Experimental Study of Thermoelectric Cooler Box Using Heat Sink with Vapor Chamber as Hot Side Cooling Device

by Adi Winarta

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Adi Winarta, I. Made Rasta, I. Nyoman Suamir, and I. G. K. Puja

Abstract Thermoelectric refrigeration system is considered environmentally friendly because it does not use refrigerants which have huge potential for damaging the ozone layer. In this experimental work, a vapor chamber heat sink was used to absorb heat at the hot side of Peltier module of the cooler box. The cooler box has 215 mm × 175 mm × 130 mm of inner dimension. The performance of cooler box is analysed for each different current supplies to the thermoelectric module. The result shows that increasing the current result in larger temperature difference of the hot and the cold side, increase the cabin temperature, decrease the COP of the cooler box. The experimental result also stated that highest COP with 500 ml of water within the cooler box is 0.72.

Keywords Thermoelectric · Cooler box · Vapor chamber · COP · Thermoelectric refrigerator

1 Introduction

Refrigeration is the mechanism of decrease space temperatures to a level that is lower than its environment. There are at least eight types of refrigerant systems. Among them are vapor-compression, absorption, thermoelectric (TEC), air-standard, steam jet, solar, thermo acoustic and metal hydride refrigeration [1]. The most popular refrigeration system is vapor compression (VC). It is not surprising due to its highest efficiency compare with others systems. Unfortunately, the majority of refrigerants used by the vapor compression system still contained chlorine which causes global warming and thinning of the ozone layer [1].

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Thermoelectric is one of the solutions to reduce the detrimental effects of the refrigerants used in vapor compression system. However, not every application would be fit with thermoelectric characteristics as a refrigeration system. But in certain applications such as military, medical industries, aerospace, and instrumentation, thermoelectric might be preferred over any other system. Due to less noise and fewer mechanical moving parts, accurate temperature control, compact design, and low-cost maintenance [2, 3]. Thermoelectric also can be supplied with direct current power which can be generated from any renewable energy source which could increase its efficiency [4].

Many studies had been published concerning the evaluation of thermoelectric refrigeration performances, in the past years. Most of the studies have been conducted to increase the efficiency of the thermoelectric system as a cooling device or refrigerator. Min and Row [5] studied the performance of several types of coolers that used a thermoelectric system and compared it with a vapor compression system. They found not only the performance characteristic of thermoelectric but further improvement may be possible with reducing contact resistance, fixing the thermal design, and making a realistic model. Dai et al. [6] studied the thermoelectric refrigerator with solar cell driven. They showed the refrigerator's COP was maintained at about 0.3 under conditions suitable with cabin temperatures ranging from 5 to 10 °C. Vián and Astrain [7] experimented with increasing the performance of thermoelectric refrigeration using a heat exchanger based on the thermosiphon principle for the hot and cold sides. Their device successfully increases the C.O.P of the thermoelectric refrigerator. Jugsujinda et al. [8] studied the thermoelectric cooler box with 0.022 m^3 cabin volume. They could decreased the cabin temperature from 30 to -42 °C in 60 minute using 3.5 A of electric current to Peltier module. The COP of thermoelectric was 0.22 for the supply power of 40.46 W. Gökçek et al. [4] experimentally studied mini-channel water as the cooling device of thermoelectric hot side. They reported that increased the flow rate of water to mini-channel decrease the inner temperature of the cold side. Mirmanto et al. [8] used two different types of heat sink units on the hot side of thermoelectric cooler box to improved the system performance. Their result stated the experimental COP increase with time for COP increases sharply for while and then get flat as long as the device operation. They also stated that heat sink fan is more reliable if the energy consumed became a consideration. Mirmanto et al. also studied about the position of Peltier module at the thermoelectric cooler box with the effect COP from its position variation. Their box was 0.004891 m^3 in volume and made from 50 mm of Styrofoam. The also put a 360 ml of water as a cooling loads. They result stated that Peltier module which attached at the side wall of cooler box giving the best performance. Lertsatitthanakorn et al. studied the performance of thermoelectric air cooling using the vapor chamber [9]. Their result shows that vapor chamber increase the system performance up to 32.2% compare with conventional heat sink.

