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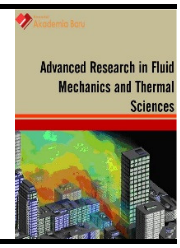

Analytical Investigation of Thermoelectric Performance for Cooling Application

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ABSTRACT

This paper presents the method used to predict the internal parameters of thermoelectric module (TEM) and the several factors that affect the temperature reduction of air in Thermoelectric (TE) cooling system. A TE cooling system consists of three TEMs attached on the top of an air duct with the dimensions 9.3 cm × 9.3 cm × 55 cm. Ambient air flows through the duct and its outlet temperature is estimated by using the log mean temperature difference (LMTD) method for different weather conditions. At the considered conditions, results showed that 6 A is the optimum operating current, and the maximum temperature reduction can reach to 2.41 °C. The performance of TE cooling system strongly depends on the ambient condition and for the considered 40 hours weather conditions, the maximum temperature reduction happened at around 3 pm. It was also found that the increase of inlet air velocity causes the temperature reduction to decrease exponentially. As a result, this study identified the correlate effects of the ambient weather, the operating current and the air velocity on the TE cooling system. As one does not have control on the ambient weather, selecting the optimum operating current level and inlet air velocity of the system is important to fully utilize the cooling effect of the system.

1. Introduction

Malaysia is a tropical climate country that seated in the center of Southeast Asia, with coordinate of 3.1°N and 101.7°E. The daytime temperature ranges between 27°C and 34°C coupled with relative humidity 70% to 90% [1, 2]. According to Center for Environment, Technology and Development, Malaysia (CETDEM), 67% of the electricity in residential buildings is utilized for Heating, Ventilation Air Conditioning (HVAC) system [3]. This system is highly required in most of tropical climate countries to cool the indoor environment and maintain the thermal comfort of occupants. However, the working fluids, or refrigerant such as chlorofluorocarbons used in the conventional Vapor Compression Air Conditioning (VCAC) system have high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). They emit large amount of greenhouse gases to the environment and the leakage of refrigerant causes irreversible damage to the ozone layer [4]. Thus, an environmental

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friendly refrigerant is needed in the usage of VCAC or an alternative air conditioning system like TE air conditioning should be used.

Thermoelectric Module (TEM) is an energy converter that creates temperature difference when electric current passes through it. This phenomenon is known as Peltier effect [5]. TEM contains no moving components, requires less maintenance, long life span and able to perform under severe environment [6]. In recent year, researchers initiated a lot of efforts on developing and determining the feasibility of Thermoelectric (TE) cooling system due to its advantages. Abdul-Wahab *et al.,* [7] experimentally investigated a portable solar thermoelectric refrigerator, and this system mainly used in Oman in areas where there is no electricity. Lertsatitthanakorn *et al.,* [8] developed a Thermoelectric Ceiling Cooling Panel (TE-CCP) with 36 pieces of TEMs and the system able to maintain the test room at 27°C. Irshad *et al.,* [9] built a Thermoelectric Air Duct (TE-AD) system and studied its performance by using a test room. This system able to reduce the indoor temperature by 6.8°C at 6 A operating current. However, the developed systems are still low in COP compared to conventional VCAC, which ranged in 2.6 to 3 [10]. So, heat transfer enhancement in the heat exchanger system is necessary to improve its cooling performance [11]. Irshad *et al.,* [12] investigated a TE-AD system at different hours, and the study found that the temperature reduction of the system is varied with different ambient temperatures. Maneewan *et al.,* [13] found that the performance of thermoelectric air conditioner is depending on the operating current and air flow velocity. In the Shen *et al.,* [14], the COP of thermoelectric cooling system is influenced by the operating current level and heat transfer coefficient (h). So, this paper highlighted the factors that affect the cooling performance of a TE cooling system. Besides, the method to obtain the internal parameters of TEMs such as Seebeck coefficient (S_{TE}), thermal conductivity (K_{TE}) and resistivity (R_{TE}) is demonstrated and the results are compared with the performance curves that are available in the manufacturer datasheet.

