EXPERIMENTAL INVESTIGATION OF THERMOELECTRIC COOLING SYSTEM WITH PHASE CHANGE MATERIAL (PCM)

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Abstract:Thermoelectric cooling technology presents evident advantage in solving the climate crisis problemsand beneficial over conventional cooling systems for space conditioning applications. Due to its low energy efficiency, thermoelectric cooler (TEC) consumes more poweras compared to a conventional cooler does with the same cooling capacity. A test experimental set up has been developed to improve the energy efficiency i.e., coefficient of performance (COP)of TEC and work reliability, by introducing suitable PCM with transient temperature and large storage capacity to the cold and hot side sinks for thermal controls with air-forced convection. The optimal thermoelectric cooling performance and desirable input supply of TEC module was experimentally tested and the temperatures at thermal sides of TEC was controlled and maintained below the working ranges. The results of tests conducted show that, attaching PCM to the cold side of TEC improved the COP by 8.57% for the test set up. Further, it also gives the cooling storage capacity, which would be particularly useful in case of power failure. The use of PCM at the hot side of the TEC keeps the temperature at the hot side below the maximum working temperature range of 40-43℃ for much longer time, thereby improving the COP of TEC from 0.58 to 0.685 with percentage improvement of 18.1%. Thus, it demonstrated that the use of PCM could regulate thermal temperatures, improving TEC's performance and work reliability.

IndexTerms **-** Thermoelectric Cooler (TEC), Phase Change Material (PCM), Coefficient of Performance (COP), space conditioning, large storage capacity.

I. INTRODUCTION

Conventional air-conditioning systems are energy intensive devices. Vapour-compression technologies currently dominate the HVAC market, which produces cooling effect by the means of heat removal from space by using refrigerants such as R134a. Although these refrigerants do not have the ozone depleting properties of Freon, nevertheless is a terrible greenhouse gas. The US Department of Energy has proposed cutting-down hydrofluorocarbon (HFC) refrigerants and develop thermoelectric cooling/ heating technology for HVAC equipment in buildings and automobile air-conditioners over the next 20 years [1], as thermoelectric cooling technology presents evident advantage in solving the climate crisis problems. Further, advantages over the conventional vapor-compression cooling includes compact in size, light in weight and high reliability with no mechanical moving parts, no noise and no refrigerant. More importantly can be potentially powered by direct current (DC), suggesting an easy integration with photovoltaic (PV) panels, fuel cells and automobile DC electrical sources [2].

A thermoelectric module (TEM) or thermoelectric device (TED) consists of a bunch of thermoelectric couples wired electrically in series and thermally in parallel, integrated between two ceramic plates, which form the cold and the hot surfaces of the module. Thermoelectric devices (TEDs) have become highly attractive because of their solid-state mechanism that does not require any moving parts, which decreases mechanical failure and does not employ working fluids that are harmful to the environment. As TEDs allows quite precise cooling/heating and power-generating operations demands use in multiple applications unlike the conventional compressor based refrigerator and fuel-based electric generating systems. Thermoelectric coolers (TECs) are highly involved in heating, ventilations and cooling systems (HVAC), bio-technology, medical equipment and electronic cooling devices due to their high manufacturability and reliability in the temperature controlling and stabilizing [2,3].