In thermoelectric refrigeration, cooling device usually applied as thermal management for the hot side of TEC. One method to improve thermoelectric cooling performance is to maximize the absorption of heat released at the hot side. Better performance of TEC was achieved if the temperature of hot side can be reduced to desired level with the use of heat pipe [10]. Many researches also had been performed with many passive device such as heat pipe, thermosyphon as a cooling device [7, 10–12].

Vapor chambers plates are other types of passive device cooling which is one of the heat pipe family [13–15]. Vapor chamber generally used to collect heat from flat and larger area sources of heat transfer. Vapor chambers are generally used for high heat flux applications due to its characteristic as a latent passive cooling. It has unique or genuine two-dimensional spreading area from other conventional heat pipe like tubular pipe.

Many types of heat sink, includes active and passive, have been investigated by many researchers to achieved the maximum cooling at thermoelectric refrigeration [4, 7, 9, 10, 16]. However, very few work have been conducted with the vapor chamber as a thermoelectric hot side cooler, especially for the cooler box. To the author best knowledge there is no study performed using vapor chamber in thermoelectric cooler box yet. Therefore, the objective of the research was to find the performance of thermoelectric cooler box using vapor chamber as the cooling device of the hot side.

2 Method and Material

To study the vapor chamber as a cooling device of hot side thermoelectric, a cooler box was built made from polyurethane and has a thickness of 40 mm. Configuration of experimental test of thermoelectric cooler box is shown in Fig. 1. It is composed of a cooler box with thermoelectric module unit, data acquisition unit for temperature logging, power supply units for thermoelectric module and fans, a power meter for electricity power measurement. The inner dimension of the cooler box was approximate 215 mm × 175 mm × 130 mm with the thermoelectric module inserted at the top of the box. Peltier module TEHC1-12710 for cooling from ®Thermonamic was used as a cooling device for the cooler box. It has dimensions of 40 mm × 40 mm × 3.6 mm. Seeback coefficient, thermal conductivity and internal resistance of thermoelectric are 0.00023 V/K, 1.5 W/m °C, 1.25 Ω, respectively. The vapor chamber heat sink used in this experiment was supplied from Dongguan Awind Electronic Technology Co., Ltd. The device dimension was approximately 90 mm × 90 mm × 2.4 mm exclude the heat sink which embedded into one part as shown in Fig. 2. An extender used between the hot side of TEC and vapor chamber which made from copper block with a dimension of 40 mm × 40 mm × 35 mm. The cooper block dimension is 40 mm × 40 mm × 35 mm A cold sink with a dimension of 90 mm × 90 mm × 20 mm was clamped tight at the cold side of TEC using the bolt and nut structure. Two DC axial fan were used at the top of vapor chamber and the bottom of cold sink to increase the convective heat transfers. This fan has a dimension of 90 mm × 90 mm × 24 mm and operates at 12 V/0.15 A. Thermal paste with 1.97 W/m °C of thermal conductivity was used to minimize all the contact resistance between vapor chamber with heat sink, thermoelectric module,

