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To cite this article: Adi Winarta *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1034** 012033

Experimental study of thermoelectric cooler box using heat sink with u-shape heat pipe and methanol working fluid

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Abstract. Thermoelectric refrigeration system is considered environmentally friendly because it does not use refrigerants which have huge potential damaging the ozone layer. In this experimental work, u-shape heat pipe with heat sink was charged with methanol working fluid with different filling ratios to observe its effect on the thermoelectric performance. The cooler box has 240 mm x 180 mm x 130 mm of inner dimension. 37.3 watt DC power supply supplied constantly to the thermoelectric module to performed cooling action. The result shows that methanol with 45% and 55% filling ratios has the maximum COP about 0.03881 and 0.03885 respectively. This filling ratio also provides for a lower cabin temperature and temperature difference between the cold and hot thermoelectric sides.

Keywords: thermoelectric cooler box, u-shape heat pipe, filling ratio, methanol, COP.

1. Introduction

Refrigeration is one of the important technologies that has wide range application from cryogenic temperature for industries and research, food chain industries until residential applications. Mechanical based of vapour compression system is the most dominant usage system at domestic and commercial refrigerator. It also has the highest coefficient of performance compare with other refrigeration system, such as absorption, thermoelectric and magnetic. However, the detrimental effect of refrigerant used by this system also becomes a serious issue to the environmental.

Most of the refrigerant used by vapor compression system still contain halocarbon compound, which is synthetically produced by adding chemical element hydrogen (H), carbon (C), chlorine (Cl) and fluorine (F). Those elements in the refrigerant, especially chlorine, have been proven to damage the ozone layer, which subsequently letting more UV-B reach the earth's surface. Skin cancer, cataracts in humans and animals, decreased immunity system are some of the negative effect of UV-B radiation [1]. Therefore, looking for alternatives to vapor compression system is an effort to save the earth's atmosphere from ozone layer depletion.

IOP Conf. Series: Materials Science and Engineering 1034 (2021) 012033 doi:10.1088/1757-899X/1034/1/012033

One of the pragmatic solutions is thermoelectric cooling (TEC) or sometimes said Peltier module. It considered that for future replace of vapor compression system. This kind of cooling system has fewer mechanical moving part, less friction and noise, no refrigerant needed, compact design and almost has free maintenance [2, 3]. Better temperature control for refrigerated area and it can be supplied with DC power become the special benefits of this cooling system. Many researchers agree that thermoelectric performance is low enough to compete with vapour compression system [3]. Nevertheless, it should be not considered as a huge shortcoming. In some application such as military, medical industries and aerospace, temperature stabilization is more important than just a low performance. Therefore, cooling systems use thermoelectric are still one of the top research interest in refrigeration for the next future.

A lot of study have been performed on evaluation about thermoelectric refrigeration performances. One of them studied by Min and Row [reference]. Their experiment showed the thermoelectric COP of 0.3-0.5 for cooling temperature at 5°C with outside environment at 25°C [4]. Dai et al. also found almost the same magnitude of COP for thermoelectric refrigerator with power supplied from photovoltaic module and battery [5]. Vián and Astrain proposed a thermoelectric refrigerator with two different heat exchanger based on the principle of thermosyphon. One of them using technology of capillary lift and the other using motionless part. They claim 66% increase in COP if compare it with thermoelectric refrigerator with conventional finned heat sink [6]. Jugsujinda et al. [6] investigated a thermoelectric cooler box with 0.022m^3 cabin volume. They claim temperature decreased of the cooler box from 30°C to -4.2 °C for 60 minutes with 3.5 ampere of current supply. They showed the COP of thermoelectric of 0.22 which generated using 40.46 watt power supplied [7]. Gökçek et al. performed an experimental study of a thermoelectric cooler box with water mini-channel as the cooling device of thermoelectric hot side [8]. The performance of thermoelectric refrigeration using two different type of heat sink was investigated by Mirmanto et al. Both of them serves as cooling device for the hot side of thermoelectric module. The device were heat sink fin with fan and heat sink heat pipe with double fan. They conclude that the heat sink fin was more reliable when it is considered about energy consumed [9]. Mirmanto et al. [9] also studied the performance of thermoelectric refrigeration with different positions of peltier module. The volume of cooler box was 4.891 litre with the insulation wall around 50 mm. Inside the box they put 360 ml of water as product load. They found that best positioned of thermoelectric device was on the wall [10].

