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*by* Adi Winarta

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# Experimental Study of Thermoelectric Cooler Box Using Phase Change Material for Thermal Energy Storage

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**Abstract.** Thermoelectric refrigeration has advantages that other refrigeration systems do not have, such as accurate temperature stability settings. In some applications, like medicine purpose, this feature is very important. This study examined the performance of a thermoelectric cooler box with a cold sink that fills with a Phase Change Material (PCM). The cooler box has 240 mm x 180 mm x 130 mm of the inner dimension and is supplied with two thermoelectric modules with 133-watt DC power. The power supply to the module was controlled by a thermo-controller and set to interrupt the supply if a temperature condition was achieved during the test. The purpose is to exchange the cooling supplied of thermoelectric with PCM for reducing the cooler box's power consumption. The result shows that PCM was able to hold the temperature of the cooler box for 24 minutes. The result also indicated that Bio-PCM has potential energy storage in thermoelectric application devices compared with commercial PCM.

## INTRODUCTION

Vapor compression is the most familiar system uses in refrigeration system. Its high performance is one of the reasons this system become so popular in industry and residential. However, the use of refrigerant in this system results in detrimental effect on the global environment [1]. Therefore, the development and research of other refrigeration systems are very important for a better environment for the future. Moreover, nowadays, solar PV has better performance and can be powered to many energy applications including refrigeration. Thermoelectric (TEC) is one of refrigeration system which is well suited with solar PV for future green technology application [2].

Thermoelectric has fewer mechanical moving part, less friction and noise, no refrigerant needed, compact design, almost has free maintenance, better temperature control for refrigerated area [3-5]. Unfortunately, it has relatively low coefficient of performance (COP) compare with other systems. Thus, it is becoming the main shortcomings of thermoelectric cooling module, especially in large applications.

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Many authors have carried out several methods to increase thermoelectric efficiency. They do with various very complex designs and optimizations. One of them uses phase change materials (PCMs) as thermal energy storage (TES), as is widely used in vapor compression systems (VCS). In VCS, this is one of the methods which can improve the energy efficiency of several components and mainly reduce their compressors' electricity consumption and environmental impact [6, 7]. Also, the approach is often used with vapor-compression refrigerators. In thermal energy

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storage, the PCM is a material that maintains the temperature of an object, which is in heat contact for a specific period. This material stores the heat based on its characteristic and then released at relatively constant temperature conditions. The heat exchange of this material is subsequently used as cold Thermal Energy Storage (TES) to extend the refrigerator downtime, reduce the energy consumption, and ensure an optimal overall operation. Several studies have been performed regarding to evaluating the performances of thermoelectric refrigeration, such as Min and Row [8]. The study was conducted on the performance of TEC domestic refrigerators, which specifically considered COP and cooling rate. The results showed that the thermoelectric COP was observed at 0.3-0.5, with operating and ambient temperatures of 5 and 25°C, respectively. Also, Dai et al. [9] showed a nearly similar COP at 0.3 for thermoelectric refrigerators, although the system was operated by a photovoltaic module with the battery as power storage. Moreover, the solar thermoelectric refrigerator was studied by Abdul Wahab et al. [10] experimented with a portable solar thermoelectric refrigerator. Their finding COP of the system was about 0.16. The cabin temperature was successfully reduced from 27 °C to 5°C within 44 minutes.