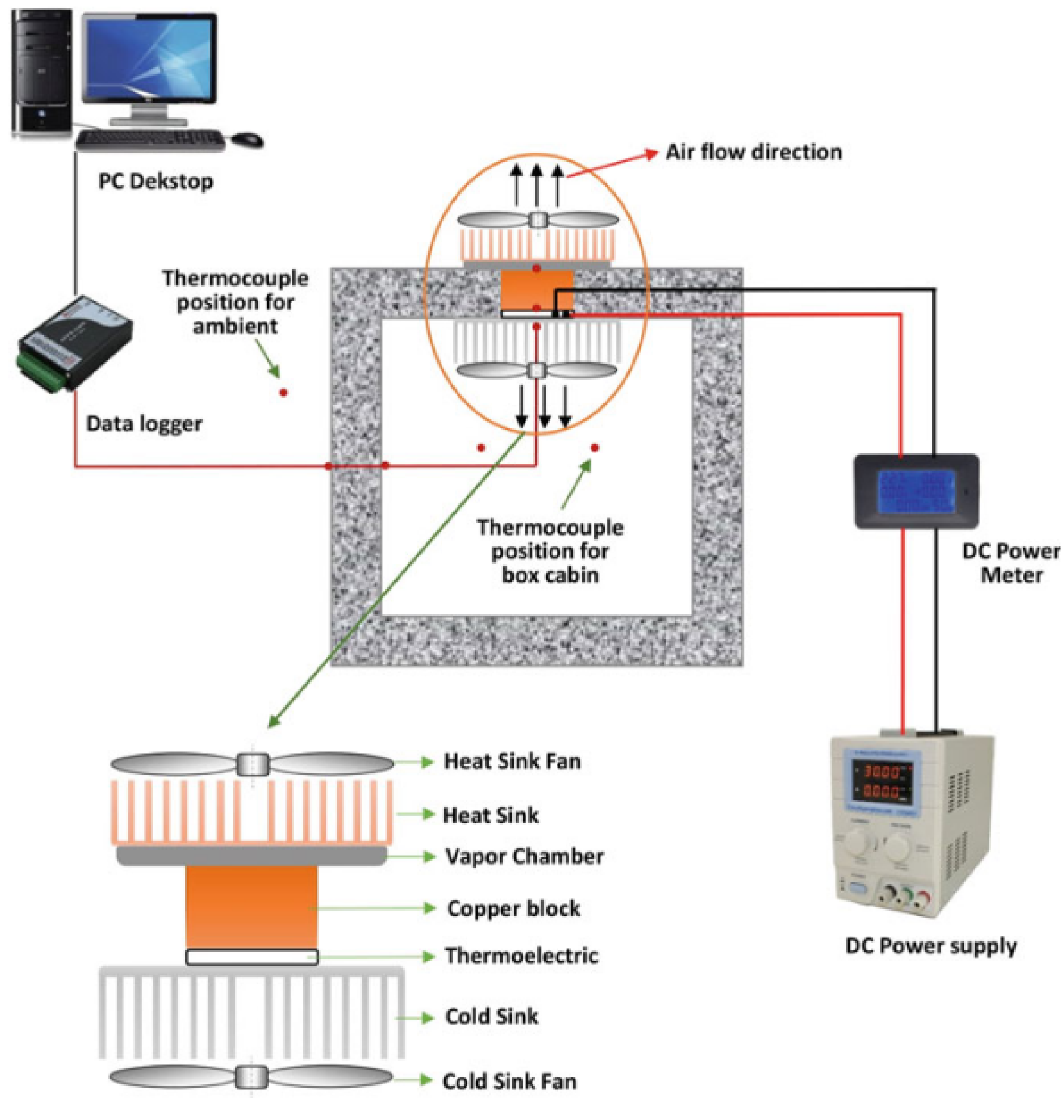

Fig. 1 Schematic of experimental setup

cold sink and copper block. The DC power flows to the thermoelectric module was measure using PZEM-017 power meter with measurement error of 1%. The DC power supplied for both fans was handle by ®Sanfix DC power regulator. Type-K thermocouples (accuracy ± 0.5 °C) was used to measure all the temperatures and connecting it with data acquisition from National Instrument (NI 9213 and NI 9274). Thermocouple positions are displayed in Fig. 1 with the red dots. Temperature data were record with data acquisition software and store on a desktop PC.

