in each variation included the cold-side temperature (T_c), hot-side temperature (T_h), temperature difference across the thermoelectric module (ΔT_{hc}), cooling capacity (Q_c), and coefficient of performance (COP) obtained through the Equation (1) to Equation (4) [3, 5, 16, 19].

Table 3. Experimental Variations

Item	Variation
Hot-side heat exchanger	Rectangular heatsink (1) Round heatsink (2) 2-pipe heat pipe (3) 4-pipe heat pipe (4) Liquid cooler (5)
Voltage	12 V 9 V 6 V

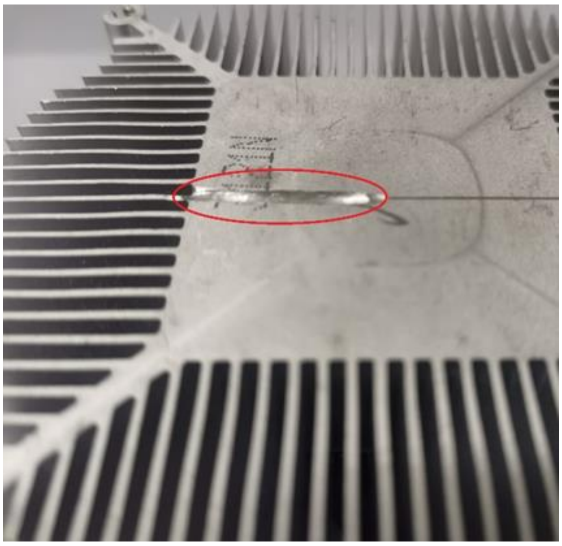


Figure 2. Gap in the Heat Exchangers for Sensor Placement

$$COP = \frac{Q_c}{Q_h - Q_c} \tag{1}$$

$$Q_c = \alpha I T_c - \frac{I^2 R}{2} - K_t . \Delta T_{hc} \tag{2}$$

$$Q_h = \alpha I T_h + \frac{I^2 R}{2} - K_t \Delta T_{hc} \tag{3}$$

$$\Delta T_{hc} = T_h - T_c \tag{4}$$

where α, K_t, and R refer to the Seebeck coefficient (V/K), thermal conductivity of the thermoelectric module (W/mK), and electrical resistance of the thermoelectric material (Ω), respectively, obtained through Equation (5) to Equation (7).

$$\alpha = \frac{V_{max}}{T_h} \tag{5}$$

$$K_t = \frac{(T_h - \Delta T_{max}) V_{max} . I_{max}}{2 T_h . \Delta T_{max}} \tag{6}$$

$$R = \frac{(T_h - \Delta T_{max}) V_{max}}{T_h . I_{max}} \tag{7}$$

3. Results and Discussions

The performance of the thermoelectric modules under various hot-side cooling methods was tested in a room with a constant temperature of 24 °C Each test variation involved running the system for 15 mins to ensure stability and consistency of the results.

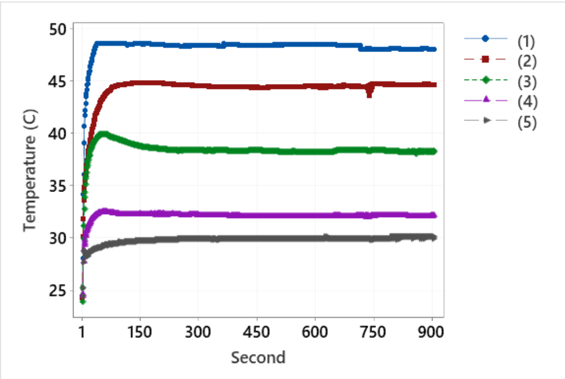
The experimental findings (Figure 3) revealed considerable variations in the T_h. Heat exchanger (1) consistently exhibited the highest T_h across all tested voltage variations. Conversely, heat exchanger (5) demonstrated the lowest T_h under all the cooling methods examined, which indicates its superior performance.