In a comprehensive review of thermoelectric cooling parameters and performances for a given system, Enescu and Virjoghe [11] conclude that for a temperature difference of 20 °C, the COP value cannot exceed 0.5 for a system powered by conventional electricity. In addition, if the system uses solar-powered systems, the COP value could reach higher than >0.5. Jugsujinda et al. [12] reported reducing the cabin temperature from 30°C to 4.2°C for one hour inside the thermoelectric refrigerator. For power supply 40.46 watt the performance cooling of thermoelectric around 0.22. The thermoelectric cooler box in his study design with 0.022m$^3$ of cabin volume. Martinez et al. [13] studied the thermoelectric refrigerator using PID control, on/off controller, and operating system with idling voltages. The last method was successfully reduced 32% of power consumption and improved the performance of the thermoelectric cooler box by 64% if compared with the conventional on/off system. Gokçek and Shahin [14] tried to increase thermoelectric refrigerators' performance using a water cooling system based on a mini channel. In their experimental result, the COP was evaluated at 0.41. The study of the performance analysis of the cooler box using different types of heat sink units at the hot side was carried out by Mirmanto et al. [15]. In their work, a Heat Sink Fan (HSF) and Double Fan Heat Pipe (DFHP) were used to cool down the heat release from the hot side. They found that the HSF has more reliable energy consumption. Riffat et al. [16] studied the experimental of thermoelectric refrigeration using heat pipe and phase change material (PCM). The PCM was enclosed in a cold sink container and contacted with the cool side of the thermoelectric system through the aluminum block extender. The results subsequently showed that encapsulated PCM improved the COP of the refrigeration system. Omer et al. [17] then continued the study of Riffat et al. by adding the thermal diode between the cold sink and thermoelectric module. Their result indicated a similar cooling effect during the cold phase compared to the previous study. Likewise, Tan and Zhao [18] carried out an experimental study to increase the thermoelectric COP, using PCM as a cold heat sink to reduce the hot-side temperature of the Peltier module. They showed that the COP system increased from 0.5-0.78, as a comprehensive PCM-integrated thermoelectric guide was proposed for room cooling purposes, using a heat exchanger.
The study of Midiani et al. [19] also conducted an experimental test on the effect of using an internal fan on a thermoelectric-based cooler box with a heat pipe. Meanwhile, Winarta et al. [20] conducted an experimental test on the TEC's hot-side cooling effect, using a vapor chamber. The results obtained the potential use of the vapor chamber, to provide a more compact cooler box design.

As cold storage for cooling applications, the use of PCM is one of the technologies to optimize energy consumption. This material has recently become the focus of energy study interest, especially in making the HVAC systems more efficient. The study of Omer et al. subsequently tested the potential application of PCM in a thermoelectric cooler box, as a source of thermal energy storage within the cold sink [17]. In this study, a novel cooler box was developed and tested by using a PCM-integrated thermoelectric system within an enclosed cold sink. Therefore, this present study aims to determine the feasibility of cold sink PCM, to increase the performance of thermoelectric cooler boxes.

## DESCRIPTION OF THE EXPERIMENTAL SETUP

Figure 1 shows the detailed thermoelectric cooler box employing PCM inside the cold sink and attached directly to the Peltier module. The experimental rig comprises of the cooler box (285 x 240 x 260 mm$^3$) with two thermoelectric modules (TEC1-12710), two heat pipe heat sink (HPHS), cold sink, power supply unit, mustimeter for power measurement, temperature data acquisition unit and thermo-controller unit (with relay). All contacts between the cold sink, thermoelectric, extender block and heat sink heat pipe were considerably set with minimum thermal resistance by using silicone grease.

The cooler box material was made from polyurethane board with thickness of 40 mm. Two of TEC1-12710 was employed as the cooling device with 40 mm x 40 mm x 3.3 $mm^3$ dimension. Their voltage and ampere are 15.4 Volt and 10 amperes. Two multimeters were used to record the power supplied for each thermoelectric module. A heat sink with an embedded heat pipe was mounted on the hot sides to extract the heat out to the ambient.

Meanwhile, the cold side of the thermoelectric module was firmly attached to the cold sink, which has a PCM container inside with dimensions 120 x 100 x 15 $mm^3$, made by an aluminum sheet. Two kinds of PCM was used as thermal energy storage. First is Bio-PCM, which is 95% water and 5% soya ester. The other is a commercial product which is already familiar in the market. DC fan was used to circulate the air through the cold sink. The temperature measurement was done using thermocouple type-K pairing with National Instrument data acquisition (NI 9213 and NI 9274).

