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Design and construction of a cooling system using a Peltier based thermoelectric device.

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ABSTRACT

Improvement of the Coefficient of the thermoelectric cooling system's performance by mitigating the losses in operation is the basis of this research work. Implementing a heat exchanger module and the Peltier thermoelectric module investigates how it helps minimize the thermoelectric cooling system's operating losses. The measured coefficient of performance of the developed single-stage cooling system was 0.285 before adding the heat exchanger and 0.33 after adding the geometrical alternations for the heat exchanger. So, it has increased the coefficient of performance by 15% in this research work. These results are essential to design a cooling system using a Peltier thermoelectric module.

Keywords — Global Warming, Peltier Effect, Coefficient of Performance (COP), Thermoelectric Cooling Systems

1 INTRODUCTION

The thermoelectric module (TEM) utilizes the Peltier effect to produce a heat flux at the junction of two different semiconductor material types [1]. During this process, a direct current (DC) is applied, which causes the created heat to be transferred between the two sides of the thermoelectric module, which creates a hot and cold side [1]. This technology's main disadvantage is the low Coefficient of Performance (COP)[1]. The latest inquiry then focused on improving the COP for thermoelectric cooling systems by developing new materials for thermoelectric module semiconductors, Optimizing module system design fabrication, and Efficiency Improvement of heat exchanger (i.e., heat sink and heat rejector) [1]. The heat absorbed at the cold side and the heat dissipated at the hot side depends on the Peltier coefficient and the current circulating through the semi-conductive material [3],[4]. This paper describes implementing a small-scale thermoelectric refrigerator with a higher performance coefficient and increases efficiency by mitigating the system's operation losses.

2 METHODOLOGY

2.1 Coefficient of Performance (COP)

COP of a thermoelectric cooling system (ε)is defined as the ratio between net heat absorbed at the thermoelectric module's cooling side(Q_c) and the electric power (Q_E) applied to the thermoelectric module[1], [5].

$$\varepsilon = \frac{Q_c}{Q_E} = \frac{\alpha I T_c - k\Delta T - (1/2) I^2 R}{I^2 R + \alpha I T_c} \tag{1}$$

Where ε=the COP of the thermoelectric couple, α =seebeck coefficient of thermoelectric material, I= current, K=thermal conductivity of thermocouple, ΔT=temperature difference between hot & cold end (°C), R=electrical resistivity of the thermocouple.

Using equation 1, we can determine that the COP(ε) is a function of; "Material dimension property" of thermocouple**,** the temperatures of both the hot side and cold side (i.e.T_h, T_c), and the current input (i.e.,I) [1].

2.2 Improvement of Efficiency of the Heat-Exchanger System

The COP will be improved by increasing the T_c and decreasing the T_h[1]. The maximum value for the COP of the thermoelectric effect-based cooling system is around 0.9 – 1.2 [1].The practical value of the COP of a thermoelectric cooling system is lower than the above range because the hot and cold side temperature difference of the thermoelectric module is larger than the difference between the cabinet and the ambient temperatures [1], [3]. .

2.3 Heat Recombination From Hot Side Of The Thermoelectric Module

The thickness of the thermoelectric cooling module TEC1-12705 is 4.0±0.1 millimeters [8]. When it is operating, the hot side's heat starts to move towards the cold side. When this heat recombination occurs, the hot side's heat will be added as an additional heat load. This effect will decrease both the coefficient of performance and efficiency. In this research, a heat block is used in order to reduce the effect of heat recombination. With this heat block, it can change and redirect the heat flow through the thermoelectric module. By using this, it increases the distance between the hot surface and the cold surface of heat-sinks. Also, geometrically altered heat exchanger with trapezoid shapes will further reduce the heat recombination process (Figure 6). Due to the trapezoidal shape of heat exchanger, the heat flux is disturbed and can be caused for an additional reduction in the heat recombination process. This is illustrated by the Figure 6 and the optimum angle for heat exchanger is decided using analyzing the Figure 4.

