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Performance Evaluation of Thermoelectric Cooling with Two Different Fluids Medium

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ABSTRACT

Thermoelectric has been used in various applications related to cooling systems (TEC). Most researchers focused on expanding the application of TEC and improving heat transfer. The improvement of the heat transfer relied on the configuration, heat exchanger, and fluid medium. However, no previous work has reported the influence of air and water as the fluid's medium on the TEC performance. Therefore, in this study, the performance of TEC with water and air as working fluids is evaluated experimentally. Besides, several input parameters are controlled to evaluate the TEC performance under different conditions. The results reveal that the variation of working fluid and input parameters influenced the overall TEC output. The increment of TEC cooling capacity is proportional to the input power, mass flow rate, and inlet temperature of the working fluid. While the input power and inlet temperature also vary the heat exchanger thermal resistance. The overall thermal resistance of the water block is averagely ten times lower than that of the heat sink, therefore, the water block is significantly better compared to the heat sink. While the highest COP obtained from the water and air system is 1.72 and 1.41, respectively.

KEYWORDS
Thermoelectric
TEC
Coefficient of performance
Fluid medium
Water
Air

INTRODUCTION

A thermoelectric is an electronic component that can convert electrical energy into thermal energy or vice versa [1]. At least two effects are working inside thermoelectric, the Peltier and the Seebeck effect. The Peltier effect converts the voltage difference from the power supply into a temperature difference on both sides [2–4]. The temperature difference that occurs allows the heat to be transferred from one side to the other side of the thermoelectric, in this function it is known as the thermoelectric cooler (TEC). While the opposite utilizes the Seebeck effect and the device is called the thermoelectric generator (TEG). TEG can generate electrical energy from the temperature difference on both sides of the thermoelectric [2–4]. These two effects occur

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simultaneously in one device, therefore only the dominant conditions (either input power or temperature difference) make the thermoelectric a TEC or TEG [5].

As a cooling system, TEC has many advantages including compact size and make no noise when operates [1,6,7]. It is also very reliable and requires no maintenance as it has no moving part inside [6–8]. TEC is also environmentally friendly due to the absence of refrigerant which is known as one of the contributors to global warming and ozone depletion [9,10]. Easy operation is also one of the advantages of TEC such as the ease of switching between heat pump and refrigeration modes as well as easy integration with renewable energy such as photovoltaic [1, 6].

TEC is widely applied to various types of cooling systems, both as stand-alone systems and integrated systems [4]. The utilization of TEC as an air conditioner was analyzed (Irshad, et al., 2019). A total of 6 TEC capacities ranging from 240W to 840W were used to cool down a test chamber. The thermal comfort of 15 research subjects was then used to assess the performance of the cooling system. The result revealed that as the capacity increases, the thermal comfort of the subject also improves. However, the deterioration of cooling performance occurred when the 840W capacity is used. Garayo et al. [6] reported the successful integration between TEC and heat recovery ventilation (HRV). Through the combination of these two devices, they claim the cooling and heating performance of HRV can be increased up to 10% and 25%, respectively, during summer and winter. TEC can also be applied as a cooling system in a refrigerator to store the perishable product, where the performance of this application has been analyzed by Gokcek & Sahin [11]. A water-cooled system was attached to the hot side of TEC to dissipate the heat. The coefficient of performance (COP) of this application was reported varied from 0.19 to 0.41 depending on the mass flow of the water, while the cabin temperature can be kept at -0.10C.

The application of TEC as electronic cooling was also reported by several studies. Hu et al. [12] make use of cooling produced by water-cooled TEC equipped with temperature control to cool down a central processing unit (CPU). Temperature control was used in the cooling systems with the purpose of preventing condensation and energy saving. The performance of TEC was then analyzed and compared with conventional water-cooled systems, and it was proven that TEC had much better performance. Wang et al. [8] paired the TEC with a corona wind generator and used it to cool down the high-power light-emitting diodes (LED) chips. Corona wind was used to dissipate the heat from the hot side of the TEC. Using this method, the cooling performance can be increased by 40%. An electronic cooling device that can adjust the cooling capacity close to the thermal load has been developed by Siddique et al. [13]. The cooling device employs a TEC coupled with a closed-loop liquid cooling system. The performance of the developed device was observed and compared with a similar commercial system. With the same amount of thermal load, the developed system can reduce the temperature of test object 40C lower than the commercial ones.