Thermoelectric technology has made admirable progress in recent years.Laboratory figure of merit (ZT values) have increased several-fold, business has grown significantly, start-ups have emerged and next-generation thermoelectric technology and devices are now appearing in domestic refrigerators, car seats temperature control and electronic cooling devices in significant numbers. However, applying TEDs to domestic space cooling faces much more challenging and remains limited [1,3]. Dominguez *et al.*[4] proved that for each 1℃ the temperature drop between the hot side of TEC and the ambience, increases the COP of TEC in more than a 2.3%.Thus, a Peltier cooler must be designed with heat sink (HS) thermal resistance as small as possible. In recent years,various researchersare working on thermal sides of TECs and proper designing of heat sinks to improve the performance of present TECs, which includes phase change material, thermo-syphonic heat exchanger and micro-channels. For increasing the efficiency of heat sinks, by maximizing the exposed surface area or by using heat pipes to enhance the heat transfer. Alternatively, the heat sink with a large heat storage capacity, which would help to keep the sink temperature low relative to the junction temperature. This latter solution could be achieved by using a phase change material (PCM). PCMs have long been identified as candidates for thermal storage systems, due to the high energy densities (MJ/m^3). A further advantage of PCMs is that heat transfer normally takes place at a constant temperature (the transition temperature). This is appropriate for thermoelectric cooling, and refrigeration units, especially for those that require precise temperature control [5]. The principle of using PCM on thermal sidesof TECs, the PCM absorbs energy first as sensible heat and then as latent heat, when the phase change temperature is reached. During this period, the temperature remains constant at the TEC junctions until the phase change is completed.

PCMs are available with a large range of phase change temperatures, and thus can be utilized on both the cold and hot junctions of a TEC and for a range of applications and environments. By selecting a PCM with suitable transient temperature and large storage capacity, the temperature difference across the thermoelectric module (TEM) would be maintained at a low value, thus improving the performance of the device. Raffit*et al*.[6] investigated conventional heat sink system with an encapsulated PCM (melting at 7°C), gave an improvement in the performance of thermoelectric refrigeration system as well as the cooling storage capability, which would be particularly useful for handling the peak loads, and overcoming losses during door openings and power off periods. Hasan *et al.* [7] studied influence of different PCMs for improving cooling performance of heatsinkfor electronic devices. The experimental results showed that integration of all of the PCMs into the HS improves its cooling performance carried out finned HS with and without PCM under natural ventilation (NV) and forced ventilation (FV) at different heat loads.

Nomenclature			
Cabin Temp	Cabinet air temperature (°C)	$T_{c,\ pcm}$	TEC cold side temperature with PCM (°C)
COP	Coefficient of performance	$T_{c,\ w/o\ pcm}$	TEC cold side temperature without PCM (°C)
$COP_{,\ pcm}$	Coefficient of performance with PCM	T_h	TEC hot side temperature (°C)
$COP_{,\ w/o\ pcm}$	Coefficient of performance without PCM	$T_{h,\ pcm}$	TEC hot side temperature with PCM (°C)
$DT_{,\ pcm}$	Temperature difference between hot and cold sides with PCM (°C)	$T_{h,\ w/o\ pcm}$	TEC hot side temperature without PCM (°C)
$DT_{,\ w/o\ pcm}$	Temperature difference between hot and cold sides without PCM (°C)	T_m	Average temperature of cooling (°C)
I	Current intensity (A)	***Greek symbols***	
K	Thermal conductivity (W/K)	α	Seebeck coefficient (V/K)
Q_c	Cooling power (W)	ΔT	Temperature difference bet. TEC junctions (°C)
R	Resistance (Ω)	***Abbreviations***	
R_Q	Thermal resistance of heat sink (Ω)	PCM	Phase change material
N	Energy consumption (W)	TEC	Thermoelectric cooler
T_a	Ambient temperature (°C)	TEM/TED	Thermoelectric module/device
T_c	TEC cold side temperature (°C)	ZT	Dimensionless figure of merit

II. METHODOLOGY AND EXPERIMENTAL SET UP

2.1Objectives and Methodology

The main objective of the present work is to improve the cooling performance of TEC Module, by means of attaching suitable phase change material directly to cold/hot side sinks for space conditioning. Temperature inside the cabinet was to be maintained around 22°C. The variation of temperature at TEC junctions were recorded over a period of time and COP of TEC has been calculated. The value of COP and operating period are two important factors to characterize the cooling performance of TEC. The value of COP were estimated by the following equation (2.1) [8]:

$$= \qquad (2.1)$$

Where , *N*, α, *I*, are the cooling power, energy consumption, Seebeck coefficient, current intensity, TEC cold side temperature, resistance, thermal conductivity and TEC hot side temperature respectively. The characteristic parameters α, *R* and *K* of TEC changes with the average temperature between cold and hot side and are determined using following experimental equations (2.2), (2.3) and (2.4) [9]:

$$K = 0.42 + 0.006 * \frac{T_h+T_c}{2} (W \qquad (2.2)$$

$$V/K \qquad (2.3)$$

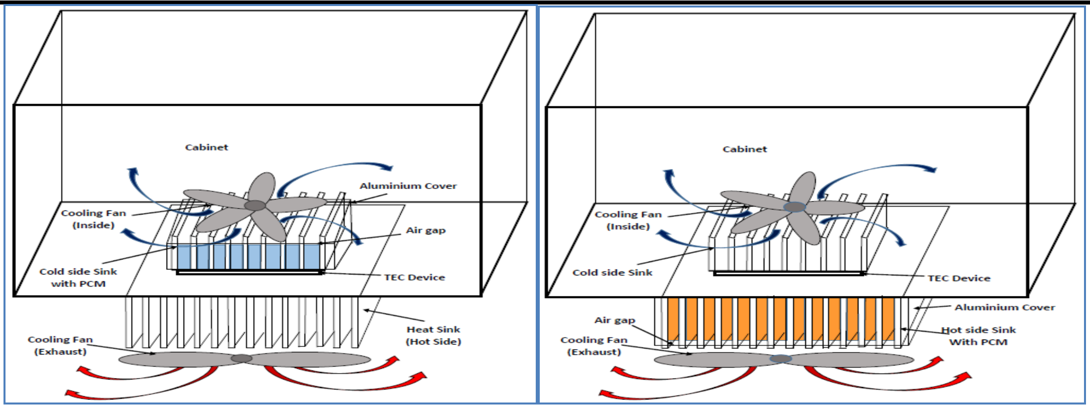
$$R = 2.25 + 0.015 * \frac{T_h + T_c}{2} (\Omega) \qquad (2.4)$$

However, these correlations was not taken into consideration. Average temperature of cooling was taken as a constant value (T_m=25°C) in calculation process, the characteristic parameters of the corresponding temperature were obtained to be α=0.0477V/K, R=2.375Ω, *K*=0.497W/K and the values of and are measured every few seconds.

2.2Experimental set up

2.2.1 System design and construction

A cabinet of size 200 mm x 200mm x 450mm was consider for space conditioning, fabricated out of 2mm thick bakelite sheet. Thermoelectric cooling system consists of TEC device sandwiched between cold and hot side sinks by applying thermal paste and cooling fans used to induce air-forced convection to enhance the effect of convection heat transfer.



(A) (B)

Fig.2.1. Schematic diagram of experimental set up (A) PCM at Cold side (B) PCM at Hot side

To prevent the loss of PCM during phase change period, closely packed hermetically aluminium casing has been used due to its high thermal conductivity and low cost. Since, PCMs have low thermal conductivity small metal pieces been used to enhance the heat transfer rate. A schematic arrangement of test set up has shown in Figure 2.1. (A) and (B) for PCM at cold side sink and hot side sink respectively.

2.2.2 Selection of thermoelectric module

Based on the cooling load calculations, to pump out heat at a rate of 23W for space conditioning thermoelectric module TEC1-12706 was selected based on the maximum cooling performance parameters as shown in Table 2.1.

Table 2.1. Cooling performance specifications for TEC1-12706

T_h(°C)	27	50	Hot side temperature at environment: dry air, N_2
DT_{max} (°C)	70	79	Temperature Difference between cold and hot side of the module when cooling capacity is zero at cold side
U_{max} (Voltage)	16.0	17.2	Voltage applied to the module at DT_{max}
I_{max} (amps)	6.1	6.1	DC current through the modules at DT_{max}
Q_{cmax}(Watts)	61.4	66.7	Cooling capacity at the cold side of the module under DT= 0°C
AC resistance(Ohms)	18 ~2.2	2.0 ~2.4	The module resistance is tested under AC

2.2.3 Selection of heat sinks

Heat sinks for thermoelectric cooling are selected based on thermal resistance calculations using formula below:

$$. I + Q). R_Q \quad (2.5)$$

Where , , Q, (V.I) and R_Q are the hot side temperature of TEM, ambient temperature, heat load in watts, power rating of TEM and thermal resistance of heat sink. For smaller thermal resistance larger is the sink. However, it is best to use sinks with a high thermal design power. Here, air-cooled aluminium heat sinks were used with a thermal design power of 80-120W.