Under stable conditions, the average T_h achieved by heat exchanger (1) were 48.3 °C, 39.75 °C, and 34.04 °C at voltages of 12, 9, and 6 V, respectively. By contrast, heat exchanger (5) attained T_h of 30.09 °C, 28.6 °C, and 26.8 °C at 12, 9, and 6 V, respectively, under similar conditions.

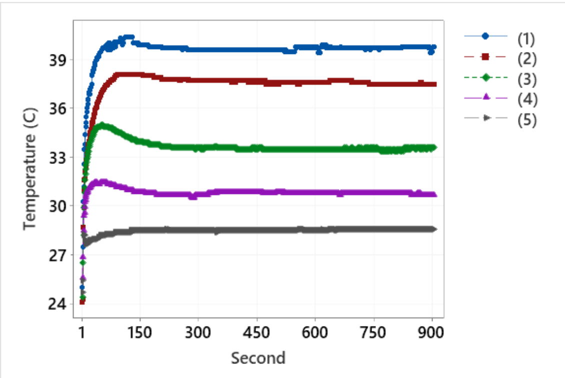
Comparison under different operating voltages revealed that heat exchanger (3) yielded relatively lower T_h values at the operating voltage of 6 V. This finding suggests the more efficient cooling performance of this heat exchanger than other methods at low voltage settings.

Table 4. Specifications of Measurement Tools

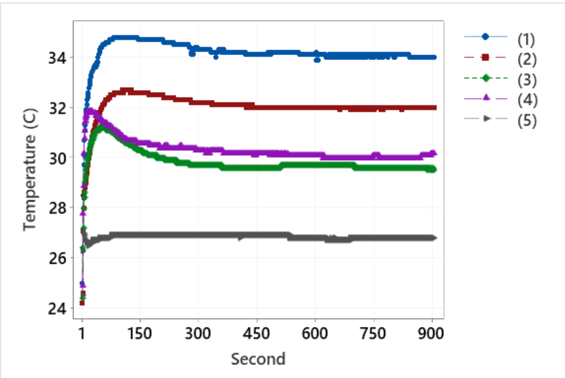
Item	Model	Operative Range	Resolution	Accuracy
4-channel Temperature Data Logger	TA612C	−40 °C to 250 °C	0.1	± 0.4%
Digital Clamp Meter	UT204A	40 A DC 40 V DC	0.01 0.01	± 2% ± 0.8%



(a)

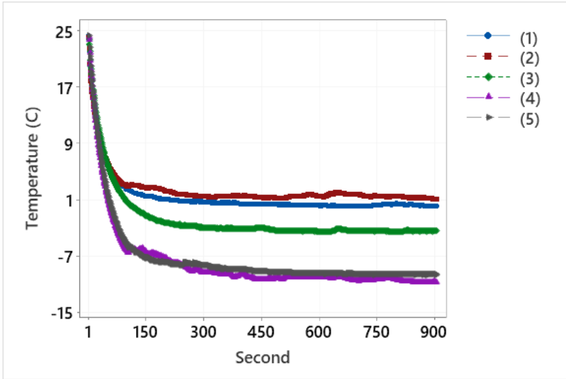


(b)

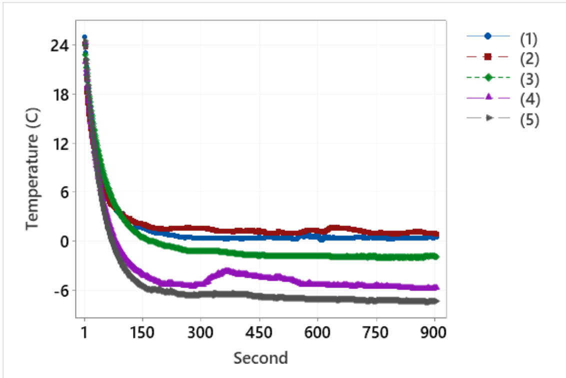


(c)