Knowing the advantages, it seems very promising to commercialize TEC as a cooling system. However, this device still has limitations, especially when the system performance is lower than other refrigeration systems, such as the vapor compression refrigeration cycle [1,3,4,6,10]. Therefore, efforts are needed to improve TEC performance.

Attempts to improve the performance of TEC have been extensively put forward by researchers to overcome the only drawback of this device. Jeong [10] proposed a new dimensionless parameter that can be used to obtain the best composition to maximize the cooling capacity of the TEC when the heat source temperature, heat sink temperature, heat exchanger thermal resistance, and contact resistance are known. Meanwhile, Shen et al. [7] tried to enhance the cooling performance by using a segmented configuration of TEC. The two-segmented configuration has managed to improve the maximum cooling capacity and temperature difference by 118.1% compared to the traditional configuration, while the COP can be increased by 2.1%.

With a similar goal, experiments involving better heat dissipation techniques from the TEC hot side also have been carried out. Five TEC hot-side cooling methods have been compared by Liu and Su [1]. This method includes fan-enhanced heat-pipe cooling; forced convection water cooling; forced convection air cooling; free convection water cooling; and free convection air cooling. The result revealed that the fan-enhanced heat-pipe cooling method provides the highest COP, while the second was forced convection water cooling. Dizaji et al. [14] conducted the experiment on a multi-TEC consisting of 2, 4, and 6 modules in a series configuration. In addition, perforated and spring wires heat sink were also introduced into the system. A 6-jointed TEC can provide around 100% increment of COP over the 2-jointed one, while the perforated and spring wire heat sink can improve the COP by 50% and 130%, respectively, at the same input power. Wiriyasart et al. [15] investigated the impact of working fluid difference on the performance of water-cooled TECs. The experiment employed TiO2 nanofluid and Fe3O4 ferrofluid with concentrations of 0.005% and 0.015% in addition to deionized water. The result revealed that ferrofluid had the highest heat transfer rate, 11.17% and 12.57% higher than nanofluid and water. Application of nanofluids and ferrofluids also lead to a decrement of thermal resistance of the heatsink by 4.6% and 9.6%, respectively. However, the pressure drops of ferrofluid and nanofluid at 0.015% concentration were also rose by 2.7 kPa and 0.5 kPa, respectively, compared to deionized water.

Based on the literature review above, it appears that TEC has been used in various applications related to the cooling system. Most of the researchers focused on expanding the application of TEC and improving heat transfer. The improvement of the heat transfer relied on the TEC configuration, heat sink, and fluid medium. However, no previous work has reported the influence of air and water as the fluid medium on the cooling performance of the TEC. Therefore, in this study, the cooling performance of TEC with water and air as working fluids is evaluated experimentally. The TEC performance is evaluated through the variation of input power, temperature, and mass flow for each fluid medium.

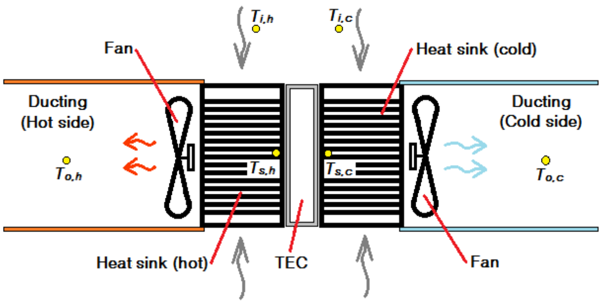
METHODOLOGY

There are two apparatus employed in this experiment, as shown in Figure 1. An air system (Figure 1.a) consists of the heat sink, TEC module, dc fans, and ducting. The heat sink applied in the air system has a dimension of 10cm x 10cm with a height of 2.5cm, while the TEC dimension is only 4cm x 4cm. To prevent direct heat transfer between the hot and cold heat sinks, thermal insulation is installed over the remaining areas of the two heat sinks. A dc fan of similar size was installed on top of the heat sink to draw the air from outside to ducting. Subsequently, the air will receive or release heat from the TEC while flowing through the heat sink.