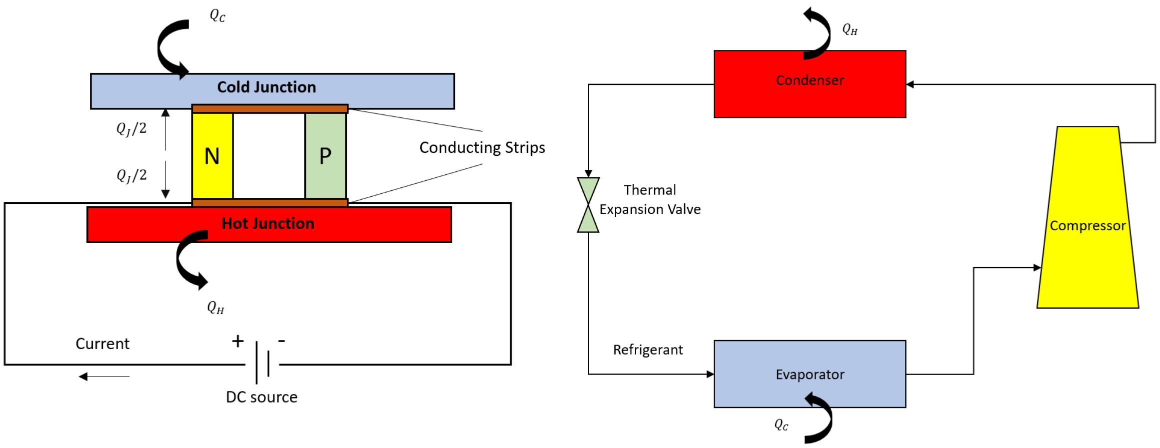
2. Methodology

2.1 Principle of TEM

TEM, or Peltier cooler consists of several p-n junctions and these semiconductors are sandwiched between two insulators made from ceramic. Figure 1 (a) shows the working principle of TEM and its principle almost same as the refrigeration cycle, as shown in Figure 1 (b). The working fluid in the refrigeration cycle is refrigerant whereas TEM is driven by electron which is harmless to the environment. TEM consists of hot and cold sides, heat from the surrounding is absorbed by the cold side and released back to the ambient at the hot side. Compared to the refrigeration cycle, the cold side is same as the evaporator while the hot side is representing the condenser. After heat is absorbed by the TEM, electrons receive the thermal energy and jump to a higher energy state at the n-junction. These electrons are then flow from one junction of the semiconductor to the another by passing through the lattice of material. At p-junction, electrons are dropping to a lower energy state by releasing the energy through the hot side of the TEM. So, p-n junctions in TEM behave like the compressor and thermal expansion valve in the refrigeration cycle that alter the energy level of the working fluid.

TEM involves 4 different types of heat, these are Peltier cooling (Q_{PEC}), Peltier heating (Q_{PEH}), Joule heat (Q_J) and Fourier heat (Q_{FH}) [12]The cooling and heating capacity of TEM can be defined as:

$$Q_C = \underbrace{S_{TE} I T_C}_{Q_{PEC}} - \underbrace{K_{TE} \Delta T}_{Q_{FH}} - \underbrace{\tfrac{1}{2} R_{TE} I^2}_{Q_J} \quad (1)$$



(a) (b)

Fig. 1. Schematic drawing of **(a)** TEM cooling process with **(b)** refrigeration cycle

$$Q_H = \underbrace{S_{TE} I T_H}_{Q_{PEH}} - \underbrace{K_{TE} \Delta T}_{Q_{FH}} - \underbrace{\frac{1}{2} R_{TE} I^2}_{Q_J} \tag{2}$$

The energy balance equation of the cold and hot side of TEM can be defined as [14, 15]:

$$h_{TE} A_{TE} (T_a - T_c) = S_{TE} I T_c - K_{TE} (T_h - T_c) - \frac{1}{2} R_{TE} I^2 \tag{3}$$

$$h_{TE} A_{TE} (T_h - T_a) = S_{TE} I T_h + K_{TE} (T_h - T_c) - \frac{1}{2} R_{TE} I^2 \tag{4}$$

where *h* is the heat transfer coefficient, *A* is the area of TEM and *I* is operating current.