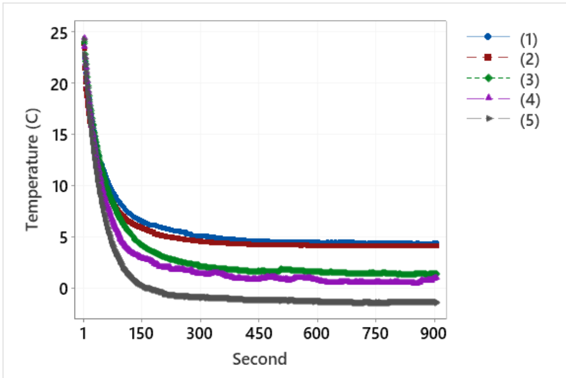
Figure 3. Variation in Th Over Time at (a) 12, (b) 9, and (c) 6 V



(a)



(b)



(c)

Figure 4. Variation in Tc Over Time at (a) 12, (b) 9, and (c) 6 V

The low T_h value shows a positive effect on the overall system performance. This condition implies that the cold-side temperature (T_c) can be reached at a low level under a similar temperature difference (ΔT_{hc}) across the thermoelectric module.

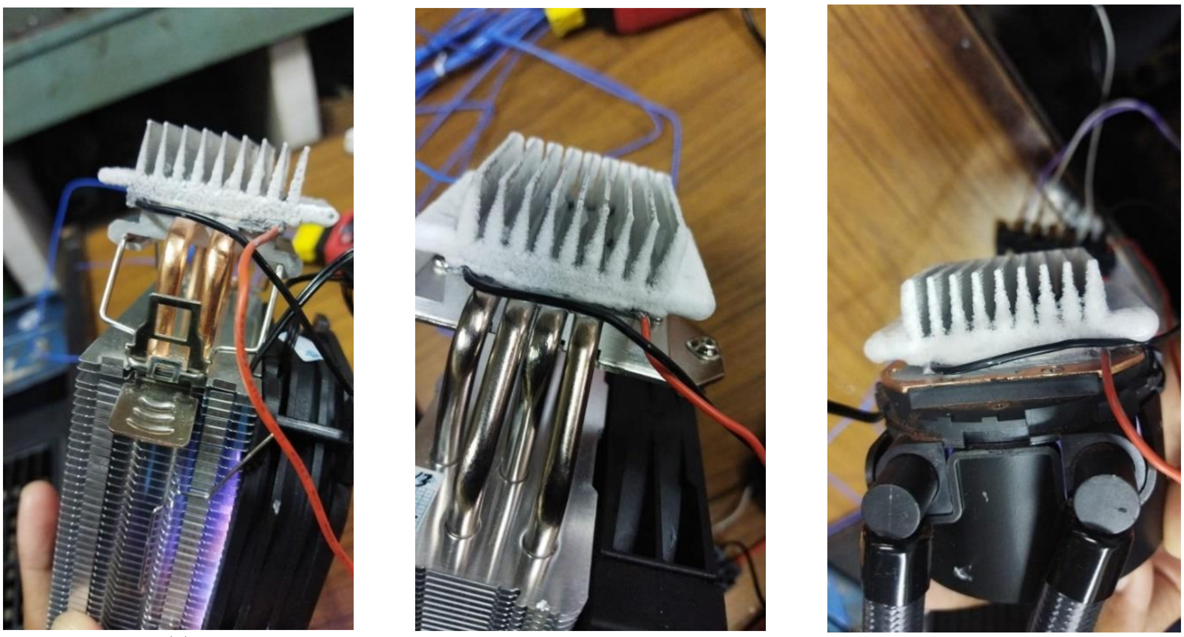
Figure 4 presents the T_c achieved by the thermoelectric module in each test. In general, the module incorporating heat exchanger (5) consistently attained T_c below 0 °C across all test variations and outperformed the other heat exchangers. At 12 V, the specific T_c reached −9.56 °C, while at 9 V and 6 V, the values were −7.30 °C and −1.30 °C, respectively. Notably, at 12 V, the thermoelectric module equipped with heat exchanger (5) exhibited a slightly higher T_c value than that equipped with heat exchanger (4), with an average difference of approximately 1 °C.