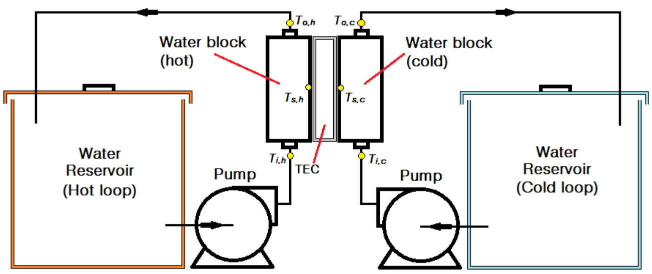
The water system (Figure 1.b) consists of water block, TEC module, pumps, flexible pipes, and water reservoirs. The water block is a block of aluminum that has a channel inside, which water can flow through while receiving or releasing heat from the TEC module. It has a dimension of 4cm x 4cm x 1.2cm and properly fits with the TEC module when mounted. The dc pump is used to circulate the water from the water reservoir to the water block through the flexible pipe. Thermal insulation is also applied in the water system to prevent the heat transfer between the apparatus and the environment. Additionally, thermal paste is applied before mounting the water block and heat sink to TEC module to reduce the contact resistance. The specification of water block and heat sink is shown in Figure 2.

Commercial TEC module with a bismuth tin (BiSn) material is used in the experiment. A complete specification of the thermoelectric shown in the Table 1. The maximum cooling capacity ($Q_{c,max}$) is achieved when the temperature difference between both side (ΔT_{hc}) is zero, while the maximum temperature difference ($\Delta T_{hc,max}$) is achieved when the cooling capacity (Q_c) is zero.

Switch-mode power supply (SMPS) is used to supply electricity to all systems. The power of TEC module is regulated using voltage and current regulator. Meanwhile, the variation of fluid mass flow is done by changing the input voltage of the fan and pump for each experiments. The working fluid temperature is conditioned before the experiments using an electric heater until the test value is achieved. All parameters set up are maintained in a stable condition throughout the measurement process.

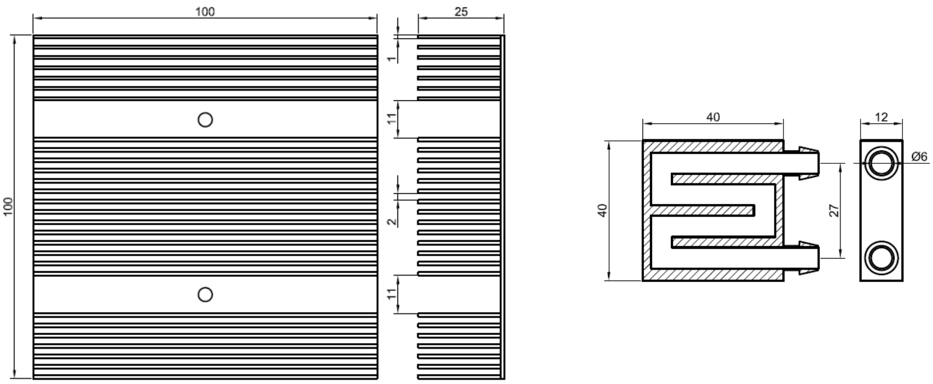


(a)



(b)

Figure 1. Schematic illustration of experimental set up (a) air system (b) water system



(a) (b)