Heat sink with u-shape heat pipe has been widely used as processor cooling device in personal computer or desktop. As a latent passive cooling, heat pipe is much more efficient than a conventional heatsink or even a water cooling. Many research also has been performed with heat pipe as a cooling device to many applications [11-17]. In thermoelectric refrigeration, heat pipe usually applied as thermal management for 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. In fact, the heat pipe performance depends on it's working fluid ratio or filling ratio [18]. Therefore, in this work methanol working fluid was injected to heat sink with u-shape heat pipe in different filling ratio and applied it at hot side of thermoelectric cooler box. The objective of the research was to find the performance of thermoelectric cooler box.

2. Method and material

Heat sink with u-shape heat pipe was used as a cooling device for the hot side of thermoelectric module. The heat sink heat pipe was injected with methanol working fluid before installed it at the thermoelectric cooler box. The filing ratio (FR) of working fluid was 30%, 45%,55%, and 85%. Figure 1a shows the filling system for charging the working fluid into the heat sink with u-shape heat pipe. Red circle at the picture pointing the heat pipe position in filling system rig. Back filling method was used to charge the working fluid as we do in our previous work [13]. Figure 1b show the picture of heat sink with u-shape heat pipe which already charged with methanol working fluid.

Figure 2 show the schematic diagram of experimental research. The test-bed consisted of a cooler box with a thermoelectric module, a heat sink heat pipe with a fan, a cold sink with a fan, power supply units, a dc power meter, and a set of temperature loggers. The cooler box has 240 mm x 180 mm x 130 mm of inner dimension. The material of box was made from polyurethane board with 40 mm of thickness. TEC1-12706 was used as peltier module and attached at side of the wall. The module was attached tightly with a cold sink, block copper and heat sink using screws as shown in figure 2. The contact resistance between cold sink, peltier module, extender (copper block) and heat sink heat pipe was minimized with thermal paste 1.97 $Wm^{-1} K^{-1}$. The material of heat sink with u-shape heat pipe was made from aluminium and copper. DC fan with a dimension of 92 mm x 92 mm x 25 mm was attached at heat sink to increased heat rejected from condenser part of heat pipe. At the cold sink, a smaller dc fan was attached with a dimension of 40 mm x 40 mm x 15 mm.

Figure 1. Mechanism of injected fluid into the heat pipe: a) Filling system, b) heat pipe which already injected with methanol working fluid.