3 RESULTS AND DISCUSSION

3.1 Selecting The Heat Exchanger Material

Several factors were considered to select the material of the heat exchanger. The material was selected by comparing the characteristics such as heat transfer coefficient, coefficient of thermal expansion, tensile and creep characteristics, corrosion, fatigue toughness, and impact strength to prevent physical pressure etc. The simulation was done using COMSOL Multiphysics. After receiving the simulation results shown in Figure1:(a), selects Aluminum as the heat exchanger material. There is no vast difference between copper and aluminum in heat conduction.

3.2 Selecting The Insulation Material

The material with the lowest thermal conductivity was selected as the insulation material using simulations. Considering the simulation below Figure1:(b), both Polyurethane Foam and Vermiculite are the best options but, Polyurethane Foam was chosen due to the availability.

3.3 Selecting The Heat Sink/Heat Rejecter Material

Aluminum alloys are the most recognized materials used to make heat sinks in the world. Generally, Al alloys 1050 (which have a thermal conductivity value of 229 $Wm^{-1}K^{-1}$, Al alloy 6060 (low stress), 6061, and 6063 are the most commonly used[2], [6]. Copper has excellent heat sink properties. It has twice the thermal conductivity of aluminum, around 400$Wm^{-1}K^{-1}$[6]. Copper is three times as dense and more expensive than aluminum. So, it cannot be extruded into heat sinks[6]. After analysis, Aluminium was chosen as the heat sink material and the heat rejecter; Figure 1: (c). There was only a minor exception between copper and aluminum, the heat sink cost, and the rejecter[6],[7].

3.4 Selecting Perspex To Build The Frame

Acrylic was used to build the frame for insulation. Acrylic has a very low thermal conductivity of 0.2 $Wm^{-1}K^{-1}$ as compared with the other materials.

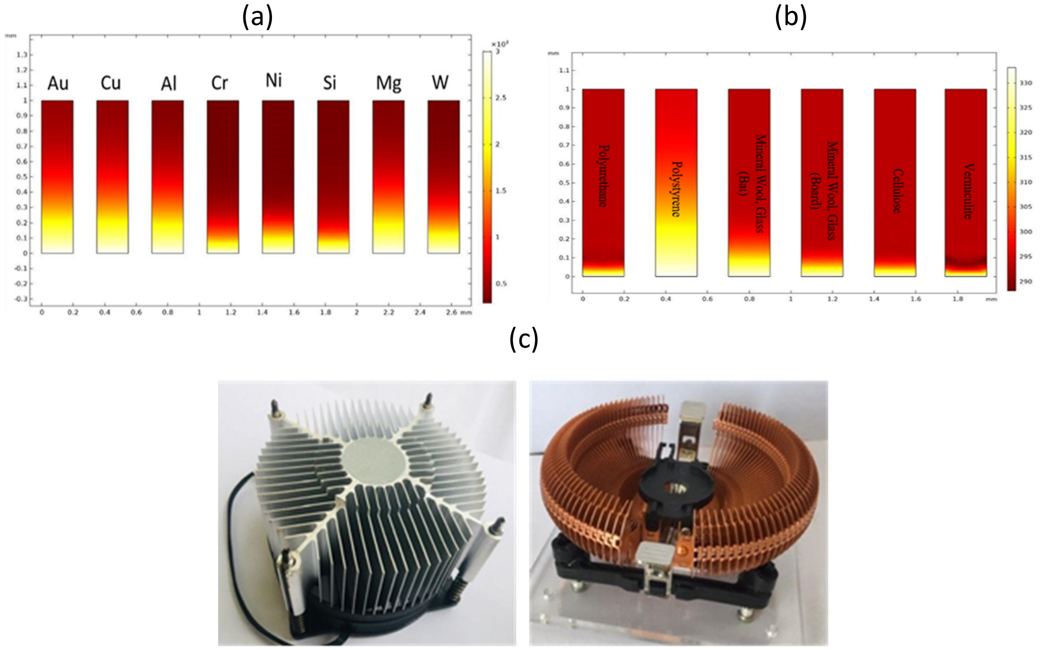
(a)
(b)
(c)

Figure 1: (a) Results of Heat Exchanger Material, (b) Comparison of Insulation Materials, and (c) Heat Sinks used on the hot side and the cold side of the TEM.