Figure 2. Specification of (a) heat sink (b) water block

Table 1. TEC specification

Items	Value
Dimension	4cm x 4cm x 0.39cm
I_{max} (A)	6.4
V_{max} (V)	14.4 (T_H = 25°C)
	16.4 (T_H = 50°C)
$Q_{c,max}$ (W)	50 (T_H = 25°C)
	57 (T_H = 50°C)
$\Delta T_{hc,max}$ (°C)	66 (T_H = 25°C)
	75 (T_H = 50°C)

Table 2. Experimental parameters

Variable	Value		
	Min.	Med.	Max.
$P(W)$	20	35	50
T_i (°C)	25	30	35
$\dot{m}$ (kg/s)	0.008	0.01	0.013

Evaluation of TEC performance involving experiments in a various conditions, accordingly, several variables are controlled. The controlled variables are input power (P), fluid medium inlet temperature of hot ($T_{h,i}$) and cold side ($T_{c,i}$), and mass flow ($\dot{m}$) shown in Tabel 2. These variables are determined by minimum and maximum value following the range operations where TEC can still work normally. Besides, the median value is also determined to antisipate the possibility of nonlinearity in the experimental result.

A total of six temperature point are measured to evaluate the cooling performance, including inlet temperature ($T_{i,h}$, $T_{i,c}$), outlet temperature ($T_{o,h}$, $T_{o,c}$), and surface temperature ($T_{s,h}$, $T_{s,c}$). The temperature measurement employed a data logger with ±0.50C accuracy (Maxim Integrated Products, Inc., California, USA). The measurement is carried out every second for 5 minutes to observe any changes that occured. Subsequently, the steady temperature data is selected for further investigation.

The cooling effect (Q_c) produced by the TEC can be calculated using equation (1):

$$Q_c = \dot{m}\ x\ C_p\ x\ (T_{i,c}\ -\ T_{o,c}) \tag{1}$$

Where C_p is the specific heat of the working fluid, and mass flow rate ($\dot{m}$) of the working fluid can be calculated from (2):

$$\dot{m} = \rho\dot{V} \tag{2}$$

The thermal resistance of the heat exchanger is calculated using equation (3) [15]:

$$R_c = \frac{T_{i,c} - T_{a,c}}{Q_c} \tag{3}$$

Where $T_{a,c}$,c is the average temperature of the heat sink or water block, which can be found from equation (4):

$$T_{a,c} = \frac{T_{i,c} + T_{o,c}}{2} \tag{4}$$

The COP of the TEC can be calculated with the following equation (5):

$$COP = {}^{Q_c}/_{P} \tag{5}$$

RESULT AND DISCUSSION

The experimental results show that variations in working fluid and input conditions influenced the overall TEC output includes the cooling capacity (Q_c), as shown in Figure 3. The increment of the cooling capacity is proportional to the value of mass flow rate ($\dot{m}$) and inlet temperature ($T_{i,c}$) of the working fluid and also the input power (P) of TEC. Therefore, a higher input power (P), mass flow rate ($\dot{m}$), and inlet temperature ($T_{i,c}$) will significantly increase the cooling capacity (Q_c) of both systems. This situation is in line with equation (1), where the mass flow rate of the working fluid contributes to a significant increment in the TEC cooling effect (Q_c).

The result reveals that increasing the mass flow rate ($\dot{m}$) from 0.008 to 0.010 will enhance the cooling capacity of water and air system averagely by 5.7% and 16.8%, respectively. While increasing the mass flow rate ($\dot{m}$) from 0.010 to 0.013 will enhance the cooling capacity (Q_c) of water and air system averagely by 11.9 and 10.7%, respectively. The average enhancement of the cooling effect (Q_c) produced by the water system is lower than the air system when the mass flow rate ($\dot{m}$) is changed from 0.008 to 0.010, but the opposite occurs when the mass flow rate ($\dot{m}$) is raised to maximum. This indicates the greater potential for improving the cooling effect (Q_c) of the water system by increasing the mass flow rate ($\dot{m}$) higher than the maximum test parameters.

