An Experimental and Theoretical Study of Forced Convection from a Peltier Thermo-electric Cooling

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Abstract. An experimental and theoretical study for heat transfer through thermoelectric cooling system in this paper was presented. An experimental work was conducted to evaluate the performance of a thermoelectric module fitted to a sunflower heat sink with a similar sized heat source. The experimental investigation was done to evaluate the effect of TE input voltage, flow rates of cooling air and heat source (heating element) power input on the performance of a thermoelectric cooling system. Four low heating load (1.7, 2.4, 3.6 and 5 W) were used and hot side was fitted to a sunflower heat sink with forced convection. Experimental results show that the increasing of cooling air flow rates improves system performance, while increasing in applied TE voltage leads to deterioration it. The COP\textsubscript{max} obtained is about 4.7 at 2V TE voltages and 5W heating load, and then decreased sharply as voltage further increased and reaches 0.13 at 12V. The results of the current study show that all Thermo-electric Cooling system recorded temperatures increase with increasing in heating load at a constant TE voltage and air flow rate. In addition to that the T\textsubscript{c} decreases and T\textsubscript{h} increases with the increment of input voltage and that can lead to increase of the air temperature passing over heat sink. TE performance is highly affected by air flow rate. The theoretical result validated experimentally and shows an acceptable agreement between them.

Keywords: Thermo-electric cooling, Peltier, sunflower heat sink, forced convection

1. Introduction
Although the process of direct conversion of electrical potential difference to a temperature gradient phenomenon has been known since the discovery of the Peltier effect in 1834, however these devices became commercially available in the 60’s with the development of advanced semiconductors. Thermoelectric modules are solid-state method of heat transfer through dissimilar semiconductor materials that require a heat exchanger to dissipate heat utilizing the Peltier Effect [1]. In contrast to conventional heat pumps that transfer the heat using working fluid and moving parts, TE module transmits the heat without using any of them so it is referred to as “a sold-state energy conversion device”. Thermoelectric module consists of a set of thermocouples, which are electrically
connected in series and parallel thermally, that made from cubes of semiconductor materials (usually Bismuth and Telluride) inserted between two ceramic plates [2].

During operation, a DC current is applied to thermoelectric system, the current flowing through the semiconductors to create heat transfer and a temperature differential across the ceramic surfaces, one surface cools and the other heats up, as shown in figure 1 (the direction of the current determines which side cools). On the cold side heat is absorbed from the surroundings and rejects it on the hot side [3,4].

![Figure 1 Schematic description of the TE module [5].](image)

Many researchers have studied the different application fields of TEC. Riffat et al. [6] conducted an experimental study aimed to improve the performance of TE refrigeration system by using heat pipes and a PCMs. Murat and Fatih [7] investigated experimentally the effect of water flow rates and TE voltages on performance of minichannel water cooled-TE refrigerator system. The higher COP obtained was 0.23 in the water flow 1.5 L.min⁻¹.

Tan and Zhao [8] introduced a prototype of cooling system consist of a TE module integrated with PCM heat storage unit for space cooling. Al- Rubaye et al. [9] experimentally evaluated the performance of a portable TE- water cooling system. The effect of TE applied voltage and the speed of the cooling fan was studied. Mirmanto et al. [10] experimentally investigated the performance of thermoelectric cooler box with different positions of the thermoelectric. They used different positions for the thermoelectric which were at the top, on the wall and on the bottom. And they found that the best position of the thermoelectric was on the side wall.

Liu et al. [11] designed and experimentally investigated the performance of the TE water generator from humid atmospheric air by using two TECs. The results showed that the amount of condensed water increases with increasing relative humidity and airflow rate. Yao et al. [12] conducted an experimental study to investigate the effect of designing and operating parameters on the dehumidification rate of thermoelectric dehumidifier (TED).

Some previous studies were focused on thermoelectric [6,7], electronic cooling [13,14], space or water cooling [15, 8, 9], dehumidifiers [11,12] and fresh water production [16,17] etc.

Some parameters such as TE current, flow rates of cooling air and heat source power input have an effect on the performance of a TEC system. Therefore, there is a need to investigate all these parameters to improve the performance of a TEC system. The current work is aimed to study the effect
of these parameters. The previous studies did not investigate all these parameters for the same case. In order to validate a mathematical model, experimental tests were done. For this purpose, a test rig was built and tested.

