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PERFORMANCE ANALYSIS OF THERMOELECTRIC COOLER BOX WITH WATER COOLING BLOCK (WCB) AND HEAT SINK FAN

1) Mechanical Engineering, Politeknik Negeri Bali, Jl. Kampus Bukit Jimbaran, Badung, Bali 80362

Corresponding email : sutina@pnb.ac.id

I Wayan Sutina [1)*], Adi Winarta [1)], I Nyoman Agus Adi Saputra [1)]

Abstract. Thermoelectric cooler boxes offer an environmentally friendly, energy-efficient, and portable cooling solution. However, the performance of thermoelectric cooling systems is highly dependent on the effectiveness of heat dissipation on the hot side of the Peltier module (TEC). This study aims to experimentally investigate the impact of using a Water Cooling Block (WCB) compared to a conventional heat sink fan on the cooling performance of a thermoelectric-based cooler box. The experimental setup involved two configurations for the hot side cooling system, where parameters such as hot-side temperature, cabin temperature, and Coefficient of Performance (COP) were measured and analyzed. The experimental results showed that the use of WCB was able to significantly reduce the temperature on the hot side, with a temperature reduction in the cabin reaching 20.35 °C and an average COP of 0.09687. Meanwhile, the TEC-fan temperature in the cabin cooler box was lower at 21.45 °C, with an average COP value of 0.04718. Therefore, the Water Cooling Block demonstrates superior efficiency and thermal management compared to the heat sink fan, offering enhanced performance for thermoelectric cooler box applications in various low-temperature storage needs.

Keywords : Thermoelectric, Cooler box, Water cooling block, Heat sink fan, COP, Peltier module.

1. INTRODUCTION

Refrigeration machines have become an essential part of modern life. Refrigeration machines with vapor compression systems are the most commonly used type of refrigeration machine in industries such as hospitality, power generation, pharmaceuticals, and food storage industries, such as meat, fruit, and vegetables [1]. However, the use of vapor compression refrigeration systems carries several risks that can cause environmental damage, such as the use of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) as refrigerants, which can cause global warming and damage the ozone layer. For this reason, the use of these types of refrigerants has been widely banned around the world [2]. One system that can be used as an alternative to environmentally friendly cooling machines is the Thermoelectric (TEC) system. Cooling machines with thermoelectric systems have lower noise levels because they have fewer moving mechanical components and more accurate temperature control [3]. Thermoelectric cooler boxes are becoming a replacement for conventional refrigerators, with a compact and lightweight design that makes them easy to place anywhere. These cooler boxes do not require a lot of electricity and can be powered by DC current, so their energy consumption is relatively low and they are more flexible and easier to move [4].

The Thermoelectric Module (TEC) is an integrated circuit with a solid form that works with three thermodynamic principles known as the Seebeck, Peltier, and Thomson effects [5]. Peltier elements can be used as coolers or heaters depending on the direction of the current supplied. Peltier elements are commonly used in car air conditioning systems [6] and water temperature control systems [7]. Peltier elements become cold due to the flow of electrons from P-type semiconductor components to higher electron levels in N-type semiconductors [8]. The effectiveness of thermoelectric cooling systems depends heavily on the ability to dissipate heat from the hot side of the module. One important component that supports this process is the heat sink, which serves to conduct and dissipate heat to the environment [9]. The effectiveness and performance improvement of thermoelectric modules are influenced by the heat transfer cross-sectional area on the heat sink [10]. The use of thermoelectric modules as a 34-liter beverage cooler has been carried out with two or three TEC modules by Azridjal Aziz et al. The results show that heat absorption in a cooler box with three TEC modules is more effective than with two TEC modules [11]. Previous research has shown how the use of a water cooling block (WCB) system in TEG modules can improve the performance of thermoelectric generators (TEG) [12]. Improvements in cooling performance with thermoelectric modules still depend on the effectiveness of heat dissipation on the hot sink side.

Due to these issues, this study was conducted to experimentally examine the effect of using a water cooling block on the heat sink on the cooling performance of a thermoelectric cooler box. By conducting direct testing, this study is expected to provide important information regarding the optimization of the use of water cooling block (WCB) heat sinks that support the overall efficiency of thermoelectric cooling systems.