The goal of this study was to inspect the cooling performance (COP) of thermoelectric cooler box using vapor chamber as the hot side cooling device. Test were performed at five different currents: 4, 5, 6, 7 and 8 A. The test was carried out by supplying voltage to the thermoelectric and fan then observing the resulting temperature data. The effect of current supplied to the Peltier module which using a vapor chamber is investigated. Such as temperature of the hot and cold side of TEC, cabin temperature, temperature of vapor chamber evaporator, ambient temperature

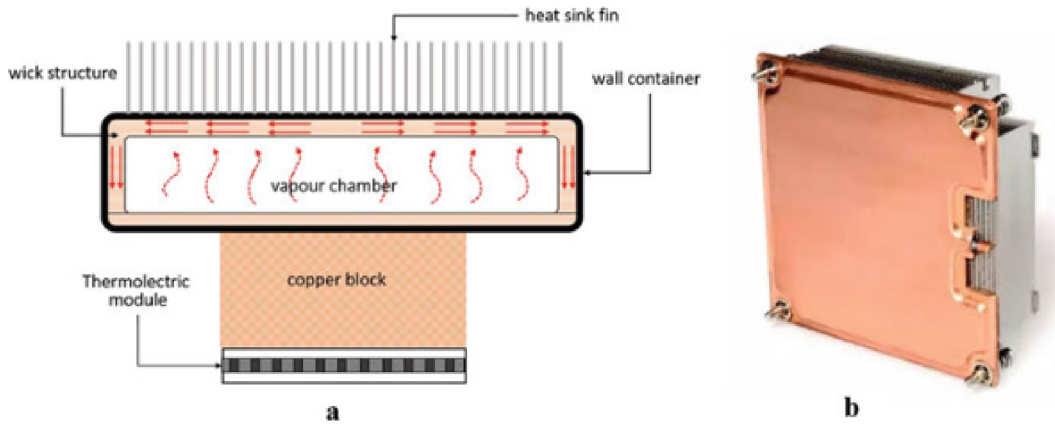

Fig. 2 Vapor chamber, **a** structure of inner side, **b** attached with heat sink

and inner and outer wall temperature of cooler box, and thermoelectric and fan power supplied. The ambient temperature was set constant around 25 °C using air conditioning.

The calculation of COP using the following expression [4, 17]:

$$COP = \frac{\dot{Q}_T}{P_{total}} \tag{1}$$

where $\dot{Q}_T$ (watt) is total rate of refrigeration load of thermoelectric cooler box and calculated from expression below:

$$\dot{Q}_T = \dot{Q}_a + \dot{Q}_c + \dot{W}_{inner\,fan} \tag{2}$$

$\dot{Q}_T$ is consist of the heat transfer of air inside the cabin box ($\dot{Q}_a$) and heat flow through the walls ($\dot{Q}_c$) entering the cabin inside the cooler box. $\dot{W}_{inner\,fan}$ also calculated as part of refrigeration load using its rate of electrical power consumption [4]. The power consumes of cooler box indicated by P_{total} (watt), which is express in following equation:

$$P_{total} = P_{vc\,fan} + P_{TEC} \tag{3}$$

$\dot{Q}_a$ is the heat transfer of air within the cabin. The rate of heat transfer was calculated based on the air property using the following equations:

$$\dot{Q}_a = \frac{dE}{dt} = m_a c_{p,a} \frac{dT}{dt} \tag{4}$$

E is the energy (J), $\dot{Q}_a$ is the air heat transfer rate (watt), m_a is the mass of air (kg), $c_{p,a}$ is the specific heat of air (J kg^{-1} K^{-1}), $dT.dt^{-1}$ is the temperature gradient per unit time. $\dot{Q}_c$ calculated using Eq. (5) below;

$$\dot{Q}_c = A \cdot U \cdot (T_{amb} - T_{cabin}) \tag{5}$$

where A is the total heat transfer surface of cooler box (m), U is the overall heat transfer coefficient, T_{cabin} is the average temperature of refrigerated space (Fig. 1) and ambient temperature T_{amb}. The calculation of overall heat transfer coefficient is using Eq. (6) below.

$$U = \frac{1}{\frac{1}{h_{int}} + \frac{L}{k_{wall}} + \frac{1}{h_{ext}}} \tag{6}$$

The heat transfer coefficient at cold sink was calculated using correlation given by Parmelee and Huebscher [4, 7]. The equation is given below as (7) and (8).