Furthermore, the combination of thermoelectric modules with heat exchangers (3) and (4) can generate T_c below 0 °C, albeit exclusively at 12 and 9 V. Apart from heat exchanger (5), this combination effectively achieved subzero temperatures.

The modules equipped with heat exchangers (1) and (2) yielded the highest T_c, with relatively close values. Although they did not reach temperatures below 0 °C, these heat exchangers showcased a notable performance in terms of T_c.

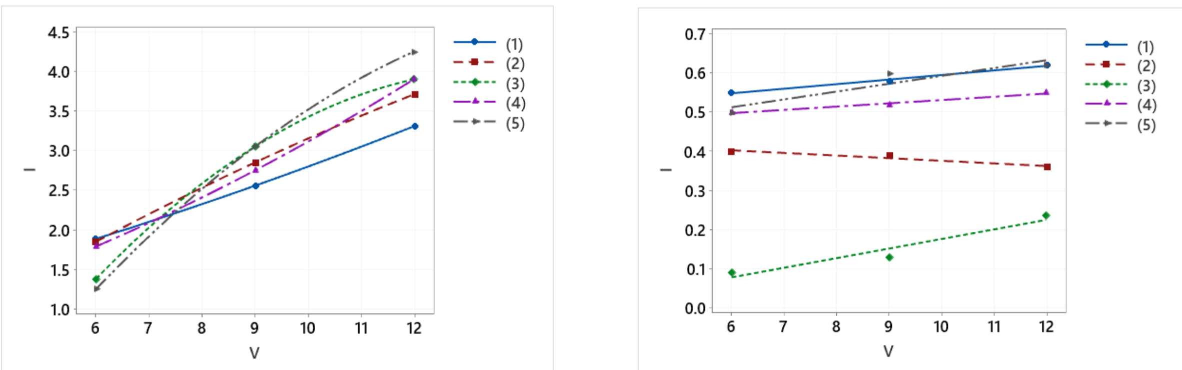
Frost formation was observed when the temperature of the cold-side heatsink dropped below the freezing point of 0 °C (Figure 5). Figure 5 reveals that the frost generated by heat exchangers (5) and (4) was slightly thicker than that produced by heat exchanger (3). This disparity in frost thickness can be attributed to the varying temperatures attained by these heat exchangers. The extent of frost formation is directly influenced by the achieved temperatures, with low temperatures leading to a substantial frost accumulation.

In addition to temperature, the electrical current consumed by the thermoelectric module and auxiliary equipment varied in each test. Figure 6 shows the measurement results of the electric current in the thermoelectric module and heat exchanger during each test variation. In general, the increase in the operating voltage from 6 V to 12 V was in agreement with the increase in the current values of the thermoelectric module. A considerable increase in the current occurred when the thermoelectric module was combined with heat exchangers (5) and (3), whereas the changes were relatively lower with heat exchangers (1), (2), and (4). Thus, in accordance with the previous explanation, the thermoelectric module tended to consume relatively substantial amounts of energy at low operating temperature ranges.