2.2 Log Mean Temperature Difference (LMTD)

The log mean temperature difference (LMTD) is a common approach that used in heat exchanger calculations. Since TE cooling system works like heat exchanger, this method is applicable to analyse the temperature of the system. Compared with arithmetic mean temperature method, LMTD method able to make prediction with better accuracy [16]. LMTD can be defined as:

$$LMTD = \frac{[T_w - T(x)] - (T_w - T_i)}{\ln\left[\frac{T_w - T(x)}{(T_w - T_i)}\right]} \tag{5}$$

where T_w is the wall temperature, x is the position of the fluid in duct and T_i is the inlet temperature of fluid. However, LMTD method can be applied when the overall heat transfer coefficient, $\bar{h}$ and specific heat, C_p of the working fluid are assumed to be constant throughout the duct.

3. Methodology

A simple TE cooling system that is utilized for this study is shown in Figure 2. The square duct has 9.3 cm × 9.3 cm inlet and outlet cross sectional areas and its characteristic length is 55 cm. Three pieces of TEMs (TEC1-12730) were placed on the top of the duct. The hot side of the TEMs are directly in contact with the ambient environment. A few assumptions were used in this study:

- The side walls of the TE Cooling System were adiabatic;
- The air flow in the duct is assumed to be laminar and fully developed;
- When electric current supplied to the TEMs, the plate of the duct is assumed to have constant surface temperature as the cold side of TEMs;
- Ambient air is drawn in directly to the system, hence $T_i = T_a$. Thermophysical properties of air were shown is Table 1.

Table 1
Thermophysical properties of air

Density (ρ), kg.m^3	Dynamic Viscosity (μ), kg/ms	Thermal Conductivity (k), W/m.K	Heat Capacity (C_p), J/kg.K
1.225	1.7894×10^{-5}	0.0242	1006.43

Based on the assumptions, internal forced convection with non-circular cross-sectional scenario is applied to study the outlet temperature of TE Cooling System by using LMTD equation (5) can be rewritten as follows:

$$T_o = T_s - (T_s - T_i)e^{-\frac{\bar{h}PL}{\dot{m}c_p}} \quad (6)$$

where T_s is the surface temperature of cooling panel, $\bar{h}$ is the average heat transfer coefficient of air P is the inlet perimeter, L is the characteristic duct length; $\dot{m}$ is the mass flow rate and c_p is the specific heat of fluid. The Reynold Number (Re) and Nusselt Number (Nu) can be defined as:

$$Re = \frac{\rho V x}{\mu} \quad (7)$$

$$Nu = \frac{\bar{h} \cdot D_H}{k} \quad (8)$$

For laminar forced convection flow in ducts, Shah and London [17] found that the Nu was affected by the aspect ratio (A.S.) of cross sectional area. If the duct A.S. is 1, Groppi and Tronconi [18] reported that Nu is 2.98.

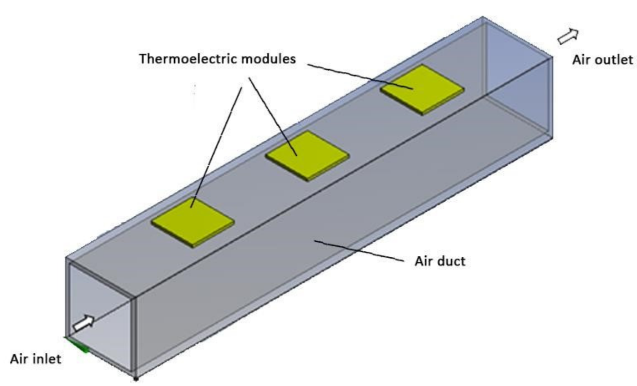


Fig. 2. Configuration of TE Cooling System.

The internal parameters of TEM, such as Seebeck coefficient (S_{TE}), thermal conductivity (K_{TE}) and resistivity (R_{TE}) are not available in the manufacturer datasheet. So a methodology that was proposed by Palacios *et al.* [19] was used to estimate these parameters. Malaysia ambient weather data that is available in the literature of Irshad *et al.* [12] literature is extracted by using WebPlotDigitizer These data are used as an input to study the air temperature reduction capability of the TE cooling for different operating currents and inlet air velocities. All the results were tabulated and discussed in the next session. A subroutine was written in MATlab environment to do the parametric studies.