2. TEC System Modeling

A simplified steady-state energy equilibrium model has been used in this study in order to evaluate the TEC system theoretical performance. In this analysis, four heat effects were defined, and they are Peltier cooling Eq. (1), Peltier heating Eq. (2), Joule heat Eq. (3), and Fourier heat Eq. (4). Joule Heat is generated by the passage of an electric current through a substance. Fourier heat occurs as a result of thermal conductivity during a material [18].

\[ Q_{PC} = \alpha IT_c \] (1)
\[ Q_{ph} = \alpha IT_h \] (2)
\[ Q_J = I^2R \] (3)
\[ Q_{CON} = K(T_h - T_c) \] (4)

It is well-known that half of Joule heat is transported from each surface (cold and hot), so the heat absorbed at the cold side Eq. (5) and that dissipated at the hot side Eq. (6) can be found by compiling the equations given above [18].

\[ Q_c = \alpha IT_c - \frac{1}{2} I^2 R - K(T_h - T_c) \] (5)
\[ Q_h = \alpha IT_h + \frac{1}{2} I^2 R - K(T_h - T_c) \] (6)

where \( Q_c \) and \( Q_h \) are the heat absorbed by the cold side of the thermoelectric and the heat transfer rate flowing out from the hot side of the thermoelectric respectively. \( \alpha \) is the Seebeck coefficient, \( I \) is the electric current, \( K \) is the thermal conductance. \( T_c \) and \( T_h \) are the temperature of the cold and hot side of the TE respectively.

The electrical power supply and coefficient of performance (COP) can be calculated by Eqs. (7) and (8) respectively [18].

\[ W = \dot{Q}_h - \dot{Q}_c = \alpha I(T_h - T_c) + I^2 R \] (7)
\[ COP = \frac{\dot{Q}_c}{W} \] (8)

The module Seebeck coefficient (\( \alpha \)), module electrical resistance (\( R \)) and thermal conductance (\( K \)) can be calculated from Eqs. (9), (10) and (11) respectively [8].

\[ \alpha = Na_{m} \] (9)
\[ R = \frac{4\pi^{2}1\sigma}{Af} \] (10)
\[ K = \frac{\epsilon Af}{l} \] (11)

where \( a_{m} \) is Seebeck coefficient of a thermocouple and its calculated from Eq (12), \( f \) is TE module packing fraction. Electrical resistivity of TE material (\( \sigma \)) and TE material thermal conductivity (\( \epsilon \)) can be computed using operation parameters (\( Q_{max} \), \( \Delta T_{max} \), and \( I_{max} \)) which available in thermoelectric technical specifications data sheet [8].

\[ \alpha_{m} = \frac{Q_{max}(T_h-\Delta T_{max})}{NT_h^{2}l_{max}} \] (12)
\[ \sigma = \frac{Af(T_h-\Delta T_{max})^{2}}{2T_h^{2}l_{max}^{2}} \frac{Q_{max}}{N_{T_h}^{2}l_{max}^{2}} \] (13)
\[ \epsilon = \frac{I(T_h-\Delta T_{max})^{2}}{AfT_h^{2}} \frac{Q_{max}}{\Delta T_{max}} \] (14)
3. Test rig Description
The main parts of the test rig used in this study are shown schematically in figure 2. Including: a heat source (load), a thermoelectric module, aluminum heat sink, cooling fan with duct and three power supplies.

![Figure 2 Schematic diagram of the main parts of TEC system.](image)

The TE module is inserted between a conventional sunflower heat sink and a heat source (load). The heating element (heat source) is a DC heater has a cylindrical shape of 42mm diameter (shown in figure 3.a)
To distribute the heat from heat source evenly over TE cold side, an aluminum block is crammed between them. A TE model TEC1-12706, has dimensions of 40 mm × 40 mm × 3.8 mm and technical specifications in table 1, was used in this study. (figure 3.b).
Heat absorbed at the cold side should be removed from the hot side as much as possible, for this purpose an aluminum sunflower heat sink (shown in figure 3.c and details are listed in table 2) with an axial flow ventilating fan were used. The fan is located inside a PVC (95mm diameter, 150mm high) air duct. The heat sink was pasted with TE hot side using thermal grease to reduce the contact thermal resistance. Three DC power supplies model (1505TA) were used as the source of power to heating element, TE module and cooling fan.
4. Experimental Procedure
An experimental setup was constructed and tested in laboratory conditions with ambient temperature 30°C and the humidity of 53%. The experiments were carried out for 30 minutes and the temperature of the hot and the cold sides of TE were measured every 5 s. The measured parameters in the experiment are voltage and current of (heat source, thermoelectric module, cooling fan), temperatures of (cold side, hot side of TE, inlet and outlet temperatures of the cooling air from duct) and cooling air speed.

Four separate K type thermocouples with an uncertainty ±0.5°C connecting with four channel temperature meter model (SDL200) were used to determine the inlet and outlet temperatures of the cooling air, the cold and hot side temperatures of the TEC. A multimeter model (DT-9205D) was used to measure currents and voltages in the experiment. Speed of air leaving the duct was measured using a digital anemometer model (GM8901).