3.5 Determining the Voltage Applying to a Single Thermoelectric Element through Simulation

COMSOL Multiphysics was used to simulate the heat separation in a thermoelectric element at different temperatures. For this test, the voltage was increased by $0.05V$, starting from $0.1V$. The voltage change was done in 60 seconds time intervals. Till $0.6V$ and observed that temperatures of both the cold side and hot side of the single thermoelectric element started to swap with each other at $0.3V$; therefore, it was able to conclude that a single thermoelectric element's supply voltage is limited to $0.1V$ as the starting temperature swapping began at the supply voltage value of $0.15V$ Therefore, for the TEM, which has 126 single thermoelectric elements, we should supply a voltage of $12.6V$.

During the practical experiment DC voltage was applied across the thermoelectric module (TEC1-12705) till $13.2V$, we observed that the temperature of the cold side decreasing, but after $13.2V$ the temperature of the cold side raises. It was also observed that temperature drops some amount of time and rises again after varying the voltage. This temperature rise can be described as an effect of Joule heat (QJ). When the current increases, the temperature gradient increases[1], [3]. However, it also increases the Joule heat. In Peltier effect, heat evolved or absorbed at a p-n junction is proportional to current, whereas in Joule's effect heat produced is proportional to the square of current. So, at the beginning stage of current increment, the effect of Joule heat is not significant but, it impacts Cold Side Heat (Qc) when current increases further.