4. Results and Discussion

4.1 Determination and validation of internal parameters of TEM

Table 2 showed the performance specification of TEC 1-12730. With these available information, the Seebeck coefficient (S_{TE}), thermal conductivity (K_{TE}) and resistivity (R_{TE}) of TEC 112730 were estimated and they are tabulated in Table 3. These estimated internal parameters were validated against the performance curves available in the manufacturer datasheet and is shown in Figure 3. At 6 A the comparison showed a maximum of 5.1% discrepancy, whereas at 12 A, the maximum discrepancy is 3.6%. Moreover, the cooling capacity increases as the operating current increases.

Table 2
Test condition provided in manufacturer.

Performance specification from manufacturer datasheets				
T_h, K	Q_{max}, W	ΔT, K	I_{max}, A	V_{max}, V
323	282	79	30.5	17.8

Table 3
Estimated internal parameter of TEC1-12730.

Estimated internal parameters of TEC1-12730		
S_{TE}, V/K	R_{TE}, Ω	K_{TE}, W/m²K
0.0405	0.5208	2.298

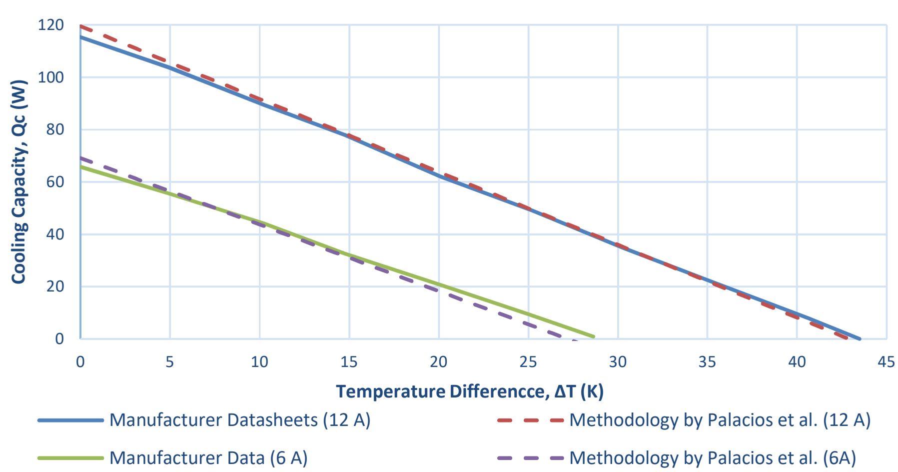


Fig. 3. Comparison of performance curve.

4.2 Effect of Ambient Condition and Operating Current on TE Cooling System

Hourly average ambient temperature ($T_{a,avg}$) from 8:00 am of Day 1 to 11:59 pm of Day 2 is used to study the effect of operating current on TE cooling performance. Figure 4 shows the hourly temperature reduction of the system at each current level (5 A, 6 A and 7 A). Regardless of the operating current, the temperature reduction is the highest at around 3 pm and the lowest is at 10 pm during night period. At 5 A, the temperature reduction ranged between 0.894°C to 2.314°C; at 6 A, the temperature reduction achieved up to maximum 2.45°C; and at 7 A, the temperature reduction ranged from 0.725°C to 2.181°C. Thus, for the considered weather conditions and at 0.1 m/s flow rate, 6 A is the optimum operating current as it has resulted the maximum temperature reduction. These results are in good agreement with some similar studies [8, 13, 20] whereby as the current further increased after the optimum level, a greater amount of Joule heat is created within the TEMs that offset the Peltier cooling of TEMs. As a result, the cold side temperature rises and causes the temperature reduction decreased drastically. Hence, increasing current does not necessarily increase the cooling performance of the TE Cooling System.

