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Thermal Management Optimization of Thermoelectric Coolers with High-Conductivity Phase Change Materials

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Abstract

Thermoelectric coolers (TECs) are increasingly employed in electronics thermal management; however, their performance is often constrained by heat accumulation on the hot side. This study numerically investigates the integration of high-thermal-conductivity phase change materials (PCMs) into finned TEC sink cavities to enhance cooling stability and efficiency. Using COMSOL Multiphysics, the effects of PCM type (gallium vs. OM32), PCM height (1.5 mm and 3 mm), and input current (1.0, 1.2, and 1.4 ampere) were examined. Results show that gallium consistently outperforms OM32 in delaying temperature rise, extending the cooling phase, and sustaining higher coefficients of performance (COP). Increasing PCM height from 1.5 mm to 3 mm further prolonged the phase change period for both materials. At 1 ampere, gallium with a 3 mm height achieved the highest COP improvement (~50% over the baseline case, where no PCM) and the most prolonged low-temperature period. At 1.4 ampere, gallium reached the lowest cold-side temperature recorded (~278 K), although with a reduced COP due to accelerated melting and increased Joule heating. Overall, gallium-filled configurations demonstrated superior thermal buffering and efficiency retention across all tested conditions, confirming the potential of high-conductivity PCMs as an effective passive thermal management strategy for compact, energy-efficient electronics and energy systems.

<i>Abbreviations</i>		<i>Notations</i>	
TEC	Thermoelectric coolers	k	Thermal conductivity
DC	Direct current	C_{ps}	Specific heat of the solid
COP	Coefficient of performance	C_{pl}	Specific heat of the liquid
PCM	Phase change material	C_p	Specific heat capacity
WTEC	Wearable thermoelectric cooler	q	Heat flux
PCCM	Phase change composite materials	S	Seebeck coefficient
LMPM	Low melting point metals	P	Peltier coefficient
Ga	Gallium	J	Electric current density
PVP	Polyvinylpyrrolidone	Q	Internal heat generation per unit volume (W/m ³).
Bi ₂ Te ₃	Bismuth Telluride	Z	Figure of merit of the TEC material
OM32	A specific type of paraffin wax with a melting point around 32°C		
BeO	Beryllium oxide		
<i>Greek symbols</i>		<i>Subscripts</i>	
ρ	Density	T_m	Melting temperature
ΔT	Temperature difference C°	L_f	Latent heat of fusion
σ	Electrical conductivity	$B(T)$	Phase fraction function
		$D(T)$	Normalized Gaussian function
		T_h	Hot side temperature of the TEC
		T_c	Cold side temperature of the TEC

Introduction

The environmental harm posed by refrigerants utilized in traditional refrigeration and air-conditioning systems is growing daily. Energy scarcity and environmental deterioration have prompted society to look for innovative, environmentally friendly cooling system solutions in recent years. The development of thermoelectric cooling systems has made this possible, and several studies on the subject have made the aforementioned situation conceivable. One approach involves the utilization of thermoelectric devices for cooling purposes.

A thermoelectric cooler is a semiconductor-based electrical device that operates on the principles of the Peltier, Seebeck, and Thomson effects to transfer heat from one side to another without employing refrigerants. Thermoelectric coolers (TECs) are being utilized in electronic cooling applications, requiring moderate heat handling in locations where conventional systems are impractical [1]. Thermoelectric devices have been included into automotive exhaust systems to alleviate the power demand on the vehicle's alternator, and in biomass or gas-fired heaters to generate electricity for fluorescent lights, televisions, pumps, fans, or controls. TECs are eco-friendly, maintenance-free, and reliable, working without moving parts. They are smaller and lighter than traditional vapour compression systems and can produce cooling or heating depending on DC power polarity [2,3]. Applying an electric current pulse can lower the cold side temperature, which can be used to cool laser equipment and enhance the quality of images captured by thermal imaging cameras and night vision. For military applications and electronic cooling which is becoming more and more crucial for eliminating heat from smaller surface-area electronic components TEC's pulse operation is especially advantageous. TECs frequently have efficiency constraints owing to their low coefficient of performance (COP) and significant temperature variations. [4]. To resolve these challenges, researchers have investigated the integration of phase change materials (PCMs), which may absorb or release substantial quantities of latent heat during phase transitions, to improve thermal management [5,6]. A small number of researchers used heat sinks using air and water as coolants in their theoretical and practical investigations to improve TEC performance.