Experimental parameters are presented in Table 3. Exp. 1, Exp.2, Exp. 3 and Exp. 4 are used to show the effect of heating load, Exps. 4, 5, 6,7,8,9 are used to show the effect of TE input voltage and Exps 9,10,11,12 are used to compare the effect of cooling air flow rate.
### Table 3: Experimental parameters

| Number of exp. | Heating load | TE input voltage | cooling air flow rate |
|---------------|--------------|------------------|----------------------|
| EXP.1         | 1.7 W        | 12 V             | 0.0337 kg/s          |
| EXP.2         | 2.4 W        | 12 V             | 0.0337 kg/s          |
| EXP.3         | 3.6 W        | 12 V             | 0.0337 kg/s          |
| EXP.4         | 5 W          | 12 V             | 0.0337 kg/s          |
| EXP.5         | 5 W          | 2 V              | 0.0337 kg/s          |
| EXP.6         | 5 W          | 4 V              | 0.0337 kg/s          |
| EXP.7         | 5 W          | 6 V              | 0.0337 kg/s          |
| EXP.8         | 5 W          | 8 V              | 0.0337 kg/s          |
| EXP.9         | 5 W          | 10 V             | 0.0337 kg/s          |
| EXP.10        | 5 W          | 10 V             | 0.0195 kg/s          |
| EXP.11        | 5 W          | 10 V             | 0.024 kg/s           |
| EXP.12        | 5 W          | 10 V             | 0.0285 kg/s          |

In order to ensure the reliability and accuracy of the experiments, the following measurement procedures were employed:

1. All the experiments were repeated two times and the data were presented using the average value of them taking into consideration the standard deviation.
2. The electric current to the thermoelectric module was provided by a high precision constant current power source.
3. Heating element was turned on for 5 min to ensure it reaches a stable state before testing.
4. Door and windows of the room were closed to ensure minimum air movement during the experiments.
5. The temperature of the hot and the cold sides of TE were measured every 5 s for 30 min in each experiment and given as the average values over the duration of the experiments.
6. To minimize heat loss from TE module to the ambient environment, a thermal insulation was provided at the bottom and sides of the assembly.

### 5. Results and Discussion

Figure 4 shows the time dependence of $T_h$, $T_c$ and also the cooling air temperature leaving the duct ($T_{air,out}$) for different loads (heating element). The experiments were done at a constant TE input voltage of 12 V and constant cooling air flow rate.

From this figure, it can be seen that at low heating load ($<$3.6 W) the $T_c$ decreases sharply at the beginning and then it continues to decline but less sharp. At heating load 1.7 W, $T_c$ decreased from 31°C to 11°C at the first 300 s, and from 11°C to 6.4°C at the other 1200 s. At 2.4 W, $T_c$ decreased from 30°C to 13°C at the first 200 s, and from 13°C to 7.7°C at the other 1300 s. At heating load ($>$3.6 W) the $T_c$ take the same behavior where its decreases sharply at the first seconds and then it gets nearly constant. Unlike $T_c$, $T_h$ increases abruptly at the beginning of operation and then becomes constant as well.
Figure 4 shows the variation of $T_c$, $T_h$, and cooling air temperature with heating load. From this figure it can be concluded that, all the temperatures increase with increasing in heating load. $T_c$ increased from 9.98°C at load 1.7W to 11.46°C at 2.4W. Further augmentation in heating load leads to the increasing in $T_c$ become more clearly due to direct connect of heating element to cold side of TE, where its increasing from 11.46°C to 15°C and to 19.95°C as load increased from 2.4 W to 3.6W and 5W respectively. The same demeanor can be noticed on $T_h$ and cooling air temperatures, where $T_h$ increased from 47.8°C to 52.3°C and air temperature increased from 31.6°C to 33.2°C as heating load increased fro1.7W to 5W respectively.

Figure 5 shows the variation of $T_c$, $T_h$, and cooling air temperature with heating load. From this figure it can be concluded that, all the temperatures increase with increasing in heating load. $T_c$ increased from 9.98°C at load 1.7W to 11.46°C at 2.4W. Further augmentation in heating load leads to the increasing in $T_c$ become more clearly due to direct connect of heating element to cold side of TE, where its increasing from 11.46°C to 15°C and to 19.95°C as load increased from 2.4 W to 3.6W and 5W respectively. The same demeanor can be noticed on $T_h$ and cooling air temperatures, where $T_h$ increased from 47.8°C to 52.3°C and air temperature increased from 31.6°C to 33.2°C as heating load increased fro1.7W to 5W respectively.