2. METHODS

2.1 Research Design

This cooling system consists of a main component in the form of a thermal insulation box equipped with a thermoelectric module. The cooling box is made of 40 mm thick polyurethane board. The internal dimensions of the box are 240 mm × 240 mm × 270 mm. As the cooling element, a double-deck thermoelectric module of type TEC2-25408 is used, measuring approximately 40 mm × 40 mm × 6 mm. This module operates at a current of 4.5 amperes and a voltage of 12 volts.

Table 1. Thermoelectric Specification

TEC specification	
Type	Double Deck Thermoelectric Cooler
Model	TEC2-25408
Voltage	12 V
Current Max.	8 A
Power Max.	70 watt
ΔT Max	80°C
Dimension	40mm x 40mm x 6mm

Cooling on the cold sink side is carried out using a finned aluminum heat sink equipped with a fan to increase heat transfer from the cooling chamber. Conversely, the hot sink side is used as a heat extraction point through the installation of an 80 mm × 80 mm water cooler block, which functions to transfer heat to the cooling water fluid. The pump used has a power of 2.52 watts with a current of 0.21 A and a voltage of 12 volts. A condenser is used to cool the water from the WCB with the help of a fan. This experimental configuration can be seen visually in Figure 1.

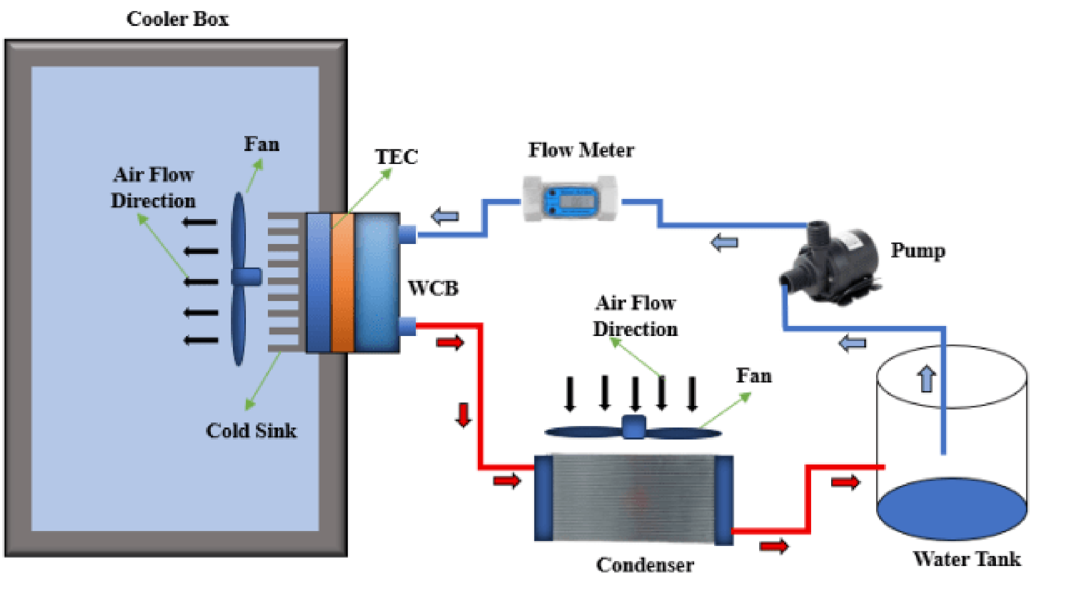

Figure 1. WCB thermoelectric experimental scheme

The initial step in the operation of the thermoelectric system with a heat sink-fan and water cooling block involves the cold side, where the heat sink absorbs heat from the cooling chamber, assisted by a fan to accelerate heat absorption. On the hot side, the TEC module is fitted with a water cooling block, where water from the reservoir tank is pumped to the flow meter for checking the water flow rate, then the water flows to the water cooling block to help dissipate heat from the TEC on the hot side. The water exiting the water cooling block flows to the radiator, which functions to release the heat from the water generated by heat absorption on the hot side with the assistance of a fan. The water then returns to the reservoir tank and the cycle continues.

