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Preliminary investigation of performance and temperature distribution of thermoelectric cooler box with and without internal fan

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Abstract. Thermoelectric cooler is one type of refrigeration system that is environmentally friendly because it does not use refrigerants which have potential damaging the ozone layer. In this study, an experimental performance of thermoelectric refrigerator using fan and without fan is presented. The result shows that the cold side temperature decreases from 25.5 degree C to -5 degree C for 37 watt (with fan) and 25.5 degree C to -7.5 degree C for 37-watt without fan. Using 43-watt power supply, the cold side decreases from 25 degree C to -5 degree C for fan usage, and from 26 degree C to -7.5 degree C in 60 minute and 75 minutes, respectively. Using fan for cold sink inside the cabin will distribute the cabin temperature of cool box evenly and also increase the capability of heat transfer performance of cooler box of thermoelectric. Maximum average COP is 0.103 and achieved by 37-watt power supply with cold sink fan.

1. Introduction

Refrigeration machine is one of the important needs of modern society. It is kind of process of moving heat from bounded system with lower temperature compare with outside environment. To keep food, stay fresher for some period is one of the familiar applications for this process. Several cooling systems have been designed by researchers since 1834 to facilitate food storages. Vapor compression refrigeration is the most widely used method [1].

Although vapor-compression refrigeration has gained the dominance HVAC market, but the refrigerants used in these systems have destructive effects on the earth environment [2]. According to the newest global agreement about climate change which attended by over 1000 delegates in Kigali, Rwanda, 197 countries agreed to reduce using hydrofluorocarbons (HFCs) by Söylemez *et al.* [3]. The summit objective was to alleviate greenhouse gasses effect which resulted in climate change and therefore the HFC refrigerants should be phase out as soon as possible. Thus, efforts to develop other alternative refrigeration systems which eco-friendlier are still considered important for the next future.

Thermoelectric cooler is one type of refrigeration system that is environmentally friendly because it does not use refrigerants which have potential damaging the ozone layer. Their working principle based on two effects simultaneously Seebeck Effect and Peltier Effect [4]. A thermoelectric cooler module (TEM) or Peltier module is a device which transfer thermal energy from lower to higher temperature by the input of dc power. It is consisting of a group of thermoelectric couples wired electrically in series.

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The device commonly used as a refrigerator or heat pump. This solid-state refrigeration was invented almost two-century ago but becomes popular application recently.

Low coefficient of performance (COP) is the main shortcomings of thermoelectric cooling module, especially in large applications. Therefore, the thermoelectric application has restricted for cases which energy is not the main issues. Increasing the performance (COP) of the thermoelectric is difficult to achieve due to low ZT value (Figure of merit) of Peltier module [5].

During recent years, quite a lot of study about thermoelectric refrigeration have been performed on evaluated its performances. Min and Row performed a study about the performance of TE domestic refrigerator, which particularly considered COP and cooling rate [6]. The thermoelectric COP around 0.3-0.5 was found by them at operating temperature 5°C and ambient temperature 25°C. Dai *et al.* [7] also showed the nearly same COP about 0.3 for thermoelectric refrigerator, however the system was driven by photovoltaic module with battery as power storage. Solar thermoelectric refrigerator was also studied by Abdul Wahab *et al.* [8]. They designed it for rural areas so it must be a portable equipment. They tested and showed that the cabin temperature was decreased until 5°C from 27°C in about 44 minutes. The calculated COP they found was about 0.16. Vián and Astrain designed thermoelectric refrigerator with two different heat exchangers for the hot and cold side of thermoelectric module [9]. Both based on the two-phase thermosyphon, one with capillary lift technology (TMP) and the other without moving part (TSV). They claimed using those two-heat exchangers increased the COP system by 66% compare with similar prototype with conventional finned heat sink. Jugsujinda *et al*. conducted an experimental test for thermoelectric refrigerator box with the cabin volume of 0.022 m^3 [10]. They showed the cabin temperature decreased from 30 °C to -4,2 °C in 60 minutes when using the electric current of 3.5 ampere. The COP of thermoelectric was calculated about 0.22 for the highest supply power (40.46 Watt). The COP and electric power consumption of thermoelectric refrigerator with different control temperature was experimentally studied by Martinez [11]. It was found the COP increase 64% and power consumption decrease 32% using this control system compare with conventional on/off system. Ohara *et al*. performed a numerically study for optimum current and geometry for small thermoelectric vaccine box for inaccessible and developing communities [12]. Using three energy conservation equations, a model of temperature hot and cold side of thermoelectric was derived, included the refrigeration cabin temperature. They also built and tested the prototype and attained minimum temperature of 3.4°C. Mirmanto *et al.* investigated the performance of thermoelectric refrigeration using two type of heat sink units at the hot side of Peltier module [13]. The first one was a Heat Sink Fan (HSF) and the second was Double Fan Heat Pipe (DFHP). They showed that DFHP has higher COP compared than HSPF, however it consumes more power than HSF. Finally, they concluded that energy consumes for HSF was more reliable of all. Mirmanto *et al*. also investigated the performance of thermoelectric cooler box with several positions of Peltier module [14]. The box volume was 4.891 liter, and the thickness wall was 5 cm. A bottle of water with 360 ml of volume was put inside the box as part of cooling loads. They conclude that COP decreased with time and best positioned of Peltier module was on the side wall of cooler box.