TE behavior changes with applied voltage on it, so experimental tests have been performed to show the effect of TE input voltage on its performance. These tests were conducted by varying input voltage from 2V to 12V by 2V interval each time, heating load and cooling air flow rate kept constant during these experiments.
Figure 6 shows trends of \( T_c \), \( T_h \) and air temperature with time for different input voltage. From this Figure, it is clear that at all voltage levels, \( T_c \) shows the same behavior that was previously concluded where its decreases quickly at the first seconds and then it gets nearly constant. Unlike to \( T_c \), \( T_h \) increased with the increment of input voltage and as a result of this, the air temperature passing over heat sink will also increase as shown in Figures 6, 7. \( T_c \) decreased from 26.2°C to 8.45°C, \( T_h \) and air temperature increased from 31.29°C and 30.46°C to 46.59°C and 36.6°C when voltage increased from 2V to 12V respectively. As \( T_c \) decrease with voltage and \( T_h \) increase, so the TE side’s temperature gradient (\( T_h-T_c \)) and heat rejection \( Q_h \) shows an increasing function with voltage, as shown in Figure 7. where \( Q_h \) increased from 2.34W at 2V to 39.66W at 12V.

![Figure 6 Trends of \( T_c \), \( T_h \) and air temperature with time for different input voltage.](image)

![Figure 7 Effect of TE input voltage on system temperatures and heat rejection.](image)

Figure 8 shows the variation of COP values with input voltages for different system heating loads. This Figure shows that COP of TEC deteriorates with increasing in its voltage. The COP\(_{\text{max}}\) obtained is about 4.7 at 2V and 5W heating load, and then decreased sharply as voltage further increased and
reaches 0.13 at 12V. Reduce the value of heating load degrade COP of system, where it decreases from 4.7 to 3.33 and 1.16 as load decreased from 5W to 3.6W and 1.26W respectively.

\[
\text{Figure 8 Variation of COP values with input voltages.}
\]

To investigate the effect of cooling air flow on performance of TEC, van speed changed by varying its input voltage and air speed is then measured using digital anemometer model (GM8901). Cooling air flow rate \( \dot{m}_{\text{air}} \) can be calculated from:

\[
\dot{m}_{\text{air}} = \rho A_{\text{c}} v_{\text{air}}
\]

Heat dissipated from hot side \( Q_h \) can then be calculated from:

\[
Q_h = \dot{m}_{\text{air}} C_p,\text{air} (T_o - T_i)_{\text{air}}
\]

Where \( C_p, T_o, T_i \) is specific heat, outlet and inlet duct air temperatures respectively.

The \( T_h \) time dependence for different air flow is shown in Figure 9. It can be seen from this Figure that \( T_h \) follows the same behavior previously observed as it increases sharply in the first 150 seconds and then becomes almost constant for all flow rates. Also, it is clear that the hot side temperature \( (T_h) \) of thermoelectric module decreases as the air flow rate used in the air duct heat sink increases, where its decreased from 45.1°C at flow rate 0.0195 kg/s to 39.36°C at flow rate 0.0337 kg/s as shown in figure 10.
Figure 9 Time dependence of recorded $T_h$ at different air flow rate.

Figure 10 shows the variation of $T_h$, $T_c$, $T_{air}$, $Q_h$ values with cooling air flow rate. At a lower air flow rate the air speed passes over the heat sink is very low so it has enough time to receive the heat from the TEC module. It can be noted from Figure 8 that all the temperatures measured in these tests decrease with increasing flow rate, but the amount of decreases in $T_h$ is more pronounced than $T_c$ and $T_{air}$. The inlet duct air temperature remains relatively constant (equal to room temperature) across the time during the experiment and the exit air temperature decreases with flow rate, the air temperature difference $(T_o - T_{air})$ in Eqn. (16) also decrease with flow rate. However, it can be noted that $Q_h$ increases by increasing the flow rate.

To validate the experimental data obtained from the tests, it's compared with the theoretical results from a mathematical model. Figure 11 shows the theoretical and experimental amounts of $Q_h$ and COP. The $Q_h$ was calculated theoretically using Eqn. (6) and experimentally using Eqn. (16). This Figure clearly confirms there is a good agreement between the results and there is an acceptable error between them does not exceed 7%.
6. Conclusions
In this study, the effect of some parameters including TE current, flow rates of cooling air and heat source power input on the performance of a thermoelectric (TE) module fitted to a sunflower heat sink and a heat source was investigated experimentally and validated theoretically. Experimental tests were done at different TE voltages, heat source power input and different cooling air flow rates. The result shows that:
1. At a constant TE voltage and air flow rate, all TEC system recorded temperatures increase with increasing in heating load.
2. TE behavior changes with applied voltage on it, the result shows that the Tc decreases, Th increased with the increment of input voltage and as a result of this, the air temperature passing over heat sink will also increase. TE temperature gradient (Th-Tc) and heat rejection Qh shows an increasing function with voltage and COP of TEC deteriorates with increasing in its voltage.
3. Air flow rate has a significant impact on TE performance. Where the increasing in an air flow rate leads to decrease TE temperature difference and increases Qh.
4. Solution of mathematical model shows an acceptable agreement with experimental results.

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