$$Nu = 0.664 \cdot Pr^{1/3} \cdot Re^{1/3} \tag{7}$$

$$\begin{bmatrix} 0.6 \le Pr \le 50 \\ Re < Re_{x,c} \approx 5 \times 10^5 \end{bmatrix} \tag{8}$$

3 Results and Discussion

Table 1 provides the power information given for each variation of the current supply to the TEC module. Figure 3 shows the cold and hot side temperature of thermoelectric due to the effect of different supply current. Increasing the current supply to the thermoelectric module result in an increase in temperature hot side and a reverse effect on the cold side temperature. The cold side lowest temperature 1.94 °C achieved by 5 A of current supply. Meanwhile, the highest hot side temperature 75.92 °C was found on a current supply of 8 A. Increase the supply current enlarge the temperature difference between the hot side and the cold side which would decrease the cooling capacity of the thermoelectric module.

Table 1 Variation of supplied current to the TEC module

Current (amp)	Voltage (V)	Power (W)
4	6.75	27
5	8.4	42
6	10.4	62.5
7	13	91.6
8	14.87	119

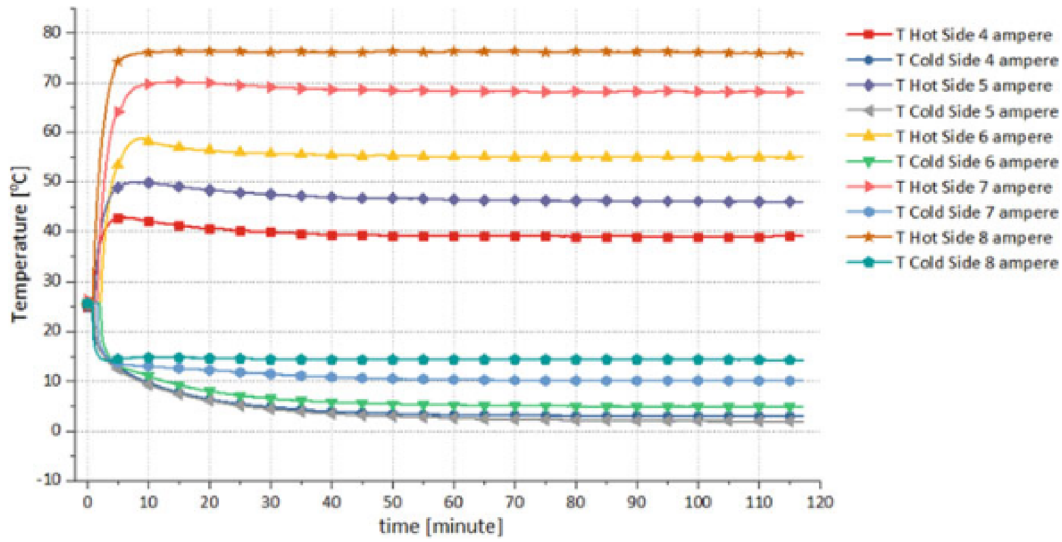

Fig. 3 Temperature of hot and cold side of TE versus times for each current supplied