PCMs provide a passive and reversible mechanism for thermal energy storage, capable of collecting surplus heat during the melting process and releasing it during solidification [7]. The melting and freezing processes allow (PCM's) to both absorb and release thermal energy. These days, phase change materials are a practical way to improve the thermal performance and reduce energy consumption in electrical devices [4,8]. PCM is being developed for use in a number of applications, including waste heat recovery, solar energy plants, photovoltaic electricity generation, refrigerators, hot water systems for homes, electronic applications, mobile devices, heating and cooling systems. The amalgamation of PCMs with thermoelectric coolers offers a stabilizing buffer for temperatures and improves the coefficient of performance [7,9-11]. Achieving the best synergy requires choosing PCMs with appropriate melting points and thermal conductivity [12].

Ling et al. [13] investigated the significance of appropriate heat management systems for solar cells, Li-ion batteries, and electronic components. It focuses on the performance, thermal characteristics, and methods for enhancing the thermal conductivity of PCMs. Additionally, the

results include hybrid passive heatsinks with active cooling and advanced structure heatsinks with multi-layer PCMs. According to Xia et al. [14], wearable thermoelectric coolers' (WTECs') large heat sinks are a drawback. Phase-change composite materials (PCCMs) are suggested as a solution because of their thermal characteristics and flexibility. Through experimental validation, numerical simulations, and theoretical analysis, the design is optimized. It was discovered that the PCCM remained anti-leakage for at least 12 hours, even at a transition temperature of 30°C. In comparison to the WTEC without PCCM, the cold surface temperature of the WTEC with PCCM was lowered by 2 to 3°C. The WTEC and PCCM heat sink was designed to cool human skin for up to ten minutes while maintaining a suitable temperature drop of two to five degrees Celsius.

For space cooling, a prototype thermoelectric system featuring a PCM heat storage unit has been investigated. The cooling load is partially carried by the PCM heat storage, which also serves as a cooling source. The module's theoretical performance was examined using a simplified analytical model. The system saved 35.3 percent of the electrical energy and produced a 7°C temperature difference. When the PCM was charging, natural convection was seen [15]. Evaluation of TEC performance parameters through numerical modeling and simulation. With 5 K intervals, the TEC is simulated using COMSOL Multiphysics software for hot side temperatures between 303.15 and 333.15 K. According to the findings, the cooler's ability to cool drops as the cold side temperature drops. Raising the hot side temperature could boost cooling efficiency. When the input current is 0–2–3 times the rated current value, the COP levels are attained. The study also shows that systems with higher hot side temperatures have larger COPs [16]. A novel class of (PCMs) with high thermal conductivity and superior heat extraction capabilities are called low melting point metals (LMPMs) [17]. A numerical investigation was conducted into the melting process of LMPMs. Dimensionless analysis and comparative simulations between LMPM gallium and paraffin eicosane are carried out. The study investigates the impact of natural convection under high Ra number conditions and proposes critical dimensionless values. The findings indicate that the LMPMs may prove beneficial for thermal energy storage and thermal management systems in the future [18].

A novel method for enhancing TEC's thermal performance involves incorporating PCM at the hot side. Input currents, cooling load conditions, geometric parameters, and various PCMs were among the conditions under which the study was carried out. The findings indicated a notable decrease in the TEC's hot and cold side temperatures. 52 to 30 °C and 25 to 12 °C, respectively, were lowered from the TEC's hot and cold side temperatures under normal operating conditions with two thermocouples. The performance coefficient of the TEC was estimated to be 30% higher than that of a cooling load of 0.05 W without PCM. Increasing the PCM fill volume also improved the TEC's thermal performance, according to the study [19]. PCM's potential for electronic device thermal management has not been thoroughly investigated. Fins have been shown in some studies to enhance cooling efficiency in PCM heat sinks [20]. Another study discovered that a PCM-filled heat sink maintains a steady temperature throughout the melting process [21]. Nanomaterial dispersion can improve PCM's conductivity and thermal stability, shortening the time needed for charging and discharging [22]. PCM's impact on thermoelectric cooling devices for MS patients was investigated by Wang et al. [23]. Caroff et al. [24] examined the effectiveness of thermoelectric coolers with PCM for motor drive applications and discovered that PCM reduced

temperature. The literature review suggests that thermoelectric coolers typically have low (COPs) and that cooling performance can be enhanced by lowering the hot side temperature.