Previous research confirmed that thermoelectric performance is very low compared to other cooling systems, especially vapour compression system [5], [14, 15]. However, at some specific applications such as aviation, aerospace and medical, thermoelectric has higher potential utilization and irreplaceable for some particularly conditions. Therefore, thermoelectric cooling systems are still becoming one of the promising fields of refrigeration research in the next future.

The used of an internal fan for the cold sink may affect the performance of thermoelectric cooler box due to the extra energy consumption for the device. However, the effect of the fan might also increase the heat transfer coefficient of the cold sink, which might be increase the cooling rate of thermoelectric refrigeration. In this study, the effect of using internal fan was experimentally tested to ensure its effect the performance of thermoelectric. Additionally, the temperature distribution inside the cooler box was also observed in this work.

2. Experimental setup description

Figure 1 shows the schematic experimental rig of the present study. The main components are consisting of cooler box with thermoelectric module unit, temperature data acquisition unit, power supply units for thermoelectric module, heat sink fans and cold sink, multi-tester units for electricity power measurement. Cooler box material was made from polyurethane board with a thickness of 40 mm. The inner dimension for the cooler box was 240 mm × 180 mm × 130 mm. Cooler box was hermetically encapsulated well with silicone glue to minimize infiltration heat losses. TEC2-25408 double deck cooler was used as thermoelectric module for present study. It has dimension about 40 mm × 40 mm × 6 mm dimension. Module rated of voltage and ampere was around 12-15.4 Volt and 8 amperes. Heat sink heat pipe was used as heat removal at the hot side of thermoelectric module with water as the working fluid of heat pipe. The heat sink material was aluminium and cooper. Fan dimension for heat pipe heat sink was 92 mm × 92 mm × 25 mm. Copper block was used as the extender between the hot side of thermoelectric module and the evaporator pad of heat sink heat pipe. Meanwhile, the cold side was attached firmly with cold sink with dimension of 80 mm × 80 mm. A small fan is attached to the bottom side of cold sink and it's has dimension of 40 mm × 40 mm × 15 mm. The supplies power for the thermoelectric module was conducted using fluke digital multi-tester with 0.05% accuracy. Digital multi-tester also measured the cold sink and heat sink power consumes. All the power consumes by the device are important parameter for calculating the performance level. All the contact resistance between heat sink, thermoelectric module, cold sink and block copper was minimize with high thermal conductivity of thermal grease.