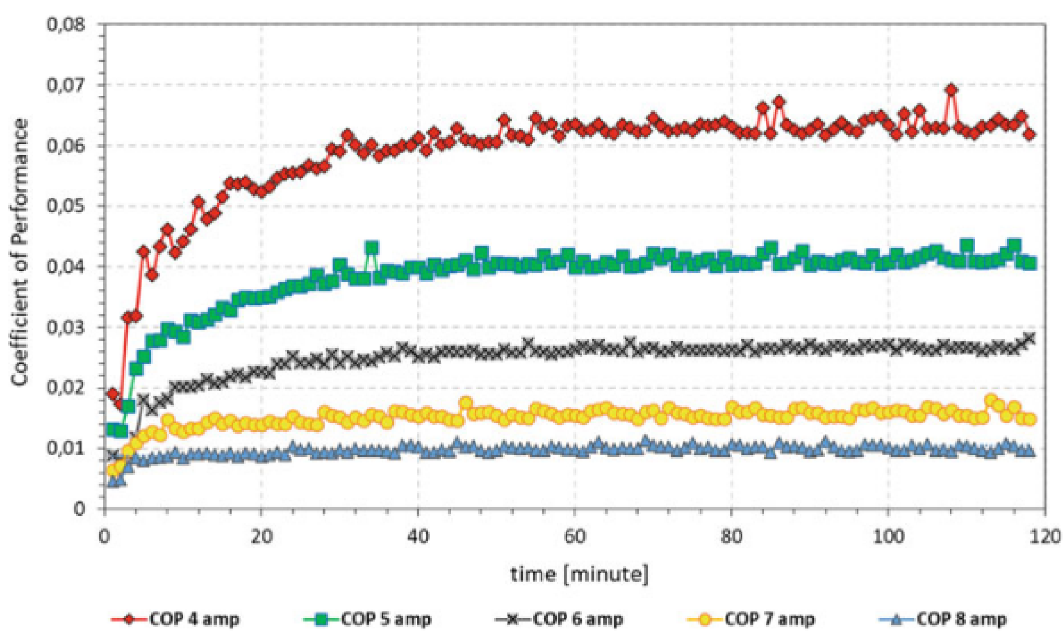

Fig. 4 Variation of COP due to different current supplied to the TE Cooler Box

The COP versus time which calculated using Eq. 1 for each different current is shown in Fig. 4. All COP values showed almost similar trends. The graph increases at an early stage and gradually stable after around 60 minutes. This trend agrees with result that had been showed by Mirmanto et al. [11]. The $\dot{Q}_c$ component in Eq. 2 increases due to an elevation of the temperature difference between the cabin and the environment during the cooling period. Therefore the COP value increases with respect to cooling time until the cabin temperature reaches a steady-state condition. A current supply of 4 A has the highest average COP value which is about 0.0588.

Increases the current to the module result in a decrease in COP. This is due to more heat that had to be rejected out from the hot side of the Peltier module. Resulting in larger of TEC temperatures different and lower cooling capacity.

Figure 5 shows the cabin temperatures of cooler box for each different current. The lowest cabin temperature was achieved by 5 A current which is around 5.94 °C. Meanwhile, for 8 A current result in cabin temperature around 17.36 °C. In fact for the refrigerator purpose, the temperature achievement for 4 A, around 6.73 °C was quite successful if we consider energy consumption which is only 27 W. At higher current supply, more than 6 A, did not give appropriate cooling for the requirement of cooler box. Therefore, we may conclude that lower current gives a more efficient cooling performance in terms of energy and achievement of temperature.

To enrich the analysis, the additional load was added and tested only for 4 A current supply, which the highest performance of the preceding test. The additional load, 500 ml tap water, also to test the response of cooler box from regenerated object. The temperature trends of cooler box using 500 ml of water depicted at Fig. 6a. The heat transfer rate for the product load is calculated using the following equation:

$$\dot{Q}_w = \frac{dE}{dt} = m_w c_{p,w} \frac{dT}{dt} \tag{9}$$

where m_w is the mass of water, $c_{p,w}$ is specific heat of water. Figure 6 shows the period time of water cooling around 200 min from 26.4 °C until 9.09 °C. This may look quite well if considering the non-use of the dangerous refrigerant that may be harmful to the environment.