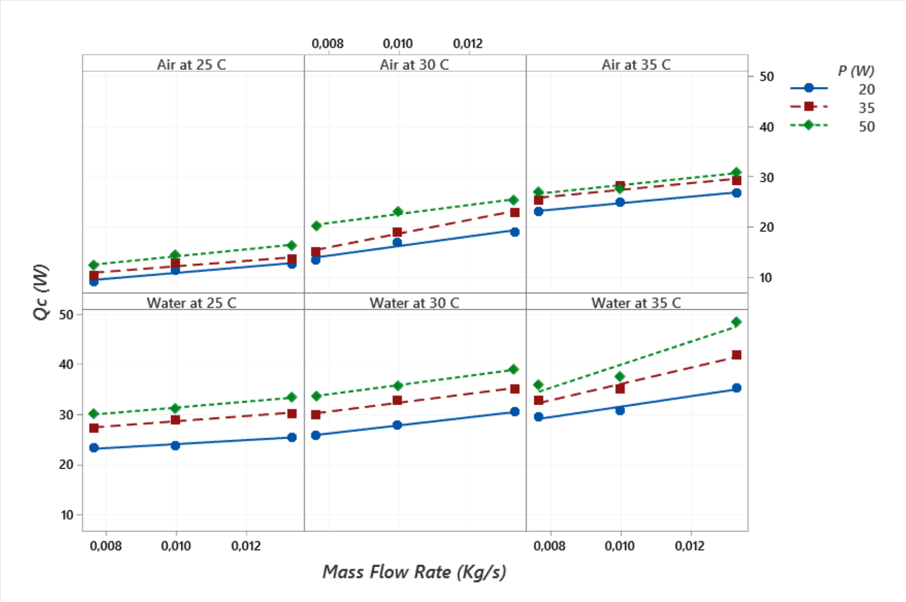


Figure 3. Cooling capacity at difference conditions

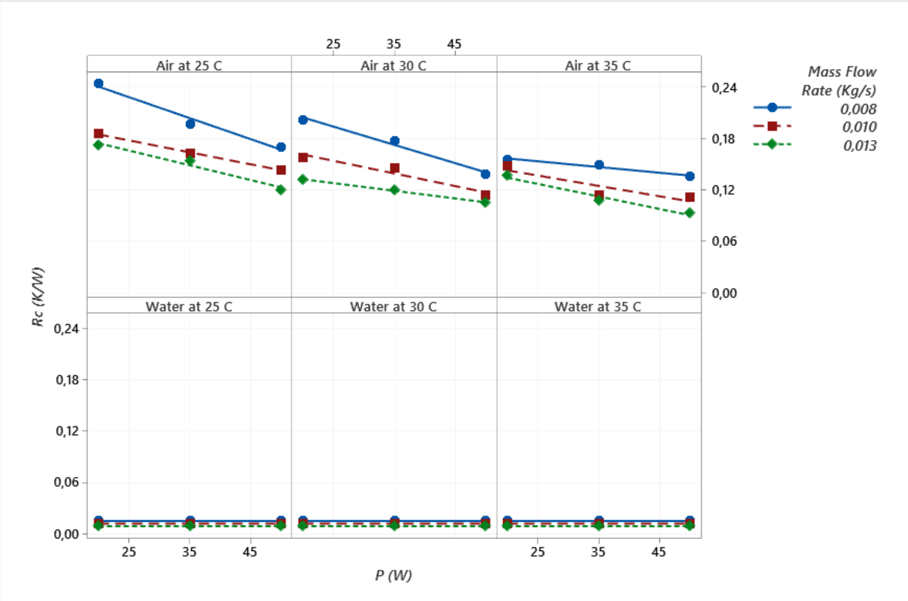


Figure 4. Heat exchanger thermal resistance at difference conditions

Meanwhile, the reduction in the average cooling effect as the mass flow rate ($\dot{m}$) increase is caused by the bypass factor of the heat exchanger. The value of the bypass factor is proportional to the increment of mass flow rate ($\dot{m}$), thereby limiting the extent to which the mass flow rate ($\dot{m}$) can be increased to enhance the cooling effect (Q_c). In this case, the water block has a low bypass factor, so the water system has the potential to enhance the cooling effect (Q_c) even further.