The performance calculation of this cooler box was carried out by analyzing the data obtained and then calculating the COP value using equation (1) as follows:

$$\mathrm{COP} = \frac{Q_t}{Pt} \tag{1}$$

$$Q_C = Q_w + Q_a + Q_{tr} \tag{2}$$

$$P_t = P_1 + P_2 \tag{3}$$

Where Q_t (watts) is the total cooling load on the cooler box cabin, which can be calculated using equation (2), consisting of heat transfer within the box cabin Qa and heat lost through the box walls Qw to the environment. Meanwhile, P_t (watts) is the total power used by the cooler box, as stated in equation (3), which can be found in previous references and studies [13],[14],[15]. In this study, air is used as the load in the cooler box cabin, so the cooling effect can be seen from the air temperature inside the cooler box cabin.

2.2 Experimental Procedure

Experimental testing was conducted using a data collection method for each type of heat sink on the hot side, namely testing heat sinks with fan heat sinks and heat sink-water cooler blocks (WCB) with dimensions of 40 mm x 80 mm and a thickness of 15 mm, using aluminium material. The DC current entering the thermoelectric device uses the PZEM-017 with a 1% margin of error, connected to the data acquisition system (NI 9274). Type K thermocouples were installed to measure all temperatures and connected to the data acquisition system (NI 9213). The thermocouple positions are indicated in Figures 2 and 3 with yellow dots, where temperatures are recorded using LabVIEW 2019 data acquisition software and stored on a desktop computer for each test. It is assumed that the air mass inside the box is constant without any transfer from the environment. The cooling load inside the box is water with a mass of 0.35 kg. The fan power in the cooling box is also calculated as a cooling load, assuming that the heat transfer generated by the fan motor is equal to the fan power (2.88 watts). The external cabin temperature is measured and serves as a free variable that can influence the heat loss through the box walls. The experimental scheme is presented in Figures 2 and 3.