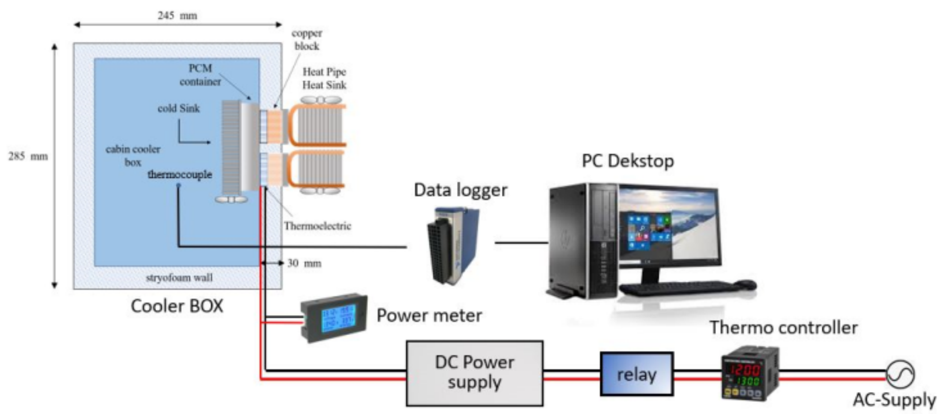


**FIGURE 1.** Schematic of experimental setup

## METHODOLOGY OF THE EXPERIMENTAL TEST

After DC power was applied to the thermoelectric module, each side (cold and hot side) absorbs and releases heat simultaneously. Then the cold side, which is attached firmly with the cold sink, cools down from its initial temperature. Due to the conduction heat transfer within the material, the cold sink will dissipate the cold air, dropping the cabin temperature. The thermo-controller and relay control the power supply to the thermoelectric module. The temperature of cold side TEC became the set point of the thermo-controller. If the cold side TEC temperature reaches the cut-off setting point of the relay, then the thermoelectric module will shut down for a while. Until the cut-in setting was achieved and the module worked again, cooling down the cabin. The differential setting was set at 5 °C between cut-off and cut-in. The cut-off temperature setting of the thermo-controller was set at -7 °C. This setup is designed to find the ability of PCM to sustain the cabin temperature without the aid of a thermoelectric cooling effect.

The COP analyses of cooler box calculated from cooling capacity ($Q_{total}$) and all electrical power consumption ($P_{total}$), which is defined on the following equations :

$$COP = \frac{Q_{total}}{P_{total}} \quad (1)$$

$$P_{total} = \sum V \cdot I \,(watt) \quad (2)$$

$$Q_{total} = Q_a + Q_c + Q_{spcm} + Q_{lspcm} \quad (3)$$

$Q_c$ (watt) is cooling capacity of the Peltier module and calculated using equation (5). $P_{total}$ (watt) is calculated using equation (2) and summation from all the power supplies to the refrigerator box. $Q_{spcm}$ is sensible heat of PCM and $Q_{lpcm}$ is latent heat of PCM. $Q_a$ is heat transfer of air inside the cabin box and computed using equation (4). $Q_c$ is heat transfer loss through the walls of box to the environment. $Q_{total}$ is defined as active heat load as stated by several literature [21-25]. In this work, air is the only product load, therefore the cooling capacity was calculated based on the air property only.