Figure 4 shows the variation of the heat exchanger thermal resistance (R_c) for each experiment. The water block's thermal resistance (R_c) ranges from 0.009 to 0.016, while the heat sink ranges from 0.067 to 0.197, depending on the input conditions. It appears that the variation of input power (P) and inlet temperature ($T_{i,c}$) varies the heat exchanger thermal resistance (R_c) value, except for the water block. The thermal resistance (R_c) of the water block is almost the same for all experiments, where a small difference occurs only when the mass flow rate ($\dot{m}$) is varied. The maximum thermal resistance (R_c) of the water block is achieved when the mass flow rate ($\dot{m}$) is within the minimum value and vice versa. Meanwhile, the heat sink thermal resistance is very dependent to the experimental conditions. The overall thermal resistance (R_c) of the water block is averagely 823% lower than that of the heat sink. Accordingly, the water block is significantly better than the heat sink in terms of heat transfer on the cold side.

The lowest heat sink thermal resistance (R_c) is achieved when all experimental input conditions are maximum, including working fluid temperature ($T_{i,c}$). By increasing the input temperature ($T_{i,c}$), it is found that thermal resistance can be decreased (R_c). However, it should be noted that increasing the input temperature ($T_{i,c}$) also influences the cooling temperature target. The input temperature (T_i) in this experiment is considered as the temperature of the working environment where the TEC is operating. This parameter is important because it affects the TEC surface temperature both hot ($T_{s,h}$) and cold sides ($T_{s,c}$). Moreover, the TEC surface temperature difference (ΔThc) is limited to a certain value depending on the specification of the TEC. In the end, the condition of input temperature will greatly affect the achievement of the cooling temperature target.

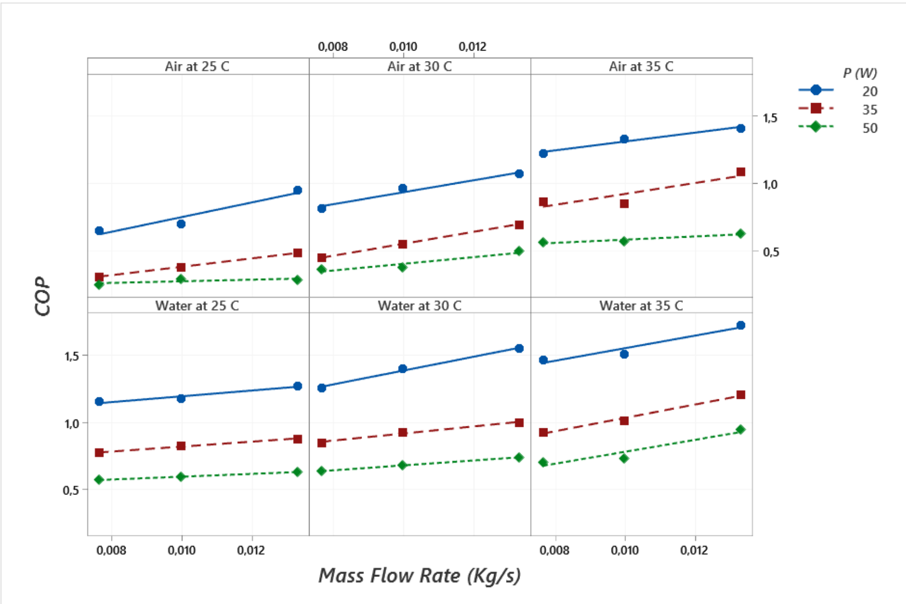


Figure 5. COP at difference conditions

Furthermore, the difference in input parameters influences the COP of the TEC. Figure 5 shows the COP variations of both systems under various conditions. The increment in the COP of both systems is proportional to the inlet temperature (Ti,c). Therefore, the TEC performance (COP) tends to be greater when it is operating in a high-temperature environment rather than low. However, the temperature conditions significantly affect the surface temperature difference (ΔThc) consequently will have an impact on the achievement of the cooling temperature target, as described previously. Besides, TEC performance (COP) is also determined by how much power (P) is given, evidenced by the fact that the two devices experience changes in the COP value when given varying input power (P). The higher the power (P) will result in a cooling effect (Q_c) enhancement. However, the increase in cooling effect (Q_c) is not proportional to the given power (P), so that the COP value tends to decrease.