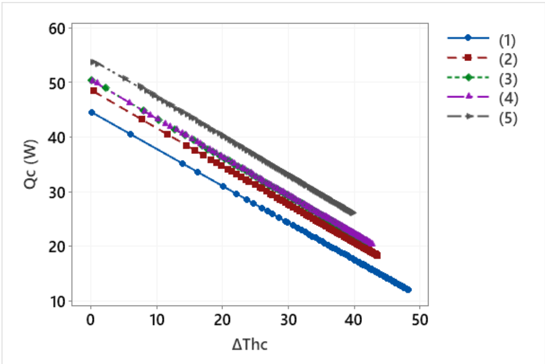
(a) (b) (c)

Figure 5. Frost Formation on the Cold Side of the Thermoelectric Heat Exchangers: (a) Two-pipe Heat Pipe, (b) Four-pipe Heat Pipe, and (c) Liquid Cooler

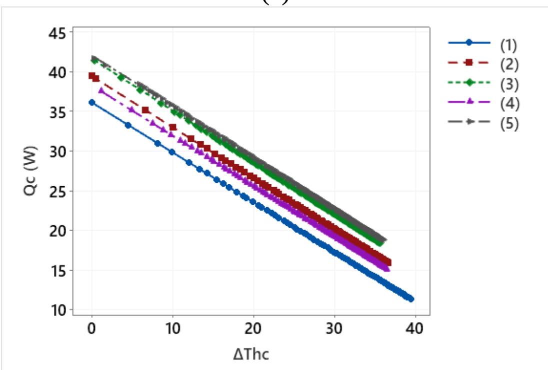


(a) (b)

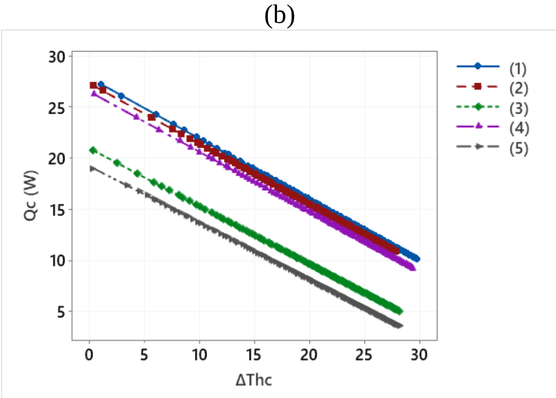
Figure 6. Current Versus Voltage Curves for: (a) Thermoelectric and (b) Auxiliary Equipment



(a)

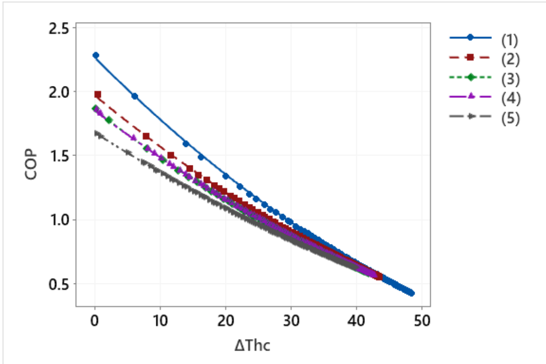


(b)

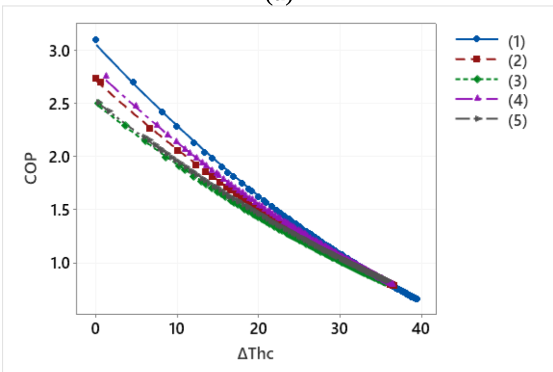


(c)

Figure 7. Qc to ΔThc Curves Produced by Each Heat Exchanger at (a) 12, (b) 9, and (c) 6 V



(a)



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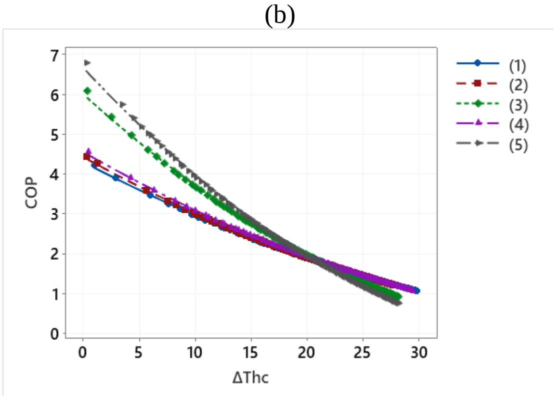