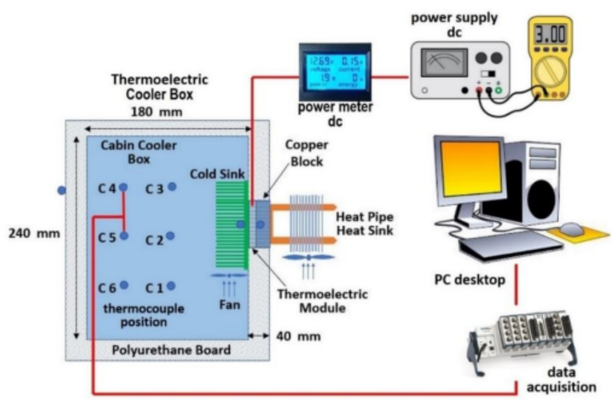

Figure 2. Schematic of experimental setup

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DC power meter PZEM-017 was used to measure the electricity consumption of peltier module with measurement error of 1%. meanwhile, the DC fan power consumption was measured using digital multimeter. The temperatures were measured by type-K thermocouples connected to data acquisition device (NI 9213 and NI 9274). Six thermocouples (C1, C2, C3, C4, C5, and C6) are used specifically to measure the cabin temperature which then calculated it as average temperature in the data analysis. The rest are attached at hot side and cold side of Peltier module, inner and outer walls, and the ambient temperature of cooler box. In this experiment the power supplied to the thermoelectric module was set at constant at 4,5 ampere and 12 Volt for each filling ratio of methanol working fluid. Also, there was no product load within the cooler box excepted air solely to shorten the experimental times.

The objective of this work is to investigate the cooling performance (COP) of thermoelectric with heat pipe heat sink as the hot side cooling using methanol as the working fluid. The calculation of COP of a thermoelectric cooler box is based on the conventional COP of refrigeration. That is, the total of cooling capacity divided by the total power consumption of the equipment. This method also verified and implemented by other researchers [2,6,8,10]. The equations is defined follows equation 1 to equation 4.

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

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

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

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

$\dot{Q}_T$ (watt) is total of cooling capacity of thermoelectric cooler box and P_{total} (watt) is the total power consumes of cooler box. Equation2 shows that $\dot{Q}_T$ is sum of $\dot{Q}_a$,$\dot{Q}_c$ and $\dot{W}_{inner\ fan}$. $\dot{Q}_a$is cooling load from the air inside the cabin, $\dot{Q}_c$ is transmission load through the wall, $\dot{W}_{inner\ fan}$ is heat generation from cold sink fan. Gökçek et al. calculated this heat generation using the rate of electrical power consumption [8]. Equation 3 computed the total power consumes. It consist of the power consumed by heat sink fan (outer fan) and Peltier module. In equation 4, m_a is the mass of air (kg), $c_{p,a}$ is the specific heat of air (J kg^{-1} K^{-1}), $dT{\cdot}dt^{-1}$ is the temperature gradient per unit time. Transmission load ($\dot{Q}_c$) or heat flow entering the inside cooler box is calculated with equation 5.

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

where A is total of heat transfer surfaces (m), U is the overall heat transfer coefficient (W m^{-2} K^{-1}), T_{cabin} is the average temperature of cabin (C1 until C6) and T_{amb} is the environment temperature. The overall heat transfer coefficient can be calculated as equation 6.

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

Where h_{int} is the heat transfer coefficient at inner surface of cooler box, h_{ext} is heat transfer coefficient at outer wall surface, L is the wall thickness and k_{wall} is the thermal conductivity of polyurethane. Equation 7 and 8 are correlation given by Parmelee and Huebscher [6, 8] for calculate the heat transfer coefficient at the inner surface.

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

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

3. Results and discussion

Figure 3 shows the temperature performance of the thermoelectric cooler box using the smallest and highest filing ratios (45% and 85%). It is intended to show the effect of filling ratio variations on the resulting temperature performance in the cooler. The graph shows cold side and hot side thermoelectric temperatures, cabin and environment with respect to times. This result is completely agree with previous experimental work [7-10,19].

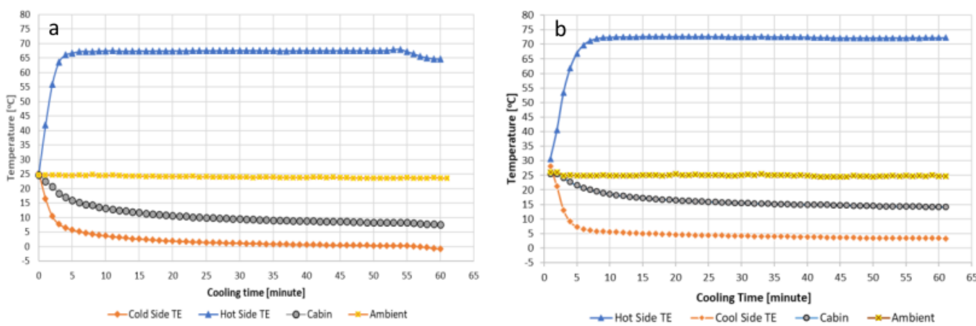

Figure 3. Temperature of thermoelectric cooling respect to time with: a) 45% filling ratio, b) 85% filling ratio