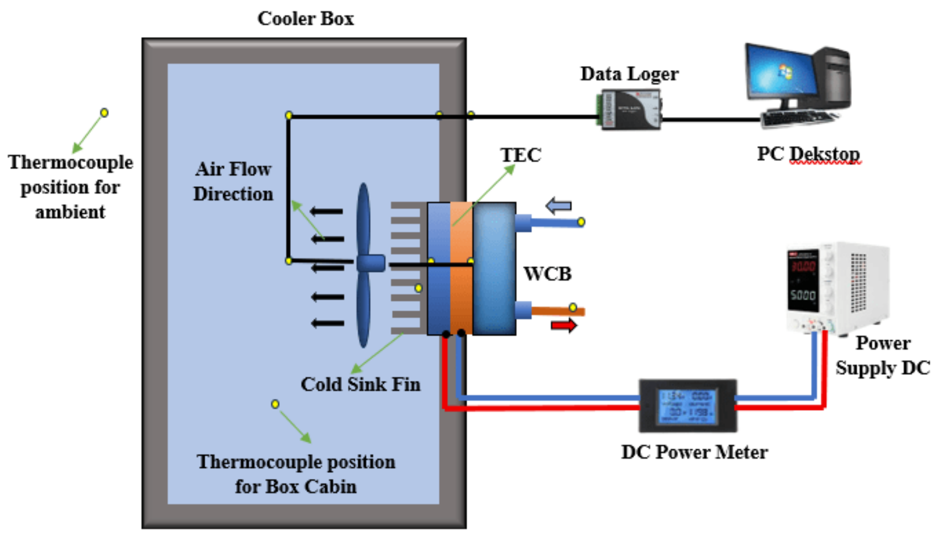

Figure 2. Experimental heat sink-WCB scheme

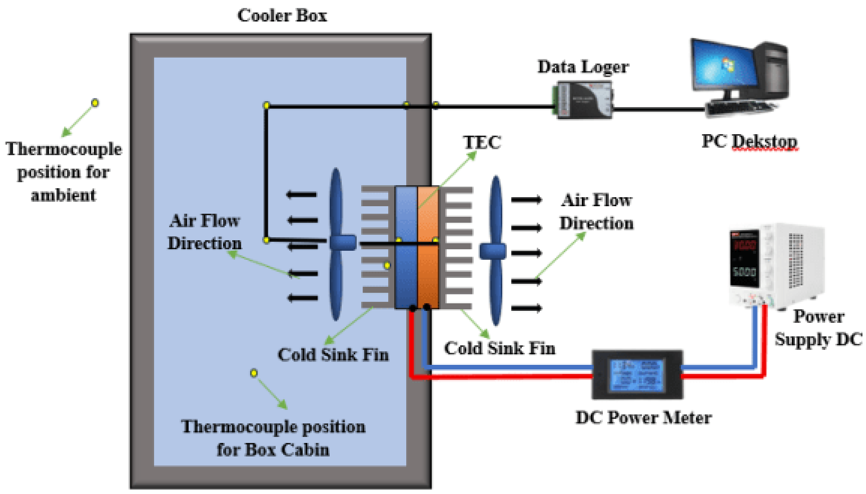

Figure 3. Heat sink-fan diagram

Experimental data collection was carried out for ± 180 minutes with a data collection interval of every 10 minutes. At this stage, the experimental data collection process was carried out twice.

3. RESULTS AND DISCUSSION

3.1 Temperature Comparison on Heat Sink

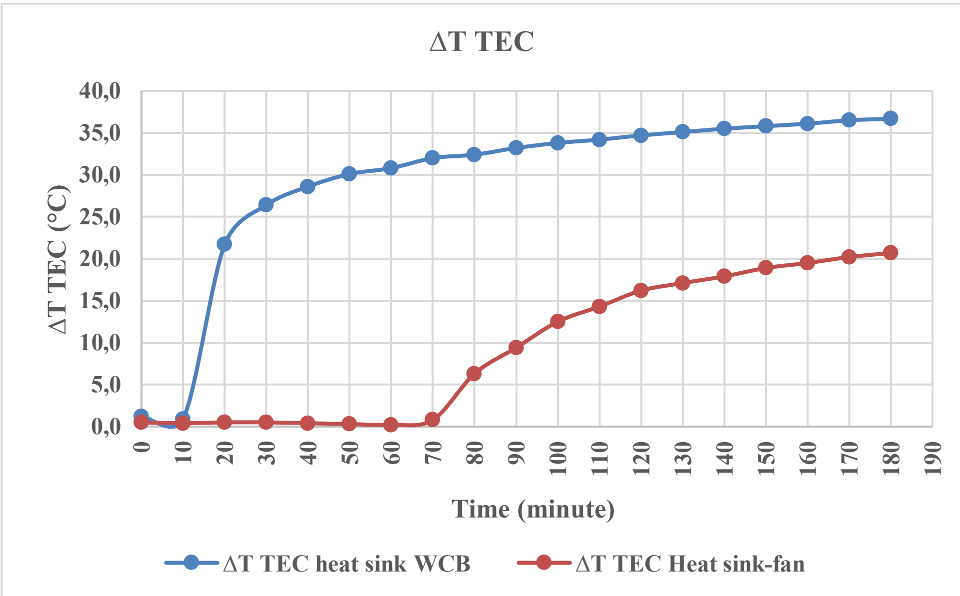

Figure 4. Temperature comparison on heat sink

The temperature difference between the hot side of the thermoelectric module is a key indicator in determining the efficiency of heat transfer from the TEC module to the environment. Figure 4. shows a graph comparing the thermoelectric ΔT against the test time between the hot side and the cold side for both types of TEC-fan and TEC-WCB tests. The blue lines and points indicate the test temperature of the TEC heat sink with WCB. The yellow lines and points indicate the temperature changes for the TEC heat sink test with a fan.

Based on the test results, the system using a heat sink-WCB showed a higher temperature increase of 36.7 °C. Significant changes began to occur at the 10-minute mark and continued gradually until the 180-minute test time. Meanwhile, the system using a heat sink-fan showed a stable temperature increase trend until the 70th minute, and then gradually increased until the 180-minute testing time with a final value of 20.7 °C. These results are consistent with those reported by Nugroho Tri Atmoko et al. [11], where the addition of WCB on the hot side of the TEC had a better effect. This is because heat transfer in the heat sink-fan system relies solely on forced convection by air, which has a relatively low specific heat capacity compared to water. In contrast, the heat sink with WCB can transfer heat more quickly through conduction and forced convection of water, and utilize a radiator to dissipate heat more effectively into the environment.