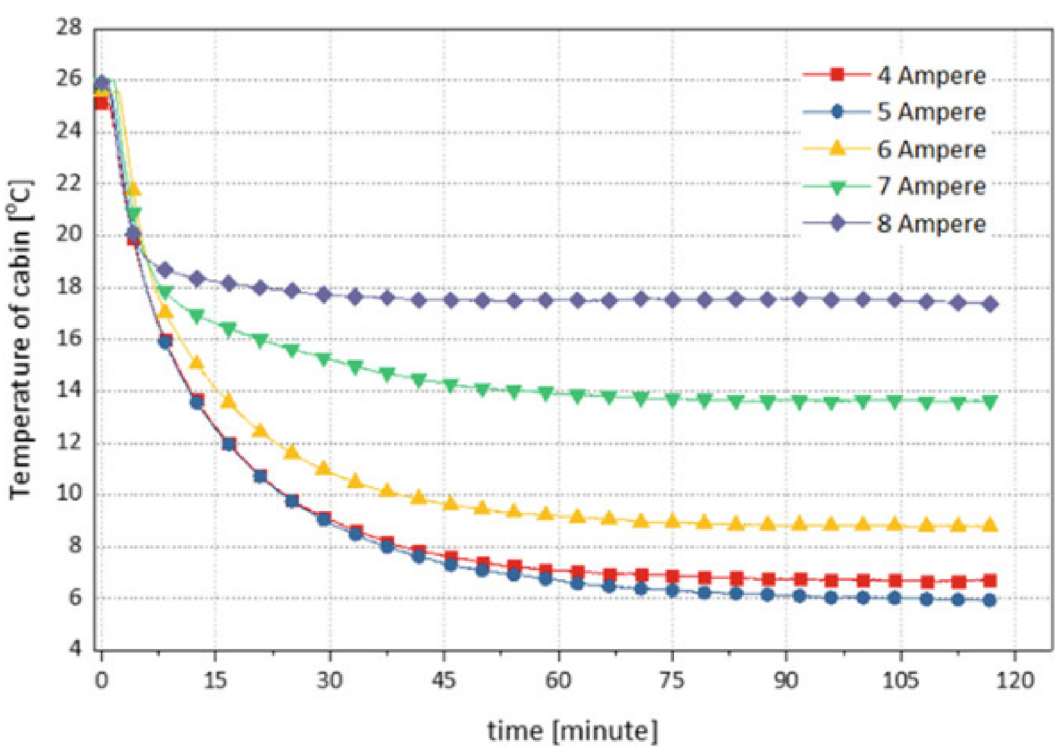

Fig. 5 Cabin temperature variation due to different current supplied

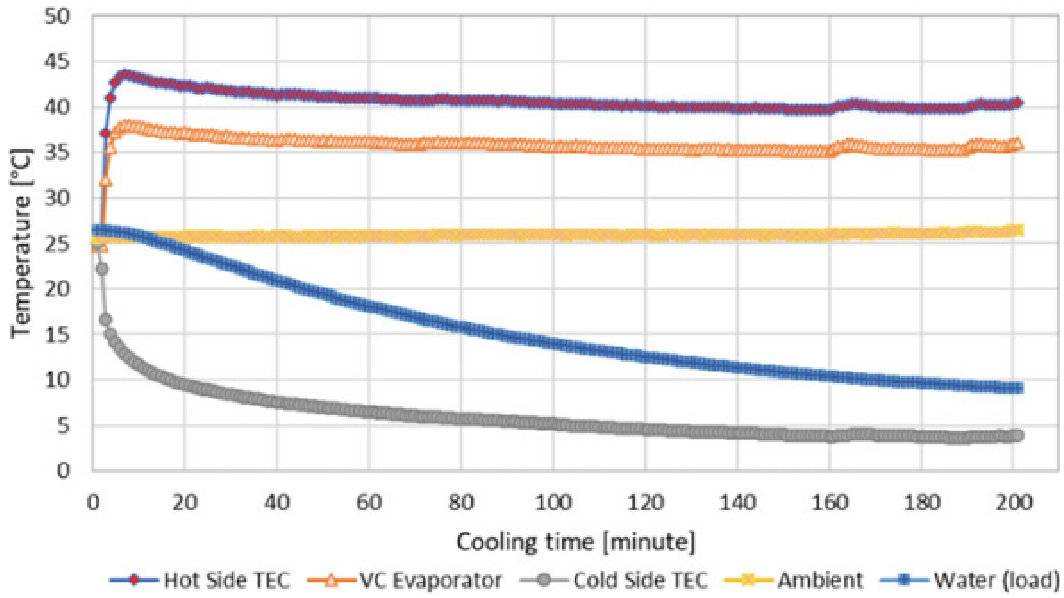

Fig. 6 Temperature trends of TE Cooler box **a** without water as cooling load **b** with 500 ml water