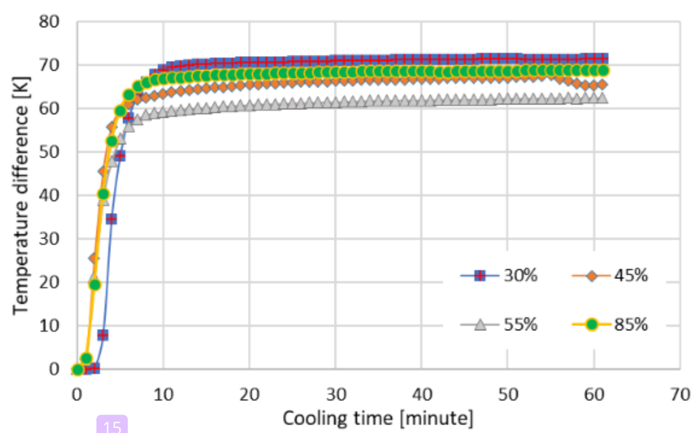

Figure 4. Temperature difference between hot and cold side of TEC

Figure 4 shows the comparison of temperature different between hot and cold side of TEC. Lower cabin temperature occurs at filling ratio of 45% if compared with 85% as shown in the figure 3. This may be related to the achievement of a lower cold side temperature at filling ratio of 45% which is around 0°C. Meanwhile, at filling ratio of 85%, the cold side temperature only reaches 5°C. The lower temperature also is achieved at the filling ratio of 45% on the hot side of thermoelectric. The cold side temperature on the thermoelectric affects the achievement of the cabin temperature inside the cooler box. The attainment of low temperatures on the cold side is the result of the cooling performance of heat pipe heat sink on the hot side of thermoelectric.

Temperature difference higher than 50 K is observed at all filling ratios of methanol working fluid. The lowest temperature difference is clearly visible at the fill ratio of 55%. While the filling ratio at 30% shows the highest temperature difference among all. Huang et al. stated that a higher temperature difference results in higher voltages and lower cooling capacity [20]. Mirmanto *et al.* also stated that the lowest cooling capacity results from the highest ΔT of TEC [10]. Therefore, we may say that all filling ratio of methanol has large temperature differences which means has low performance in cooling. It also means that the heat dissipation capability of methanol heat pipe (at the hot side) are still low.

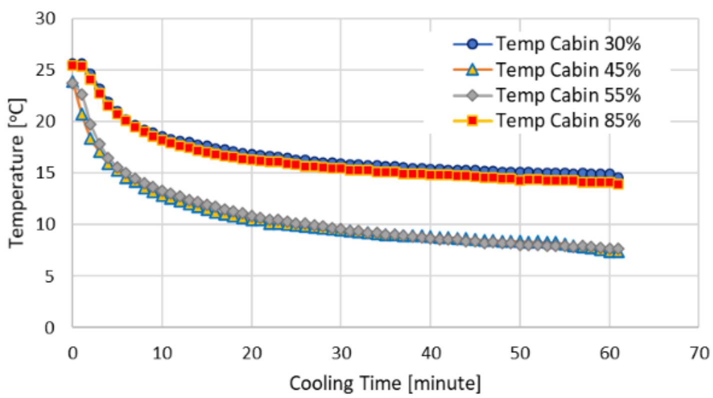

Figure 5. Temperature cabin of thermoelectric cooler box for different filling ratio

Figure 5 shows the cabin temperature of thermoelectric cooler box for each filling ratio (FR). FR of 45% and 55% shows lower cabin temperature compares with 30% and 80%. The lower cabin temperature also means better performance of extracting heat load within the box to the outside ambient. These filling ratios have lower thermal resistance to dissipating heat from hot side of TEC to the ambient through the u-shape heat pipe.