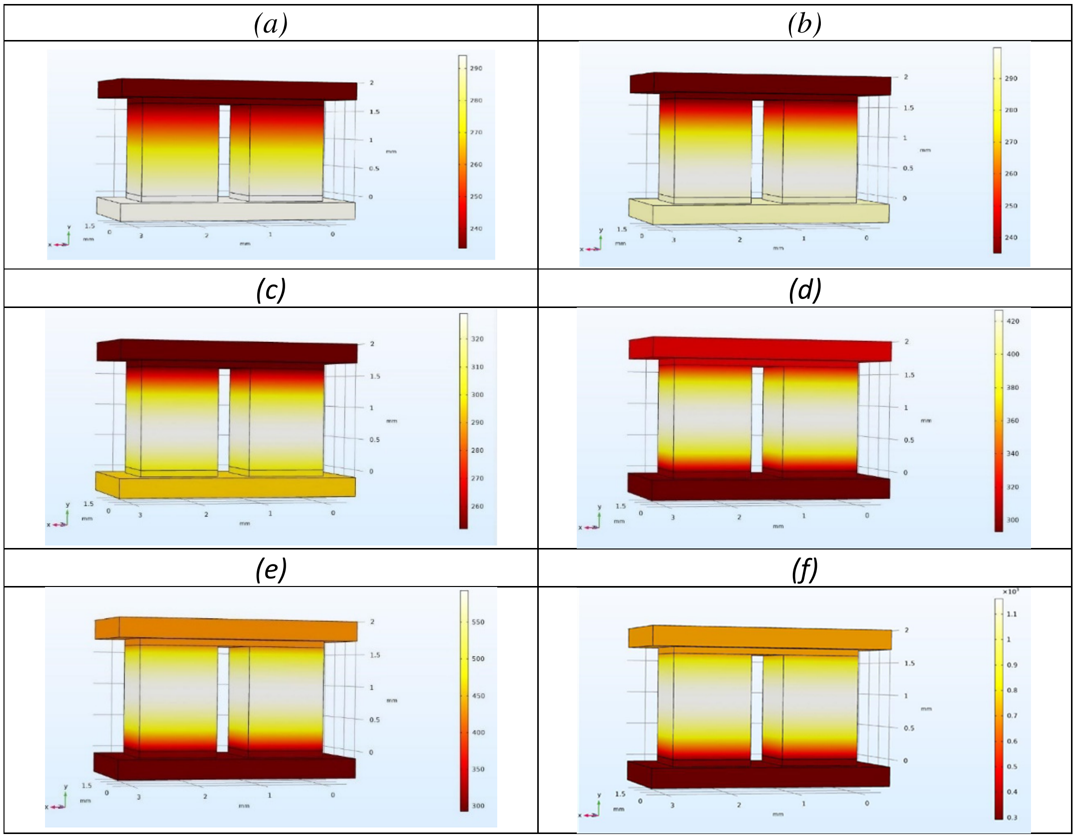

Figure 2 (a)Voltage Testing Simulation is done on a Single Thermoelectric Element at the voltage of 0.1v, (b) 0.15v, (c)0.2v, (d) 0.3v, (e)0.4v, (f)0.6v

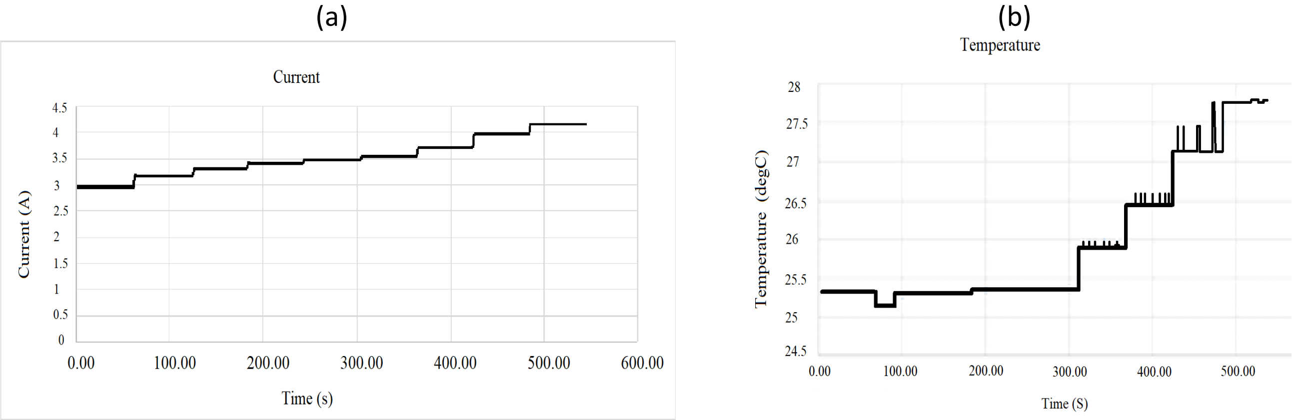

Figure 3(a) Supply direct current to the thermoelectric module concerning time intervals, (b)Respective changes of temperature with respect to the current

3.6 Deciding the height of the Heat Exchanger

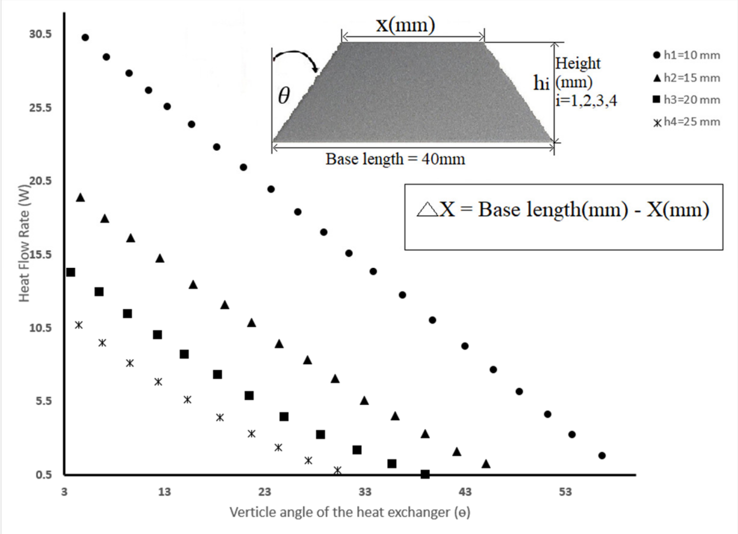

Figure 4: Heat transfer results for the different heights chosen and the heat exchanger's angle variation.