Figure 5 also shows the difference in the average COP of the two systems. The first system, which uses air as the working fluid, produces a relatively lower performance (COP) than the water system. This situation is closely related to the surface temperature difference (ΔThc) on both sides, shown in Figure 6. The variation of surface temperature difference (ΔThc) has an impact on the magnitude of cooling effect (Q_c) generated by TEC. With a fixed given power (P), the TEC will provide a higher Cooling effect (Q_c) if the surface temperature difference (ΔThc) is low and vice versa. Therefore, a lower surface temperature difference (ΔThc) of the water system compared to the air system results in higher average performance. The highest COP obtained from the water and air system is 1.72 and 1.41, respectively.

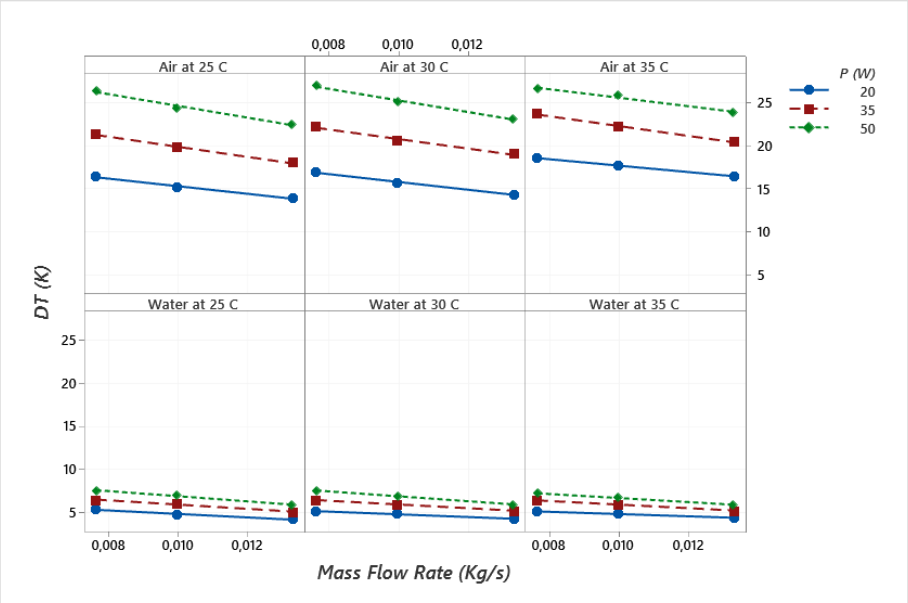


Figure 6. Surface temperature difference under difference conditions

CONCLUSION

The evaluation of TEC performance has been carried out on both devices that utilize the difference in working fluids. The result reveals variations in the TEC cooling effect, thermal resistance, and COP depending on the value of input parameters. Besides, the surface temperature difference between the hot and cold sides of the TEC is an important factor because it affects both the cooling temperature target and TEC performance.

The maximum cooling performance enhancement is achieved by the air system at 16.8% by increasing the mass flow rate from 0.008 to 0.010. While increasing the mass flow rate from 0.010 to 0.013 will give a maximum cooling effect enhancement of water system by 11.9%. Meanwhile, the highest COP obtained from the water and air system is 1.72 and 1.41, respectively.

Through these findings, it is concluded that water and air have potential as TEC working fluids with the limited operating range shown in the study. However, more extensive research is certainly needed to open up opportunities for other fluids that have not been studied or to expand the range of operations

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