2.2.4 Selection of PCMs

Selection of PCM for the cold side and hot side is very important having suitable transition temperature and high energy density. As the required inside cabinet temperature was around 22°C the PCM with melting point below 22°C and above the lowest cold side temperature obtained with forced air-convection was preferred for phase change to occur. So, the Caprylic acid with melting point 16.7°C between the temperature ranges isconsidered. While, paraffin wax with melting rangeof 38-43°C was chosen for the hot side, which is above the environment temperature and below maximum hot side working temperature. Table2.2.shows the heat capacity, melting point and latent heat of selected PCMs.

Table 2.2. Heat capacity, Melting point and latent heat for selected PCMs

PCM	Heat capacity (J/g°C)	Melting point (°C)	Latent heat (J/g)
Caprylic acid	2.05	16.7	148
Paraffin wax	1.97	38-43	212

2.2.5Experimental procedure

Experimental work to study the cooling performance of thermoelectric cooling with PCMs were performed by attaching suitable PCM to the cold side and then to the hotter side with forced air-convection. The results of variation of temperature at TEC junctions and COP were compared with and without PCM. Figure 2.2.depicts the test experimental set up of thermoelectric cooling system.

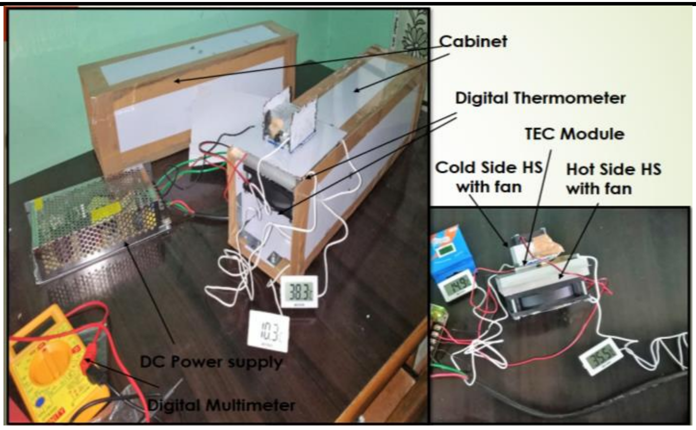


Fig.2.2. Test experimental set up of thermoelectric cooling system

When DC current is applied to TEC, it absorbs heat from the cold side and dissipates heat to the hot side, thereby creates hot and cold junctions.It is very criticalto perform tests on TEC Module for determining the desirable current for maximum cooling performance. A variable DC source was used to power the cooling system and temperature variations at cold and hot side sinks were measured using digital thermometer with sensor and recorded.

III. RESULTS AND DISCUSSION

The TEC1-12706 module could maintain a temperature difference as high as 35°C between hot and cold side sinks tested with natural convection (cold side) and forced air convection (hot side) by varying input supply.

3.1 Influence of different input supply on thermoelectric cooling

Figure3.1.shows, the temperature variation of TEC junctions at varying input supply, (voltage/current: condition 1:10V/3A; condition 2: 11V/3.4A; condition 3: 12V/3.8A; condition 4: 14V/4.6A). For condition 2: 11V/3.4A input supply, the cold side temperature reaches the lowest temperatureof 14.2°C.