The temperatures data was measured by type-K thermocouples which was calibrated previously (uncertainty around ± 0.5°C). The thermocouples were connected to National Instrument data acquisition (NI 9213 and NI 9274). Six thermocouples are used specifically only to measure the temperature distribution in the cooler box (C1, C2, C3, C4, C5 and C6) as shown in Figure 1. The others are placed on the both sides (cold and hot) of the thermoelectric module, the inner and outer walls of the cooler box and the environment

3. Experimental analysis

The main goal of this present study was to investigate the cooling performance of thermoelectric with and without the internal fan of cold sink. The COP of thermoelectric refrigerator is calculated from cooling capacity of the thermoelectric module divided by all electrical power consumption to the cooler, which is defined on the following equations:

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

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

$$P_{total} = P_{cold\,sink\,fan} + P_{heat\,sink\,fan} + P_{TEC} \tag{3}$$

where $\dot{Q}_T$ (watt) is total rate of refrigeration load of thermoelectric cooler box and it was calculated from expression (2). $\dot{Q}_T$ is consist of the heat transfer of air inside the cabin box $\dot{Q}_a$ and heat transfer loss through the walls of box $\dot{Q}_w$ to the environment. It is also defined as active heat load as stated by several literature [9, 10], [13, 14]. Heat generation by internal fan was pointed by notation $\dot{W}_{inner\,fan}$ which also calculated as part of refrigeration load. The power consumes of cooler box indicated by P_{total} (watt), which is express in Equation (3). At this present study, air is the product load and therefore the cooling capacity was calculated based on the air property, which is easily found at many literature [16, 17] using the Equation (4) below.

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

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 K), $\frac{dT}{dt}$ is the temperature gradient per unit time. Heat loss through the walls of box calculated using the Equation (5) below;

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

where A is the total heat transfer surface of cooler box, U is the overall heat transfer coefficient, T_{cabin} is the average temperature of refrigerated space (C1 until C6) and T_{amb} is the ambient temperature. The overall heat transfer coefficient is calculated using Equation (6) below.

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

When using internal fan, the heat transfer coefficient at cold sink is calculated using correlation given by Parmelee and Huebscher [9]. It is given below as Equation (7) and (8).

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

$$\begin{bmatrix} 0{,}6 \leq Pr \leq 50 \\ Re < Re_{x,c} \approx 5 \times 10^5 \end{bmatrix} \tag{8}$$

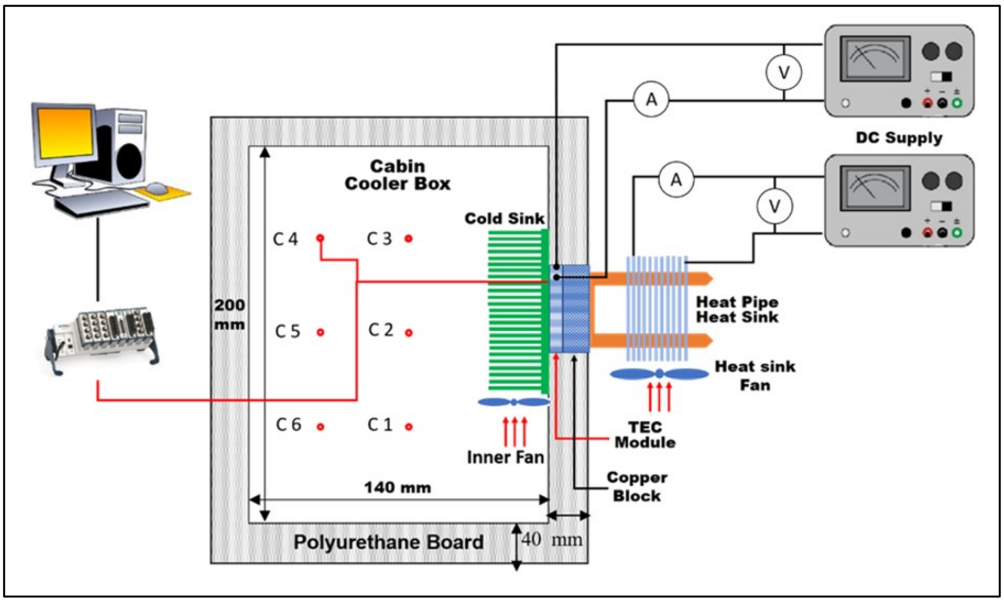

Figure 1. Schematic of experimental setup.