Thickness of the thermoelectric module is 4.0±0.1mm [8]. So, heat separation of the hot side and cold side is done by this small height. As this height is small heat recombination occurs among the hot and cold sides. Two heat blocks can be used to mitigate the heat recombination by increasing the gap between open hot and cold surfaces.

So, to minimize the effect of heat recombination, it must increase the height for the heat block, but this can also reduce both coefficient of performance and the efficiency of the thermoelectric cooling module as material's heat conduction loss increases with the height.

Also, the heat flow rate reduces when increasing the height of the heat block (Figure 4). With these observations, it can be seen that there is a massive difference between the $10\ mm$ heat block and the other blocks of height$15\ mm$,$20\ mm$ and $25\ mm$ respectively. Only 10mm height block can maintain a significant heat flow rate at high vertical angles. 10mm height can reach up to 60º vertical angle with non-zero heat flow rate (Figure 4). Therefore, with the help of this simulation, the heat block with a height of $10\ mm$ was implemented.

3.7 Model Build up And COP Calculation

The heat exchanger's base area should be equal to the thermoelectric module area ($40mm\ x$ $40mm$) as the two heat sinks were combined to each side of the thermoelectric module. When deciding the vertical angle, a trapezoidal shaped heat exchanger was used to reduce heat recombination and was done through a simulation (Figure 6). In the simulation, different vertical angles were considered starting from 0° and examined that heat recombination lines started to shift away from the cold side. When deciding the optimum vertical angle for the heat block (angle of the trapezoidal shape), two main factors should be considered to achieve the maximum COP and efficiency, such as the contact area of the heat block and heat recombination.

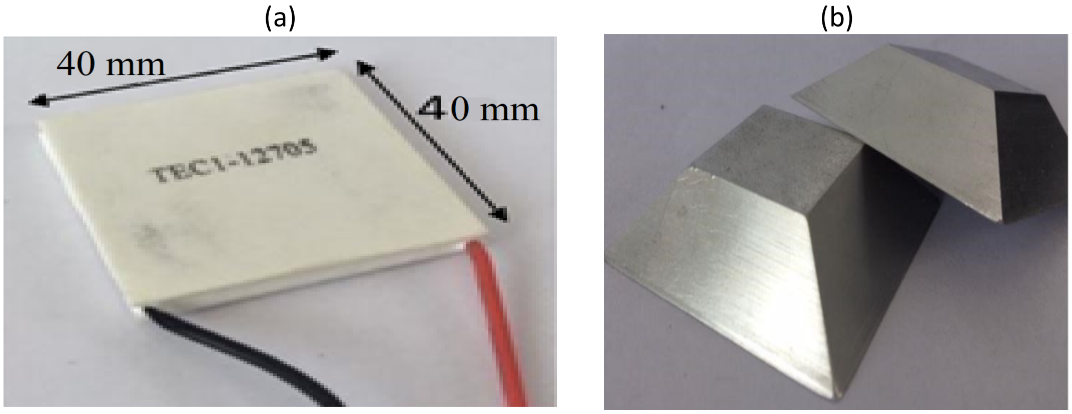

Figure 5(a) TEC-12705 Thermoelectric module, (b) Designed Heat Exchangers using aluminium as the material.

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When increasing the vertical angle of the heat block, the heat recombination decreases (Figure 6). However, when increasing the angle that reduces the heat block's surface area. This causes a decrease in the heat flow rate (heat dissipation) through the heat block. That will again cause the reduction of the COP of the thermoelectric cooling module. On the other hand, increasing the surface area will increase the heat dissipation through the heat block. However, increasing the surface area will reduce the vertical angle and increase the heat recombination in the thermoelectric module, resulting in a lower performance coefficient.