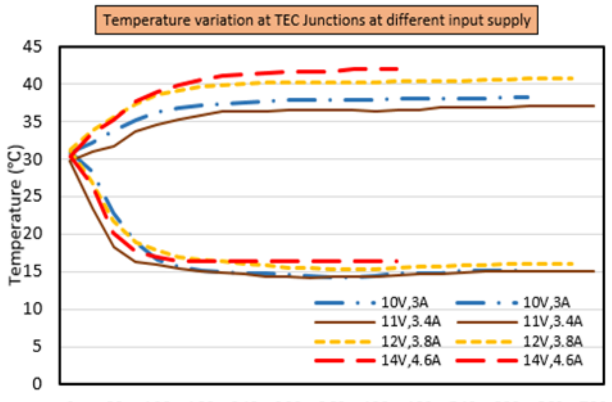


Fig.3.1. Temperature variation of TEC junctions at different input supply

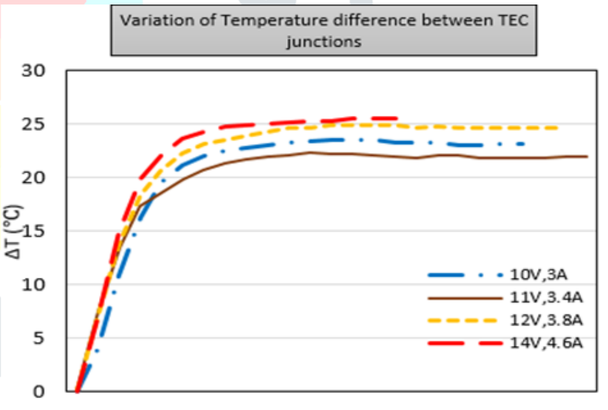


Fig.3.2.Variation of temperature difference between TEC junctions

In addition, shows better cooling performance as thetemperature difference between TEC junctions is minimumas shown in Figure 3.2.Thus, considered the same working voltage with phase change material at cold side.Moreover, the working supply of 12V/3.8A was preferred to work with phase change material at hot side to lower hot side temperature below 40°C.

3.2Results of using phase change material on cold side sink

Figure 3.3.shows, the temperature variation of TEC junctions with phase change material attached to cold side.

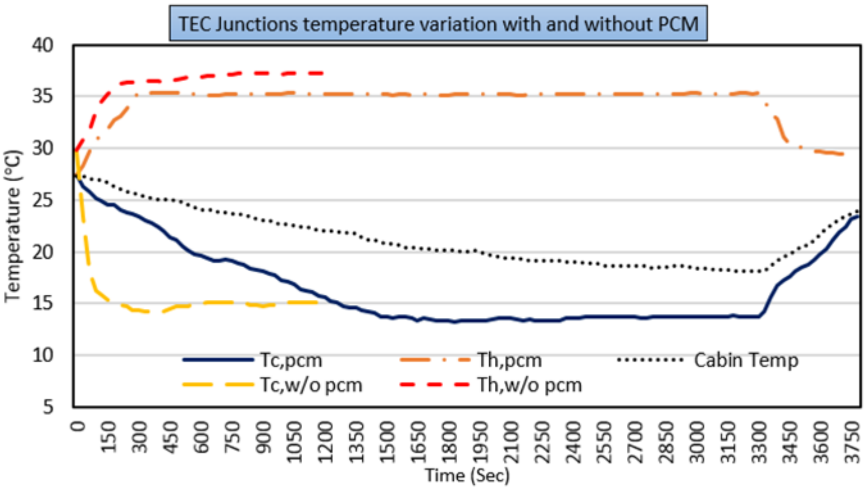


Fig.3.3 Variation of temperature at TEC Junctions with and without PCM (on cold side)

The temperature of the cold side with phase change material decreases gradually and attains constant temperature after 1320 seconds with lowest minimum temperature of 13.2°C, while the hot side temperature rapidly increases and maintains almost a constant temperature due to forced air convection. Once the temperature at cold side reaches below the melt point of phase change material, after about 1200 sec the freezing/solidification occurs until the power was turned-off. In this process the inside cabinet temperature drops down by forcedair convection through cold sink and cold energy stored, which was able to attain cabin temperate below 22°C even after power cut.