4. Results and discussion

4.1. Temperatures trend of thermoelectric cooler

Figure 2 shows the comparison of temperature trends of the cooler box between 37 and 43 watts. Each of them represents important parameters which determine the cooling performance of thermoelectric device, such as temperature of cold side, hot side, wall inside, wall outside, ambient and cabin (C1 to C6). When the power of thermoelectric was turned on then the cold and hot side of thermoelectric start to sharply separate. Steep increased temperature occurred at the hot side, meanwhile at the cold side the temperature decreases with the lower slope. After about 60 minutes, the cold side temperature decreases from 25.5°C to -5°C for 37 watt (with fan) and 25.5°C to -7.5°C for 37 watts without fan (Figure 2(a)). And then get constant until the end of the test. Both of them almost have the same hot side temperature which is around 37.5°C. Higher power supply (43 watt) shows in Figure 2(b), which also tested with fan and without fan. The cold side decrease from 25°C to -5°C for fan usage, and from 26°C to -7.5°C in 60 minute and 75 minutes, respectively. The temperature trends for both sides of thermoelectric was similar to many previous researchers which also validate the measurement system [2], [10], [13, 14], [18]. In terms of temperature observations, there is no big difference between each of the two different power supply. All the hot side temperature was increase sharply and get suddenly constant at 37.5 °C. The excellent heat absorption by the heat pipe was likely to become the reason for this phenomenon. When the operating heat flux of heat pipe evaporator was achieved then large heat was absorb at the evaporator side of heat pipe heat sink. As a result, the temperature hot side stop raising and get constant. This confirms that Heat Pipe Heat Sink (HPHE) is an effective cooler for the thermoelectric heat side. The only things that obviously different is the temperature distribution inside the box for with and without cold sink fan, which will be explained in the following subsections.

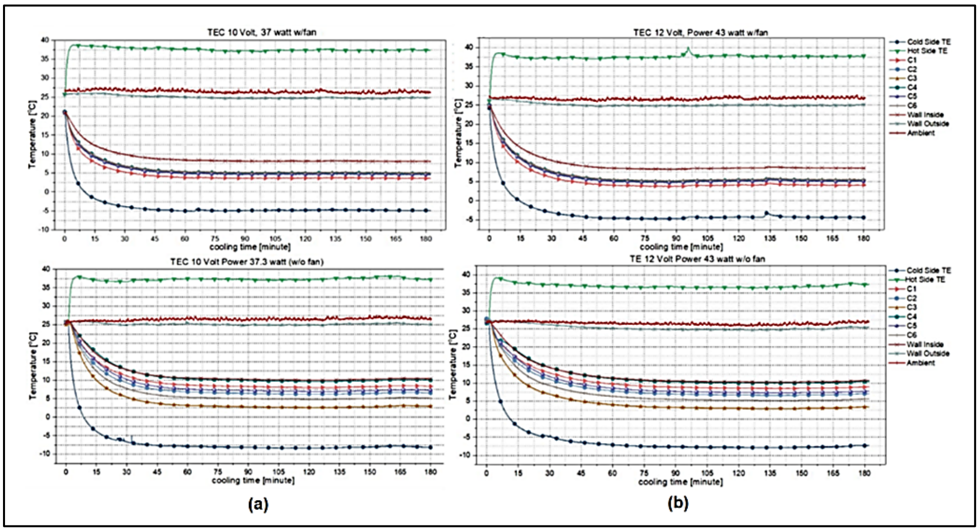

Figure 2. (a)Temperature trends of the experimental data for TEC 10 Volt with and without internal fan, (b) for TEC 12 Volt with and without inside fan.

4.2. Temperatures distribution inside the cooler box

Figure 3 shows the temperature distribution inside the cooler box with (a) and without the cold sink fan (b). As shown in Figure 3(a), using cold sink fan produces uniform temperatures at several test points Upper and lower temperature are the same due to the circulation of air flow inside the cooler box. All temperature measurement (C1 to C6) shows around 5°C. Meanwhile for cooler box without the cold sink fan, the temperature cabin varies from 2.5°C to 10°C (Figure 3(b)). The heat transfer mechanism became the reason of this phenomenon. Using no fan at the cold sink makes the circulations of air by itself or natural. Then the cold air will tend to falls down and hot air behaves the other way. On the other hand, using fan will distribute the temperature evenly. For applications that require the uniform temperature distribution, a fan must be installed in the cold sink.