With the height of 10mm heat block it can reach up to 60º vertical angle with non-zero heat flow rate (Figure4). So, to get a sufficient heat flow rate with 10mm height heat exchanger's vertical angle is limited to 45. The aluminum heat exchanger was built using Computer Numerical Control (CNC). The cooling refrigerator was built with Styrofoam as the container's material, Polyurethane foam as the insulation material. The implemented model is shown below.

The specifications for the TEM (TEC1-12706) are as follows. Seebeck coefficient = $0.0129\,VK^{-1}$, Thermal conductivity of the TEM = $0.1815\,WK^{-1}$, Module thermal resistance = 4Ω. Moreover, after measuring the hot side and the cold side temperatures by the Arduino system using three temperature sensors, COP of the single-stage thermoelectric cooling system (before geometrical alterations were done to the Heat Exchanger) was calculated as below using equation (1), (2) and (4). The hot side temperature = 58°C and the cold side temperature = 23°C (temperature of the contained cool water). Therefore, the temperature difference between the hot side and the cold side (ΔT) =35℃.

From equation (1), Qc = 13.1022J and QE = $45.8198J$ therefore $\boldsymbol{\varepsilon = 0.285}$

COP Calculation for Single Stage Thermoelectric Cooling System after Geometrical Alterations for the Heat Exchanger (same thermoelectric module was used here). The temperature of the hot side = 62℃, the temperature of the cold side = 18℃ (temperature of the contained water), Therefore, the temperature difference between the hot and cold sides (ΔT) = 44℃. Using the equations (1); $Q_c = 14.917J$ and $Q_E = 45.637J$ therefore $\boldsymbol{\varepsilon \approx 0.33}$.

However, the Peltier cooler's (TEC1-12706) cold side minimum temperature has taken as the water's minimum temperature at an equilibrium state, which will be a less value if measured by removing the water. If the COP value is calculated using the minimum cold side temperature by removing the water, it would be higher than the obtained values (0.285 and 0.33)

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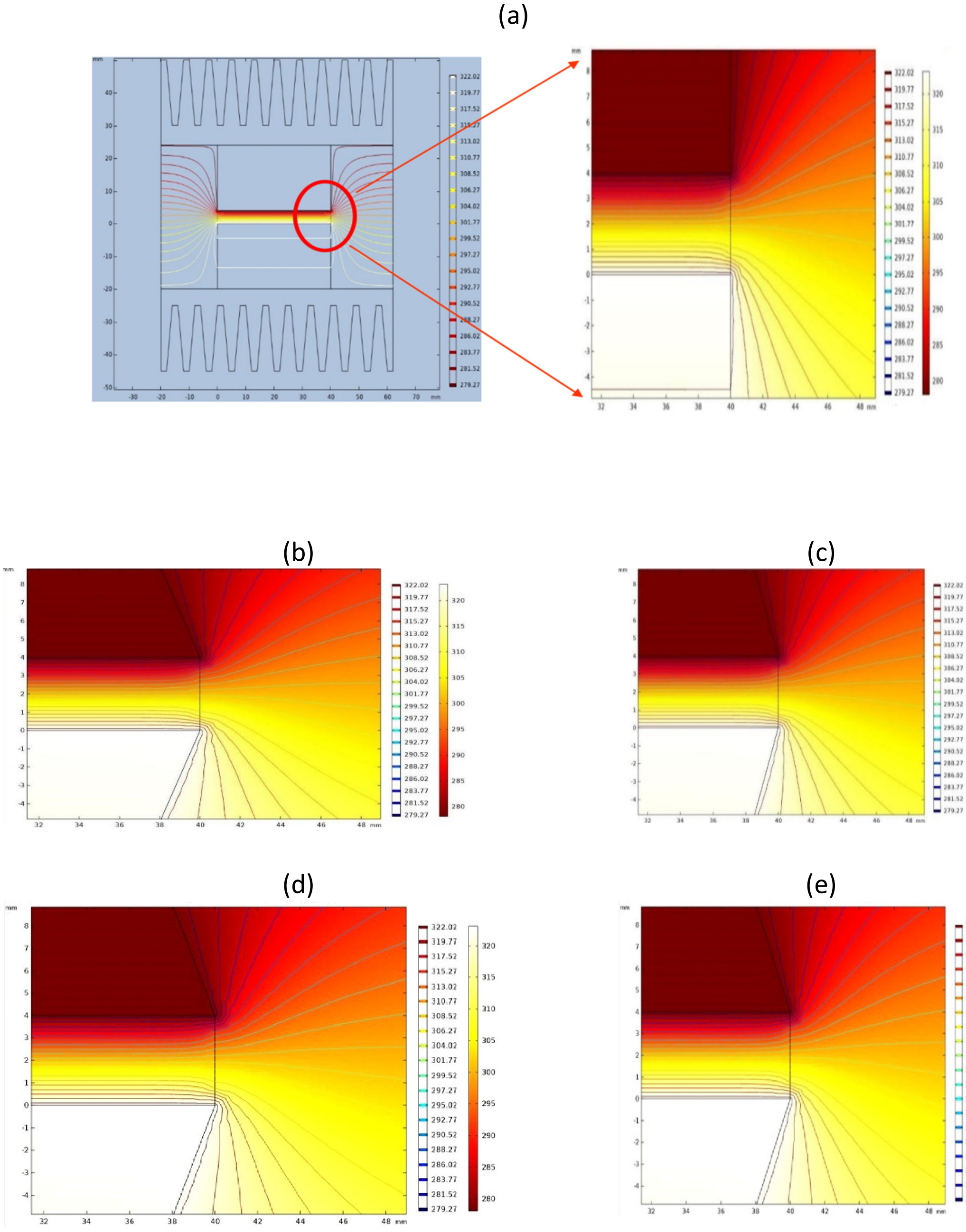
(a)