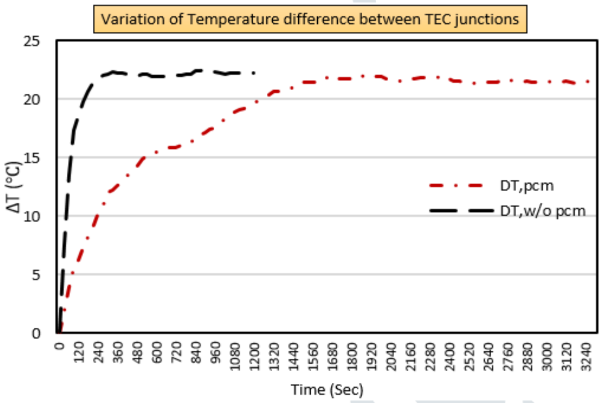


Fig.3.4. Variation of temperature difference between TEC junctions.

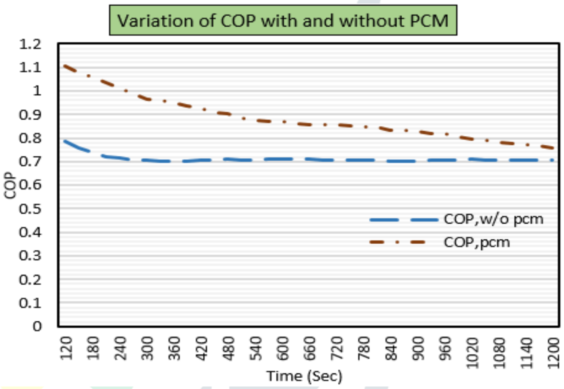


Fig.3.5. Variation of COP of TEC with and without PCM.

The value of temperature difference between TEC junctions increased steadily with PCM, while rapidly without PCM and remains stable with TEC operation as shown in Figure 3.4. The coefficient of performance of TEC drops as the temperature difference between hot and cold sides of TEC increases and COP of TEC with PCM maintained at about 0.76 and without PCM at about 0.70 as shown in Figure 3.5. This introduction of PCM increases the COP of TEC by 8.57%.

3.3Results of using phase change material on hot side sink

Figure 3.6. represents variation of temperatures at TEC junction with phase change material attached to the hot side.

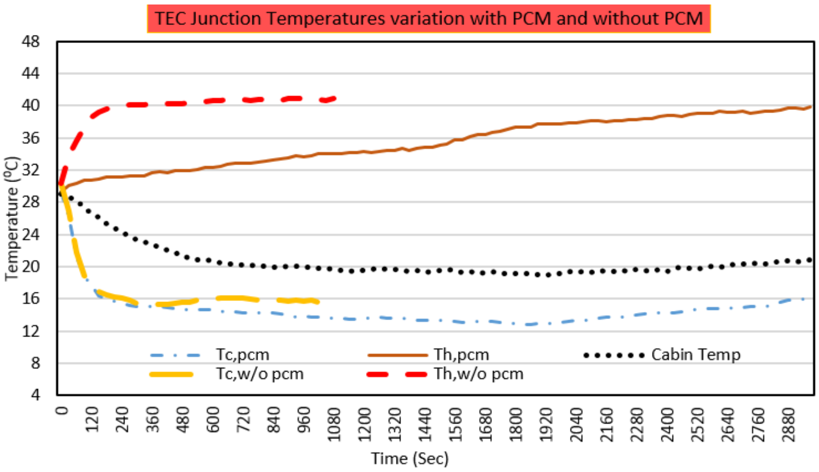


Fig.3.6. TEC Junction temperatures variation with and without PCM (on hot side)

The cold side temperature drops rapidly during cooling phase with and without phase change material while the temperature of hot side reaches to maximum value within few seconds but with phase change material rises gradually.