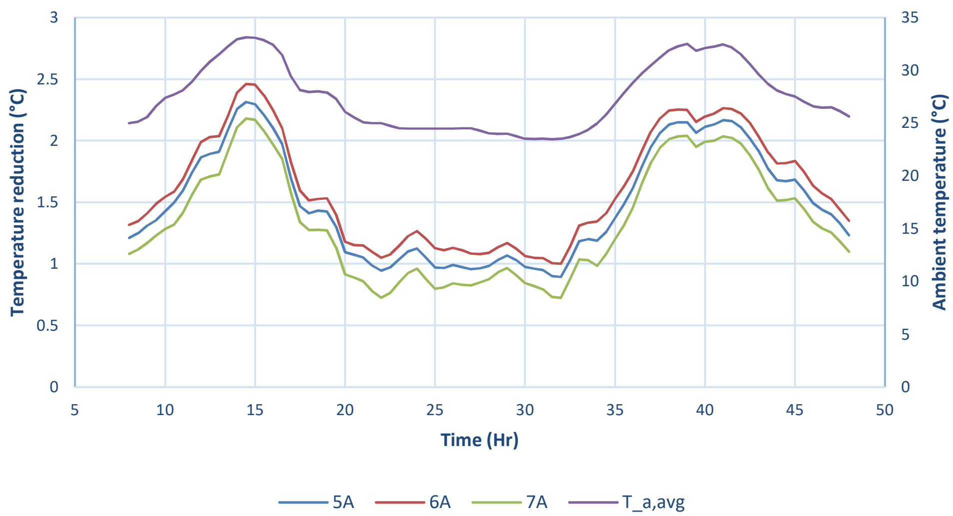
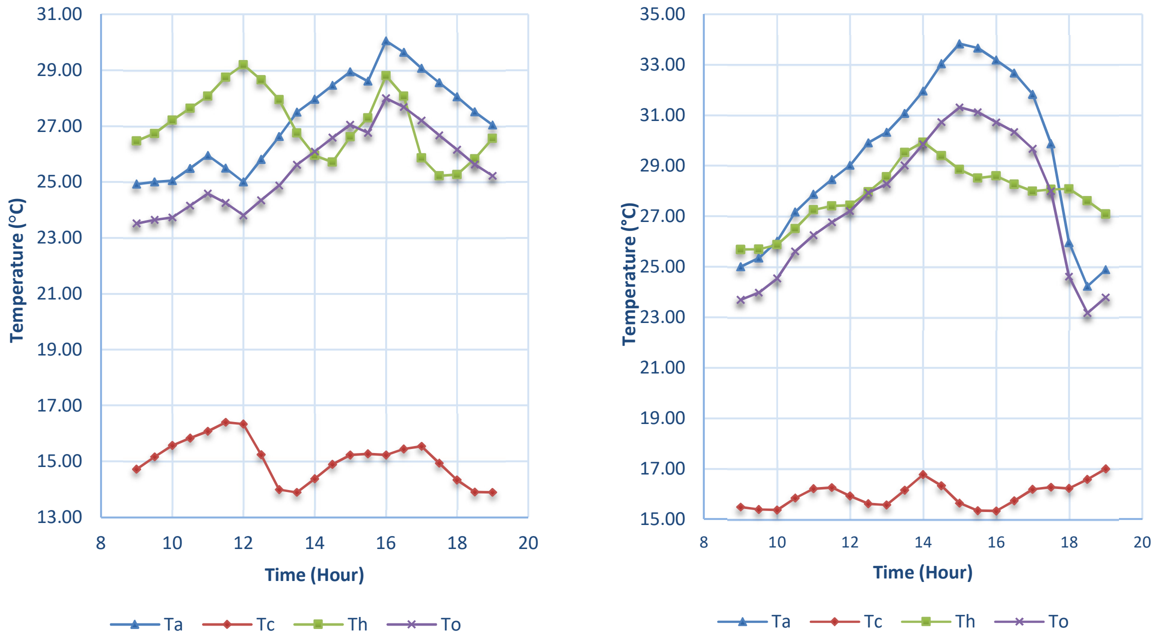


Fig. 4. Hourly temperature reduction of TE cooling system at various operating currents (V_{air} = 0.1 m/s).