This significant temperature difference shows that the WCB system has an advantage in keeping the hot side temperature low and stable. A lower hot side temperature will increase the temperature difference (ΔT) between the hot side and the cold side of the TEC module, thereby increasing the Peltier effect. This increase in ΔT directly impacts the cooling capacity of the module, as the heat transfer process from the cold side becomes more intensive. Additionally, the stability of the hot side temperature prevents overheating of the module, which can extend the overall lifespan of the TEC.

3.2 Temperature Inside the Cooler Box Cabin

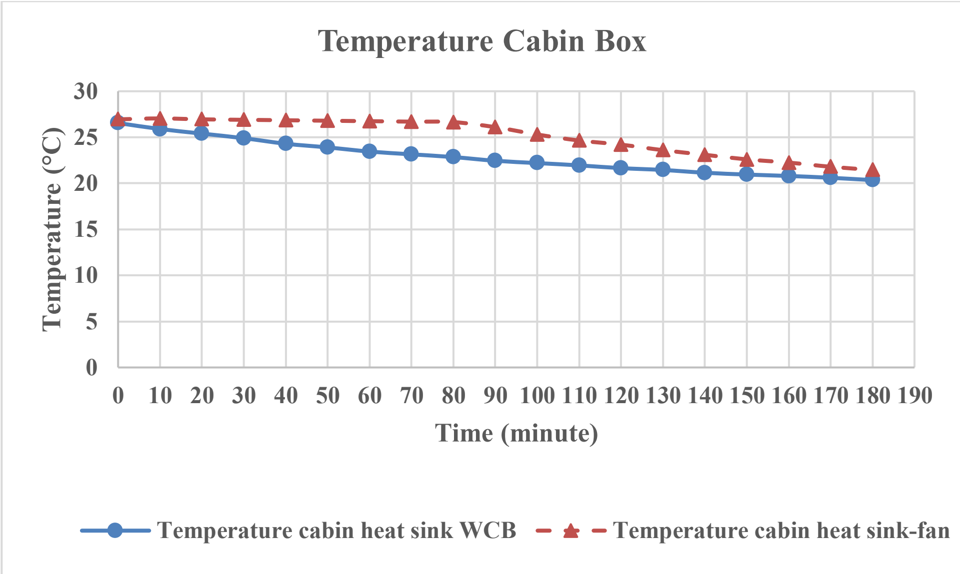

Figure 5. Comparison of temperatures inside the cooler box cabin

Figure 5 shows a graph comparing the temperature inside the cabin cooler box for the TEC-WCB test (blue line and dots) and the TEC-fan test (yellow line and dots). The experimental results show that the cooler box with the WCB system was able to achieve a lower temperature reduction of 20.35 °C within the 180-minute testing period. A significant temperature drop occurred in the first 60 minutes, indicating that the initial efficiency of the WCB system is very high in absorbing heat from the cabin air. In the heat sink fan system, the temperature drop tends to be slower and more stable. The cabin temperature began to drop at the 90-minute mark and gradually decreased until the 180-minute test, with a cabin temperature of 21.45 °C. This phenomenon is caused by the heat dissipation performance on the hot side of the TEC being influenced by the heat dissipation effect on the hot side of the TEC. With better heat dissipation in the WCB system, the cold side of the TEC module can achieve a lower temperature, and heat absorption from the load and cabin air becomes more effective and optimal, leading to thermal equilibrium. With the ability to lower cabin temperature faster and to a lower level, the WCB cooling system is highly suitable for applications requiring small-capacity cooling systems that need to achieve stable temperatures quickly, such as food storage, beverage storage, pharmaceuticals, or other sensitive materials.

3.3 Performance Comparison (COP)

To assess the energy efficiency of the cooling system, the Coefficient of Performance (COP) parameter is used, using equation (1), which is the ratio between the cooling load (Qtotal) and the total electrical power used (Ptotal). To determine the total cooling load on the cooler box, equation (2) is used. The total electrical power used can be calculated using equation (3).