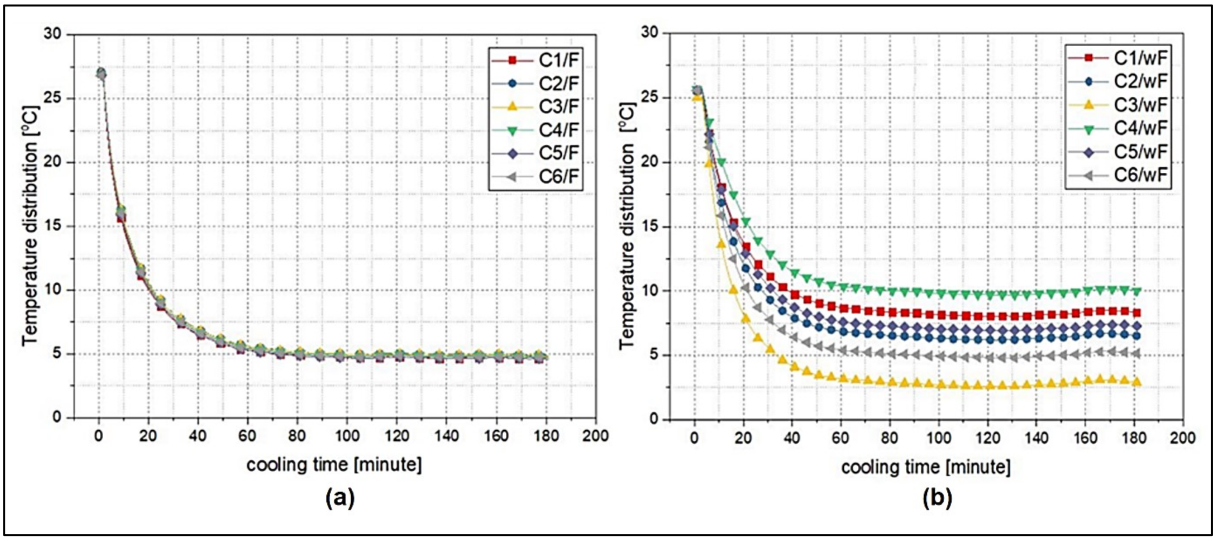

Figure 3. Temperature distribution inside cabin of the cooler box, (a) with fan (F) (b) without fan (w/F).

4.3. Heat transfer and performance analysis numbering

Figure 4 shows comparison graph of Qa and Qw and also QT for fan and without fan. Heat transfer rate from air (Qa) decreased with time and get nearly constant after 75 minutes of operation (Figure 4(a)). Basically, both of them almost has similar average of heat transfer rate for fan and no fan usage. But for heat loss through the walls of cooler box, Qw using fan has slightly higher level compare with no fan. Figure 4(b) shows the total heat absorb by the thermoelectric refrigeration. Maximum average of QT is 3.939 watt and achieved by 37 watts with fan. It is clearly state that using fan increase the capability of heat transfer performance of cooler box, due to the increase in the heat transfer coefficient.