(c)

Figure 8. COP to ΔThc Curves Produced by Each Heat Exchanger at (a) 12, (b) 9, and (c) 6 V

Compared with the thermoelectric module, the electrical current consumed by the auxiliary equipment was remarkably low. The lowest electricity consumption, which ranged from 0.09 A to 0.24 A, was achieved by the fan of heat exchanger (3), followed by that of the fan of heat exchanger (2), with a range of 0.36 A to 0.4 A. Meanwhile, the electricity consumption of the other three heat exchangers varied between 0.5 and 0.62 A.

The experimental findings reveal that the choice of cooling method on the hot side considerably affects the Q_c and the ΔT_{hc} produced by the system. Figure 7 demonstrates that Q_c and ΔT_{hc} exhibited an inverse relationship in the thermoelectric modules. High Q_c values correspond to low ΔT_{hc}, and vice versa [14]. Variations in heat exchangers and operating voltages in the experiment resulted in diverse characteristics. Specifically, at 12 and 9 V, heat exchanger (5) exhibited the highest average ratio of Q_c to ΔT_{hc}. However, at 6 V, heat exchanger (1), which initially had the lowest Q_c and ΔT_{hc}, showed the highest performance. One contributing factor to this behavior was the decrease in the current, which was particularly noticeable in heat exchangers (3) and (5) when supplied with a 6 V voltage.

Figure 8 illustrates the relationship between the COP and the ΔT_{hc} for all test variations. The highest COP of the thermoelectric module was observed during the early stages of the experiment. However, as the experiment progressed, the ΔT_{hc} increased, accompanied with a decrease in COP until it reached a stable state.

In general, the COPs of the different heat exchangers showed a slightly remarkable difference when the thermoelectric module operated at its maximum ΔT_{hc}. At 6 V heat exchangers (1) and (2) exhibited slightly higher COPs compared with the others under similar conditions. At 12 and 9 V, heat exchanger (5) yielded the highest COP of 0.63 at ΔT_{hc} of 39.65 °C and 0.83 at ΔT_{hc} of 35.9 °C. Conversely, heat exchanger (1) produced the lowest COP, with values of 0.45 at ΔT_{hc} 47.75 °C and 0.67 at ΔT_{hc} 39.27 °C for the same variations. At the 6 V operating voltage, the highest recorded COP was 1.23 by heat exchanger (2) at ΔT_{hc} 27.8 °C, and the lowest was 0.78 by heat exchanger (5) at ΔT_{hc} 28.1 °C.

4. Conclusions

In this study, the effects of different hot-side cooling methods on the performance of a thermoelectric cooling system were investigated. The experimental results reveal the considerable effect of hot-side cooling methods and operating voltage on the system performance. The key findings are as follows: a) Heat exchanger (5) consistently achieved the lowest T_h and T_c among all heat exchangers, which indicates its superior cooling performance. b) The cooling performance, as measured by the ratio of Q_c and ΔT_{hc}, varied with the type of heat exchanger and operating voltage. Heat exchanger (5) consistently achieved the highest $Q_c/\Delta T_{hc}$ ratio at 12 and 9 V, and heat exchanger (1) exhibited the highest ratio at 6 V. c) The COP values were relatively similar among the heat exchanger variations at the maximum ΔT_{hc}, with slight variations observed at different voltages. Heat exchanger (5) generally exhibited a high COP.

These findings demonstrate the importance of hot-side cooling methods in optimization of the performance of thermoelectric cooling systems. Extensive research is needed to open up opportunities for another cooling method that has not been studied to further increase system efficiency and Q_c.

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