With the data from cooler box with additional water load, the comparison was made between a cooler box with and without 500 ml of load for the same current supply. Cooler box with and without water load will be referred to as "load" and "no-load" as shown in Fig. 7. The COP calculation with load was derived from recalculation of Eq. 1. The total refrigeration load ($\dot{Q}_T$) was add with heat transfer rate from water ($\dot{Q}_w$) from Eq. 9. Adding water as product load will increases

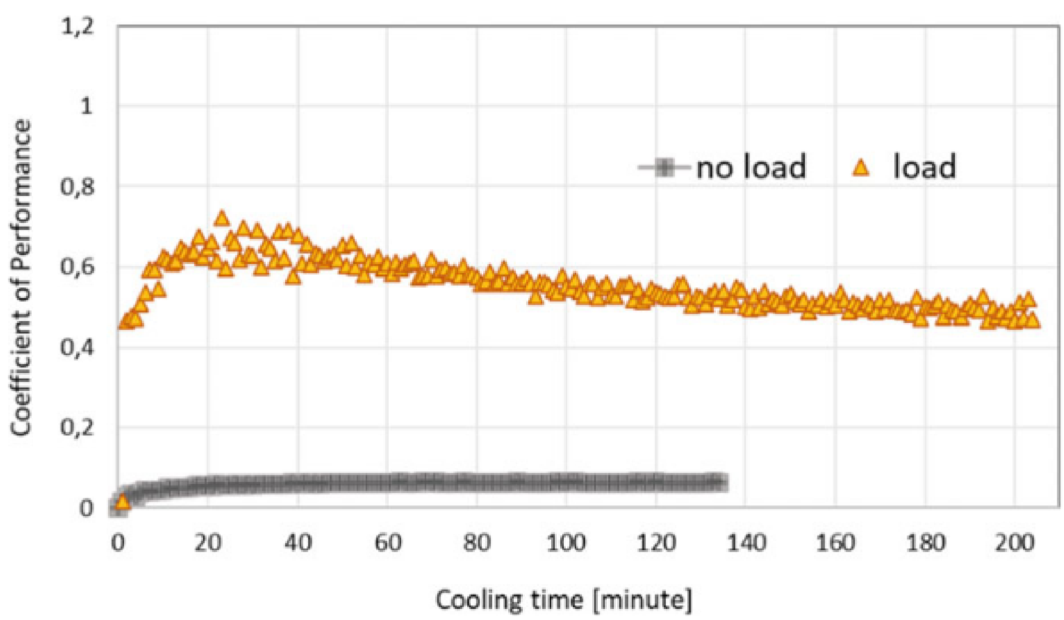

Fig. 7 COP comparation between cooler box with load (500 ml of water) and no load

significantly the performance ratio of cooler box. The COP trend also still agrees with the result that had been stated by Mirmanto et al. [11]. But also the magnitude is close to the results given by Martinez and Astrain et al. [10, 18]. The highest and average COP of cooler box with product load was 0.72 and 0.55 respectively. An enormous different between load and no-load COP is due to the very large specific heat difference between water and air (water 4180 J/kg and air 1007 J/kg at 15 °C). Therefore, the additional water load will increase the total absorbed heat by the cold side of thermoelectric module ($\dot{Q}_T$).

4 Conclusion

In the present study, thermoelectric cooler box using vapor chamber as a cooling device has been experimentally investigated. The vapor chamber with heat sink was used to absorb the heat from the hot side of thermoelectric module. The experimental data shows that increasing the current supply of thermoelectric result in higher temperature difference between the hot and the cold side, increase the cabin temperature, decrease the experimental COP of the cooler box. A current supply of 4 A has the highest average COP value which is about 0.0588. The experimental result also stated that if the 4 A current tested with additional 500 ml of water within the cooler box then the COP becomes 0.72.

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