COP is the general parameter which indicates the performance of thermoelectric cooler box. Using equation (1) the COP computed and then compared each of filling ratio of working fluid. The result of analysis is presented in figure 6. The cooler box COP are increased sharply at the beginning, then the curve begins to reduce it's slope and prepared to constant as shown in figure 6a. The filling ratio of 45% and 55% show higher COP (0.038) compared with others (30% and 85%). The trends of 45% and 55% are adjacent to each other from the beginning; likewise the trends of 30% and 80% at a lower value. The finding COP curve is somewhat different from other researchers [8, 9]. The reason is $\dot{Q}_c$ became the most significant heat transfer effect among all parameters in equation 2. Due to the COP in equation (1) is the ratio of $\dot{Q}_T$ and P_{total} then $\dot{Q}_c$ has significant effect on the calculation of it. For this reason, figure 6b is added to shows the ΔT of the system for each filling ratio. The temperature difference of system (ΔT system) was calculated from temperature ambient minus the average temperature of the cabin [8,10]. Figure 6b shows that 45% and 55% of filling ratio have higher ΔT of system compared with 30% and 80%, which means higher $\dot{Q}_c$ for the same level of energy supply to the thermoelectric module. A Higher ΔT of the system will result in the higher cooling capacity of the thermoelectric, thereby increasing the COP of the thermoelectric cooler box.

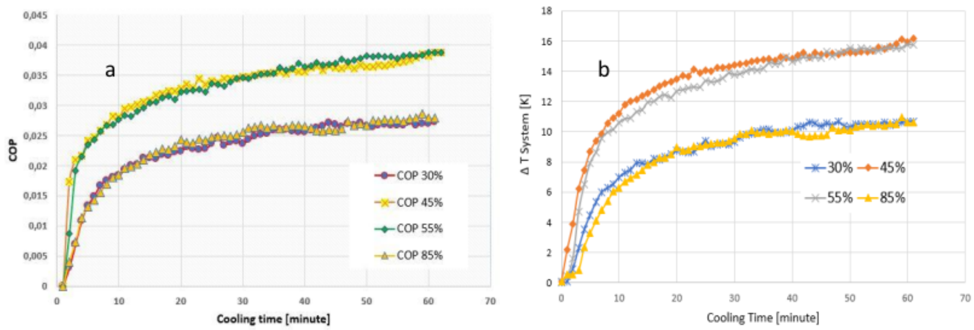

Figure 6. Variation of: a) COP, b) ΔT system for different filling ratios of methanol working fluid

4. Conclusion

Thermoelectric cooler box using u-shape heat pipe with methanol working fluid has been experimentally investigated. The u-shape heat pipe with heat sink was injected with different filling ratios of methanol working fluid to observe it's performance absorbing heat from the hot side of thermoelectric module. From the experimental data, the similar temperature trends are shown for all different filling ratios. The cooling capacity obtained from this experimental work still low at all filling ratios. The COP increased with time due to the increase of cooling capacity. The maximum COP of thermoelectric cooler box is about 0.03881 and 0.03885 for 45% and 55% FR respectively. The filling ratio of 45% and 55% have lower cabin temperature, lower temperature difference between hot side and cold side and better performance (COP).

5. Acknowledgments

The authors would like to express their gratitude to *Politeknik Negeri Bali* for funding this research through *Penelitian Unggulan Dana DIPA PNB 2019* scheme with contract number 1091/PL8/LT/2019. The authors also want to thank our students, who have worked on the experimental setup rig without tirelessly.

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