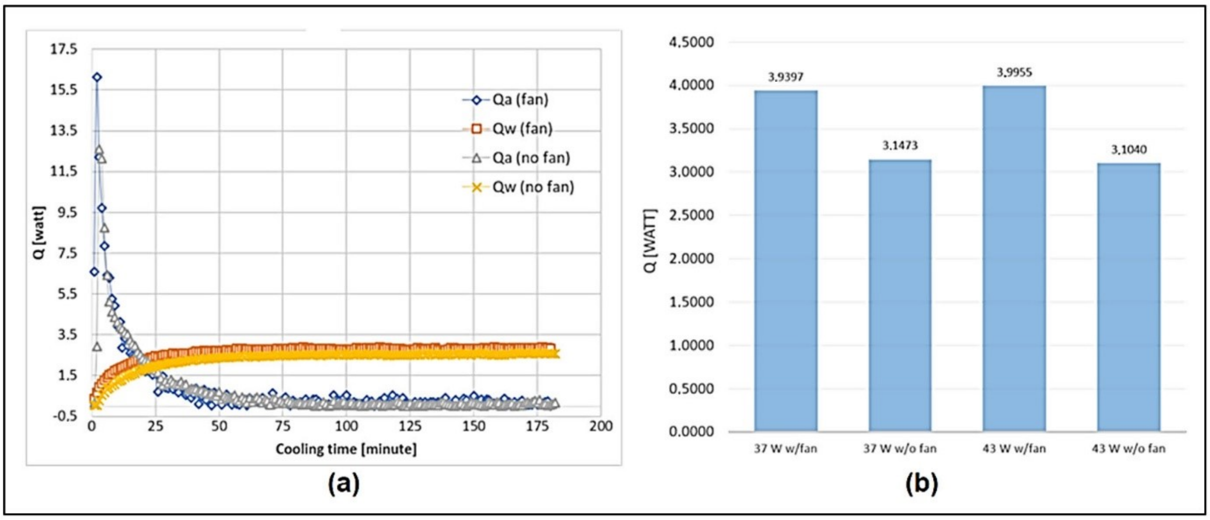

Figure 4. (a) Comparison of heat transmitted from air (Qa) and heat flow enter the cabin of cooler box from environment (Qw) for fan and without fan, (b) Comparison of QT for fan and without fan.

Figure 5 (a) shows COP of cooler box versus time for both power supplies and cold sink fan usage (with and without). COP trends decline over time which is similar to the results given by some previous researchers [10, 18]. The highest average COP is 0.103 and achieved by 37-watt power supply with fan

(Figure5 (b)). It is obvious seen at Figure 5 (a) that this power supply had the highest COP versus time. The effect of the fan is very clearly increasing the cooling capacity by thermoelectric even though there is an increase in the required power consumption. Therefore, this increase results in a higher COP if it compares without the usage of fan.

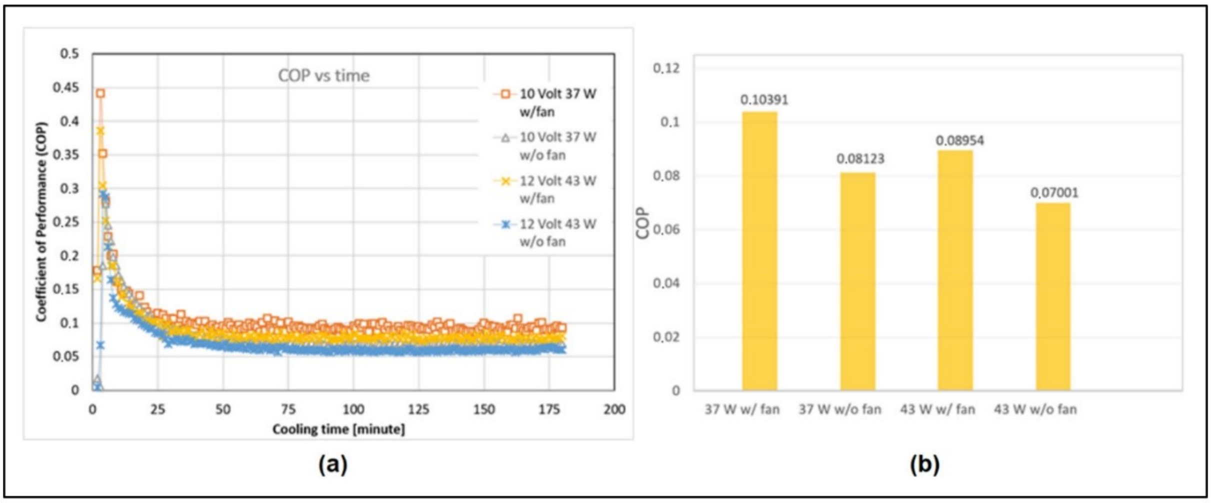

Figure 5. COP with and without fan for each power consumes, (a) COP versus time, (b) average COP.

5. Conclusions

The thermoelectric refrigeration of cooler box using fan and without fan has been tested with two different power supplies. The cold side temperature decreases from 25.5°C to -5°C for 37 watt with fan and 25.5°C to -7.5°C for 37 watts without fan. Using 43-watt power supply the cold side decrease from 25°C to -5°C for fan usage, and from 26°C to -7.5°C in 60 minute and 75 minutes, respectively. Using fan will distribute the cabin temperature of cool box evenly and also increase the capability of heat transfer performance of cooler box of thermoelectric and then at the end will increase the performance of coefficient (COP).

6. References

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