(b)

(c)

(d)

(e)

Figure6: (a) Simulation of the vertical angles of the aluminium cube with the heat exchanger (Side view-full) and zoomed view at x=40, Δx=0, (b) at x=36,Δx=4 (c) at x=34,Δx=6 (d)at x=32,Δx=8 and (e) at x=30,Δx=10 Where, x is the side length of heat exchanger which is in the opposite side of the thermoelectric module's surface and Δx is the length difference between upper and lower sides of heat exchanger.

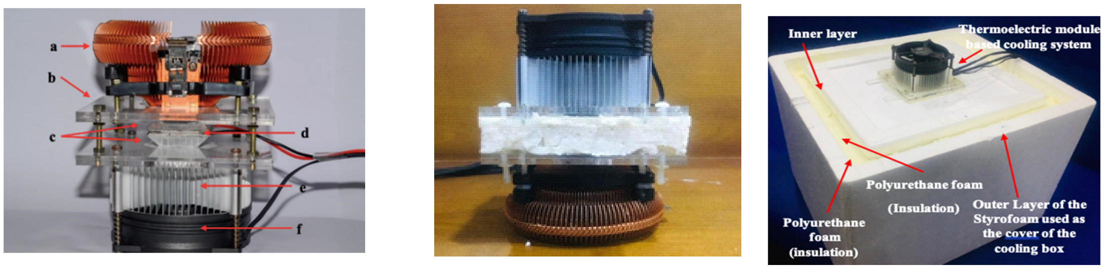
(A) (B) (C)

Figure7:(A) Single-stage thermoelectric module based cooling system [the parts of the systems are (a)Cold side Heat Rejecter, (b)Acrylic structure of the model, (c)Heat exchangers, (d)Thermoelectric module (TEC1-12706), (e) Hot side Heat Sink, (f) Hot side Fan], (B) Insulated cooling systems, (C) An insulated cooling container.

4 CONCLUSION

The COP of the designed single-stage cooling system was 0.285 before adding the heat exchanger and 0.33 after adding the geometrical alternations for the heat exchanger. So, the COP has increased by 15% in this research.

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