Figure 6 shows the COP graph for each heat sink. The trend shows that the COP in the WCB system is consistently higher than in the system with a heat sink fan. The COP value remains relatively constant from the start of the test until the 180th minute, with an average COP value of 0.09687. Meanwhile, the COP values for the heat sink-fan system tend to be stable with an average value of 0.04718. This indicates that the WCB system is more efficient in converting electrical energy into cooling energy. This advantage arises because water, as the cooling medium in the WCB, is able to maintain the temperature of the hot side at a low level, ensuring that the TEC performance remains optimal without excessive heat load [10]. Meanwhile, in fan systems, heat accumulation on the hot side causes the TEC to operate in suboptimal thermal conditions, requiring more electrical energy to produce the same cooling effect. The increase in COP also indicates significant energy-saving potential if this system is applied on a large scale or for long-term operations. Thus, the thermoelectric cooler box system with WCB is not only superior in terms of cooling performance but also in energy efficiency.

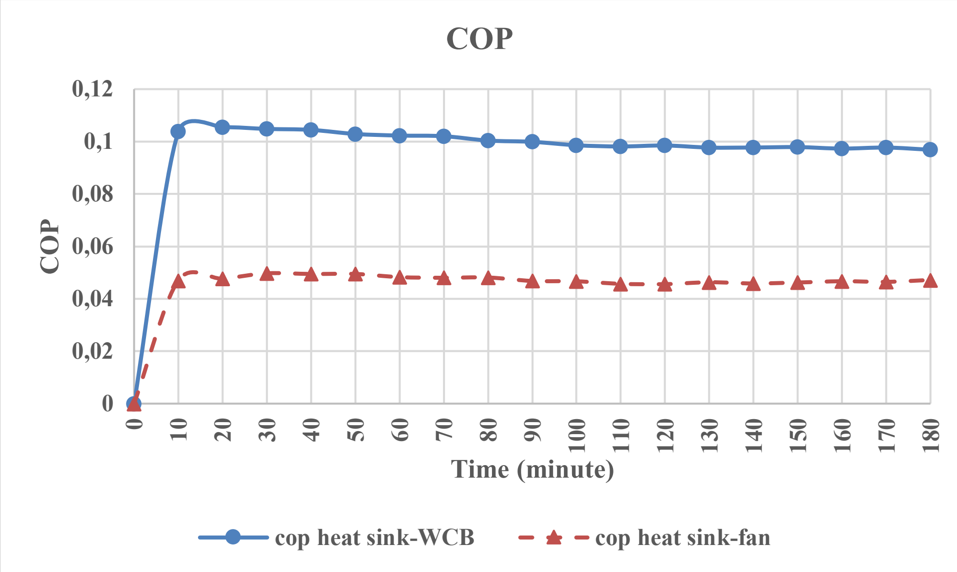

Figure 6. Performance Comparison (COP)

3. CONCLUSION

Experimental research has been conducted on thermoelectric cooler boxes with WCB heat sink cooling and heat sink fans, where water is used as the cooling medium on the hot side of the TEC-WCB and air is used as the cooling medium on the TEC-fan. The cooling load applied is water with a mass of 0.35 kg. Experimental data showed that the TEC ΔT value comparison for the heat sink with WCB reached a maximum of 36.7 °C at minute 180. The heat sink-fan had a TEC temperature comparison value was 20.7 °C at the 180th minute. The temperature drop data for the thermoelectric cabin cooler box with WCB reached a minimum temperature of 20.35 °C. This temperature achievement is better than the TEC-fan, which could only reach a cabin temperature of 21.45 °C during the 180-minute testing period. The experimental COP value of the system was found to have an average value of 0.09687 for TEC-WCB, while the TEC-fan had a value of 0.04718. From the three aspects observed, namely heat sink temperature, cabin temperature, and COP value, it can be concluded that the use of Water Cooling Block (WCB) provides a significant improvement in the performance of the thermoelectric cooling system. This system is not only able to dissipate heat more efficiently, but also improves cabin cooling capabilities and overall energy efficiency. These findings align with the research objective, which was to experimentally evaluate the impact of the WCB on the performance of the thermoelectric cooler box.

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