Ambient temperature is not at one control and it changes due to different reasons. Hence, it is important to study the impact of daily ambient temperature on the performance of the TE cooling system. In this study, the operating current and air flowrate are designed to be 6 A and 0.1 m/s, respectively. The ambient temperature data for two days, which recorded from 9am to 7pm were obtained from the literature of Irshad *et al.* [12]. Figures 5 (a) and (b) indicate the ambient temperature (T_a), cold side temperature (T_c), hot side temperature (T_h) and outlet temperature (T_o) on Day 1 and Day 2, respectively. As shown in the figures, the highest temperature reduction was found during 3 to 4 pm in both days and the maximum reduction reached up to 2.05°C in Day 1 and 2.47°C in Day 2. The maximum temperature reduction of the system was greater in Day 2 compared to Day 1 due to the higher ambient temperature, and thus the TEMs able to absorb greater amount of heat from the ambient air. This finding justified that the temperature reduction of TE cooling system is changing daily even though the system was running with the same current and is in line with the study of Irshad *et al*., [12] and Cheng *et al*., [19].



(a) **(b)**

Fig. 5. Hourly temperature reduction of TE Cooling System in **(a)** Day 1 and **(b)** Day 2 (V_{air} = 0.10 m/s; I = 6 A).

In this study, the effect of air flowrate was investigated at constant ambient temperature and operating current (T_i = 27°C; I = 6 A). Figure 6 shows the results of outlet temperature and temperature reduction of TE cooling system under different inlet air velocity by implementing equation (6). Results showed that outlet temperature of TE cooling system increases as the inlet air velocity increases. At 0.1 m/s velocity and onwards, outlet temperatures increased by smaller values with exponential effect. As the inlet air flows at greater velocity, the cooling capacity generated by the cooling panel becomes difficult to be captured by the air, and eventually the cooling effect diminished. Thus, selecting the air flow rate by referring to the ASHRAE Standard is important when operating the TE cooling system in order to fully utilize the cooling effect of the system and maintain the thermal comfort of the occupants.

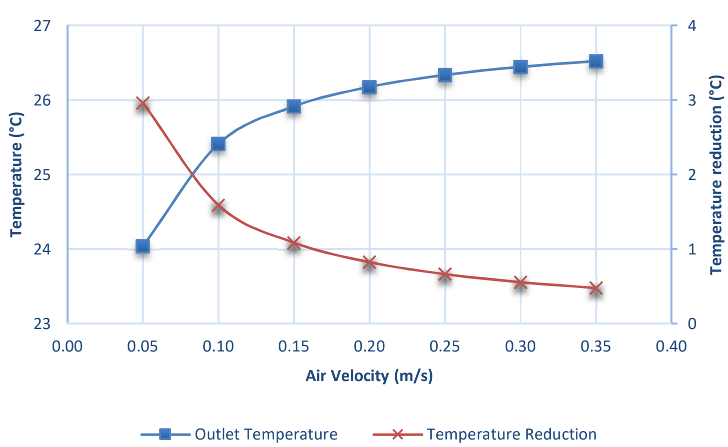


Fig. 6. Variation of outlet temperature with different inlet air velocity (T_a =27°C; I = 6 A)

4. Conclusions

In this study, a single square duct TE cooling system which consists of three TEMs was designed. The ambient air that flows in the duct of the TE cooling system was assumed to be laminar and fully developed flow. Analysis with different input conditions indicated that LMTD method is applicable to study the outlet temperature of the TE cooling system. The presented results in this paper showed that this system strongly depends on the factors such as operating current level, ambient condition and the inlet air velocity. At different operating current levels, the system has shown different temperature reduction. At the considered conditions the overall temperature reduction of the TE cooling system achieved the maximum value at 6 A operating current. Increasing the operating current level does not necessarily improve the cooling performance of the system because the Joule heat created within the TEMs will offset the cooling effect of the system once the operating current exceeded the optimum level. Ambient temperature is changing daily, and this factor has a great impact on the TE cooling system. The presented results showed that TE cooling system reduce a greater amount of temperature on Day 2 compared to Day 1 due to the higher ambient temperature. Lastly, the higher the inlet air velocity, the lower the temperature reduction. As the air flows in a greater flow rate, the air in the duct will have difficult to capture the generated cooling capacity from the TEMs.

In conclusion, the highlighted factors in this study should be considered during the operation of TE cooling system. Since the ambient temperature is unable to manipulate, thus controlling the operating current and air flowrate at optimum level by referring to standard of ASHRAE is necessary to fully utilized the cooling effect of TE cooling system as well as maintain the thermal comfort of occupants.

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