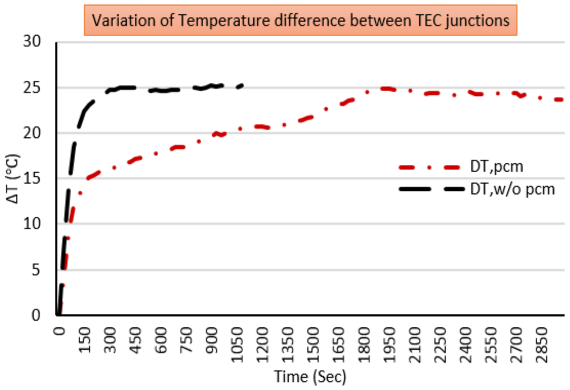


Fig.3.7. Variation of temperature difference between TEC junctions

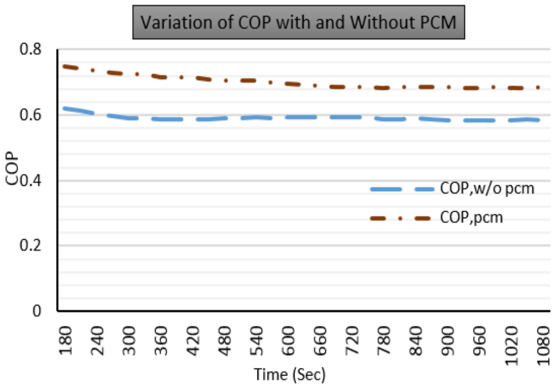


Fig.3.8.Variation of COP of TEC with and without PCM

The temperature inside cabinet dropped and reaches to minimum temperature around 19°C with TEC operation, while the temperature of hot side was maintained below 40°C (maximum working temperature) for considerable time duration. With PCM attached to the hot side the temperature difference between hot and cold sides was reduced as shown in Figure 3.7. Thus, improving the coefficient of performance from 0.58 to 0.685 as shown in Figure 3.8.withpercentage improvement of 18.1%.

VI. CONCLUSION

Thermoelectric cooling system employing phase change material to its thermal sides have been tested and studied in this work. The performance of the new system with PCMwas compared with a similar system without PCM.The results of experimental tests showed as:

- The feasibility to use phase change material to regulate the cold/hot side temperatures assisted by thermal energy storage.
- Attributing PCM to the cold side of TEC have improved the COP by 8.57% for test set up. Further, it also gives the cooling storage capacity, which would be particularly useful in case of power failure.
- The use of PCM at the hot side of the TEC keeps the temperature of the hot side well below the maximum working temperature range of 40-43°C for much longer time, thereby improving the COP of TEC from 0.58 to 0.685 with percentage improvement of 18.1%.

With this experimental investigation of using PCM, have improved the work reliability of thermoelectric cooling for space cooling application. Meanwhile, this cooling system has been able to achieve better cooling with energy savings.

REFERENCES

[1] Cronin B. Vining, "An inconvenient truth about thermoelectrics", Natural Materials vol. 8, (2009).

[2] Alaa Attar, "Studying the Optimum Design of Automotive Thermoelectric Air Conditioning", Dissertations 1163, (2015).

[3] Gang Tan, Dongliang Zhao, "Study of a Thermoelectric Space Cooling System Integrated with Phase Change Material", Applied Thermal Engineering. (2015).

[4] M. Dominguez, D. Garcia, J. Esarte, D. Astrain and J.G. Vian, "Possibilities of efficiency improvement in the thermoelectric systems", Journal of Thermoelectricity (2), 31-40(1999).

[5] M. Thakkar, A report on "Peltier (thermoelectric) cooling module", Research Gate (2016).

[6] S.A. Omer, S.B. Riffat and Xiaoli Ma, "Experimental investigation of a thermoelectric refrigeration system employing a phase change material integrated with thermal diode (thermosyphons)", App. Ther. Engg. 21, (2001).

[7]Dongliang Zhao, Gang Tan, "Experimental evaluation of a prototype thermoelectric system integrated with PCM (phase change material) for space cooling", Energy (2014).

[8]Rong-Rong He, Huai-Yu Zhong, Yang Cai, Di Liu, Fu-Yun Zhao, "Theoretical and Experimental Investigations of Thermoelectric Refrigeration Box Used for Medical Service", Procedia Engineering 205, 1215–1222 (2017).

[9]Weihan Dai, Yanjun Dai, Peng Zhang and Ruzhu Wang, "Measurement for the characteristic parameters and selection of thermoelectric cooling modules," Shanghai JiaotongDaxueXuebao, 1669-1672(2004).