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

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

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

$$Nu = 0{,}664 \cdot Pr^{1/3} \cdot Re^{1/3} \tag{7}$$

## RESULTS AND DISCUSSION

### Temperature Trends of Thermoelectric

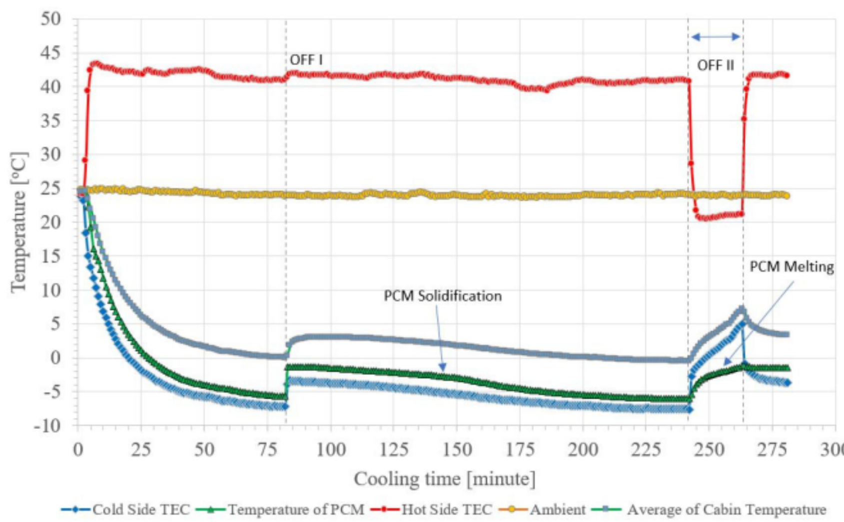


**FIGURE 2.** Temperature versus time for TEC cooler box using Bio-PCM

A thermoelectric cooler box using a cold sink with PCM container was made and then tested experimentally. PCM containers filled with different materials for each test. The experimental result is shown in Fig. 2 and 3 for Bio-PCM and commercial PCM, respectively. The ambient temperature where the experiment was conducted is regulated with air conditioning for 24-25°C. Figure 2 and 3 confirmed that ambient temperature regulation with air conditioning was well performed. Figure 2 shows the temperature history of the cooler box using Bio PCM as the thermal energy storage. When the operation of the thermoelectric system began (ON), the surface temperature of the cold side decreased, affecting the PCM container and average cabin temperature. Meanwhile, the surface temperature of the hot side increased, and the released heat was assisted by using a Heat Pipe Heat Sink (HPHS) to ensure that the heat was perfectly released to the ambient. Therefore, the heat absorption on the cool side was adequately performed through the cold sink with attached well with PCM container. If the PCM has already frozen by the cold side thermoelectric (TEC), the heat absorption should be performed well. The data in Figure 2 showed that the hot side TEC and ambient temperatures were maintained at 40 and 24°C, respectively, with the achievement of the cold segment reaching -7.26°C at 82 minutes. The cold side temperature greatly affected the freezing of PCM in the container, as the Bio-PCM temperature reached -5.67°C. The first OFF condition, as shown in Figure 2, not give any effect for the TEC power reduction. However, the second OFF condition observed in 242 minutes gives a clear power reduction effect.

The first OFF occurred in less than one minute, causing an increase in the PCM temperature, subsequently. The temperature gain happened because the PCM freezing had not completely occurred in the cold sink container. Furthermore, there were still many parts of the PCM in a liquid state, indicating the inability to withstand the rate of heat load temperature increase on the cooler box.

Continuous cooling by the TEC slowly decreases the PCM temperature. Hence, the deep solidification process of PCM (liquid to solid phase change) begins inside the container. As shown in the graph, the second OFF condition successfully maintains the cabin cooler's temperature below 10°C for about 24 minutes, even with a slightly increased cabin temperature. This effect happens because the PCM had been completely frozen after the PCM solidification phase. Hence, the latent heat of PCM is then released slowly for the cooling process of the interior cabin of the cooler box. As shown in the graph also, the hot side temperature of TEC decreased from 41°C down to 20°C during this time interval. These phenomena confirm that the TEC was off during the cooling process by the PCM.

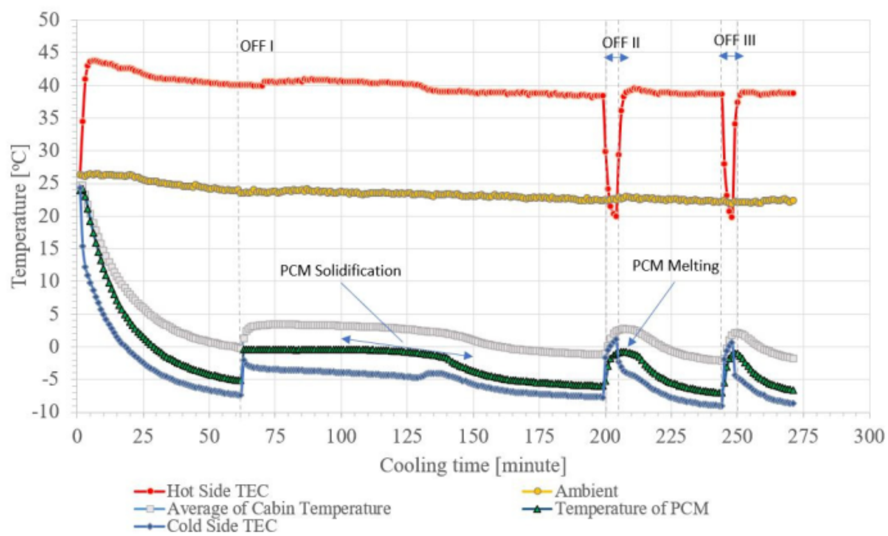


**FIGURE 3.** Temperature versus time for TEC cooler box using commercial PCM.

Figure 3 shows the temperature evolution of the TEC cooler box using commercial PCM. The first stage of the result generally showed almost the same pattern as the previous test. The cold side TEC and PCM temperature inside the container were -7.4°C and 2,079°C in 62 minutes, respectively. When the thermo-controller cut off the power supply for the TEC, the PCM temperature sharply increased immediately. In less than 1 min, the TEC subsequently obtained the thermo-controller electrical power supply. Then, the TEC cooling was conducted again, causing the cold side and cabin surface temperature to decrease gradually. Meanwhile, the temperature of commercial PCM was constant for a long time before a swing to gentle decrease (indicated by the arrow in the graph) to -5.27°C. Completely PCM solidification occurs for about 137 minutes. After that, the second OFF condition occurred at TEC. However, the commercial PCM could not maintain a longer TEC-OFF time which caused the PCM temperature to increase dramatically. The Thermo-controller resupplied the TEC power in less than 5 mins. Nevertheless, the average cabin temperature did not exceed 5 °C, which was quite different from the previous test with bio-PCM. The third OFF condition occurred 41 mins later, indicating similar characteristics as the second case. No significant power reduction was achieved for the first off. The commercial PCM temperature in the cold sink container was at -2,079°C. When the thermo-controller cut off the power supply for the TEC, the PCM temperature sharply increased immediately. Second and thirdly off still not giving a more significant effect than Bio-PCM. The commercial PCM effect for thermal storage was lower than Bio PCM in the TEC cooler box. Hence, this character is strongly influenced by the thermal properties possessed by PCM materials, such as latent and sensible heat.

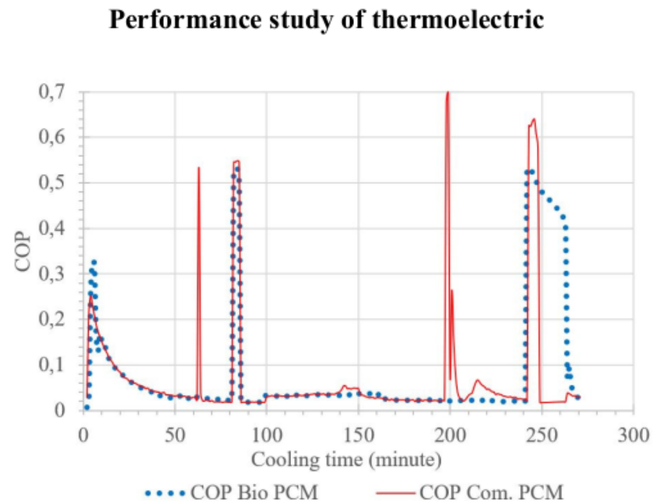


**FIGURE**. 4 COP versus time for both Bio-PCM and commercial PCM (Com. PCM).

Figure 4 illustrates the COP curve for the cooler box using commercial and Bio-PCM. The graph shows that the initial stage of COP had similar trends with several previous publications [reference]. Generally, both curve almost has an identical pattern, except some spikes occurred for the commercial PCM. This short jump increase of COP occurred due to the thermo-controller cut off, which is governed by PCM temperature. Although the spike in COP values shown by commercial PCM is more frequent than Bio-PCM, the two curves are almost identical. A clear difference was seen at 242 minutes, where the COP Bio-PCM (between 0.41-0.62) had a longer period. While in commercial PCM, although it has a higher COP value (0,634), it has a shorter duration. The increase in COP occurs due to the savings in thermoelectric power supply due to PCM as a cooling medium in the cooler box cabin. Using Bio-PCM as thermal energy storage can sustain the cooling time without thermoelectricity longer than commercial PCM.

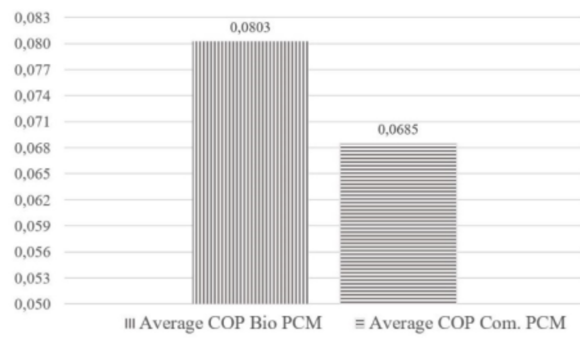


**FIGURE. 5** Average COP for both Bio-PCM and commercial PCM

Figure 5 provide a graph of the average COP for both Bio-PCM and commercial PCM. It can be seen on the graph that the average COP for Bio-PCM is 17.20% higher than the commercial material. Therefore, Bio-PCM had better thermal storage advantages compared to the commercial PCM.

## CONCLUSION

This study added a thermoelectric cooler box with a cold sink with a PCM container as thermal energy storage. The PCM container was tested using two materials (Bio-PCM and Commercial PCM). The results showed that the use of Bio-PCM produced better thermal energy storage capabilities than the Commercial PCM, indicating greater savings in thermoelectric power supply. Although the instantaneous COP of Bio-PCM is lower than the commercial ones, it has a shorter duration. This effect resulted in a higher power supply for thermoelectric power. Furthermore, the average COP for Bio-PCM was 17.20% higher than the commercial material.

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