Numerous investigations utilize liquid metals and organic-inorganic PCMs to examine the melting and natural convection phenomena. Gallium is being studied a lot as a PCM because it has unique thermal properties that are helpful for many applications in managing heat and storing energy, especially when compared to regular PCMs like n-octadecane. When integrated into thermoelectric energy harvesters, gallium outperformed traditional PCMs by 9.5 times the open-circuit voltage and 12.7 times the thermoelectric conversion efficiency under microgravity conditions [25,26]. Researchers discovered that gallium under microgravity increases overall energy storage capacity by 20.7% and 123.3% while decreasing melting time by 88.3% and 96.4%. In microgravity, melting is encouraged by thermocapillary convection; however, gallium's influence is less pronounced because of its lower Marangoni number. Under normal gravity, gallium, ice, and n-octadecane melt at a rate of 65.8%, 39.4%, and 69.2% faster, respectively. The findings demonstrate that thermal energy storage utilizing gallium is efficient for regulating the temperature of spacecraft electronic components subjected to elevated and intermittent heat input [27].

Melting of gallium in a heated container with a rectangular side face is examined. The study considers a mushy zone and thermal variations while advancing a numerical model to 3D status. New and existing data from a specially designed experimental setup are used to validate the model. The COMSOL Multiphysics software-based numerical model was contrasted with experimental data. The results demonstrate improved agreement between experimental and 3D computational data, suggesting that container boundaries have a major influence on the issue [28]. PCMEs containing Ga particles in glycerol can be employed as a stable, electrically insulating carrier fluid, as the study showed. By effectively emulsifying Ga within glycerol at Ga loadings of up to 80 vol% , the researchers created stable colloidal suspensions with high thermal conductivity and latent heat capacities using PVP as an emulsifier. With strong thermal characteristics and no discernible phase transition temperature depression, the large Ga particles maintained solid-liquid phase transition temperatures close to bulk Ga. Ga content led to a linear increase in thermal conductivity and latent heat capacities, outperforming traditional organic-based PCMEs. This development in PCME technology may prove beneficial for a number of thermal applications [29].

Phase transition between liquid and solid is a common phenomenon in nature, with potential applications in materials with minimal temperature changes. Metals with high melting points face challenges in tuning their properties due to phase transition. Nontoxic gallium-based liquid metal has gained interest due to its ability to switch between solid and liquid phases, allowing for study of phase transition phenomena. Efforts have been made to explore adjustable properties of liquid metal during phase transition, including thermal enthalpy, mechanical strength, morphology, surface adhesion force, and structure changes for various applications.

In this study, gallium was chosen as the PCM for the heat buffer in the TEC system due to its superior thermophysical properties compared to conventional paraffin waxes. Gallium's thermal conductivity is more than two orders of magnitude higher than that of paraffin wax, enabling rapid heat transfer and more uniform temperature distribution across the heat sink. This

high conductivity is critical for minimizing thermal gradients and maintaining stable TEC operation, especially under high or fluctuating heat loads. Additionally, gallium's high density allows it to absorb and store more thermal energy per unit volume, resulting in a more compact and effective heat buffer. Unlike paraffin, which often requires additional conductivity enhancers such as metal foams or fins, gallium's intrinsic properties eliminate this need, simplifying system design [30]. Studies have shown that gallium-based heat sinks can reduce peak temperatures by up to 10°C compared to paraffin-based systems under similar conditions [31,32]. Furthermore, gallium's nearly isothermal melting behavior is advantageous for protecting sensitive electronics and enhancing the reliability of TEC modules [33]. These combined advantages make gallium a superior choice for enhancing TEC performance and heat sink efficiency.

Mathematical Modeling and Geometry Selection

Figure 1 illustrates a schematic diagram of a thermoelectric cooler combined with phase change material. The setup includes a Bismuth Telluride (Bi_2Te_3) based thermoelectric cooler featuring two thermoelectric elements measuring 2 mm x 2 mm x 3 mm (L×W×H). An electric heater is positioned on the cooler's cold side to simulate the cooling load, while a heat sink integrated with phase change material is placed on the hot side. The geometry in this study was inspired by research [4,19]. It is also worth mentioning that the findings in reference [19] indicate that there is no significant change in the temperature difference of the TEC device when the number of fins is more than 5, which is adopted in the current study.

The thermal performance of a TEC integrated with different PCMs is systematically investigated in this study. The primary objective is to compare the effectiveness of gallium as a PCM against conventional paraffin-based PCMs, such as OM32, in maintaining lower hot-side temperatures and improving the COP of the TEC.

The setup consists of a Bi_2Te_3 -based TEC module with a copper heat sink mounted on its hot side, where the PCM is filled. Two PCM fill heights, 1.5 mm and 3 mm, are considered to assess the impact of PCM volume on system performance. The convective heat transfer coefficient at the heat sink's top surface is maintained at 5 W/m²K, and a constant heat load of 0.03 W is applied at the cold side of the TEC for all test cases.

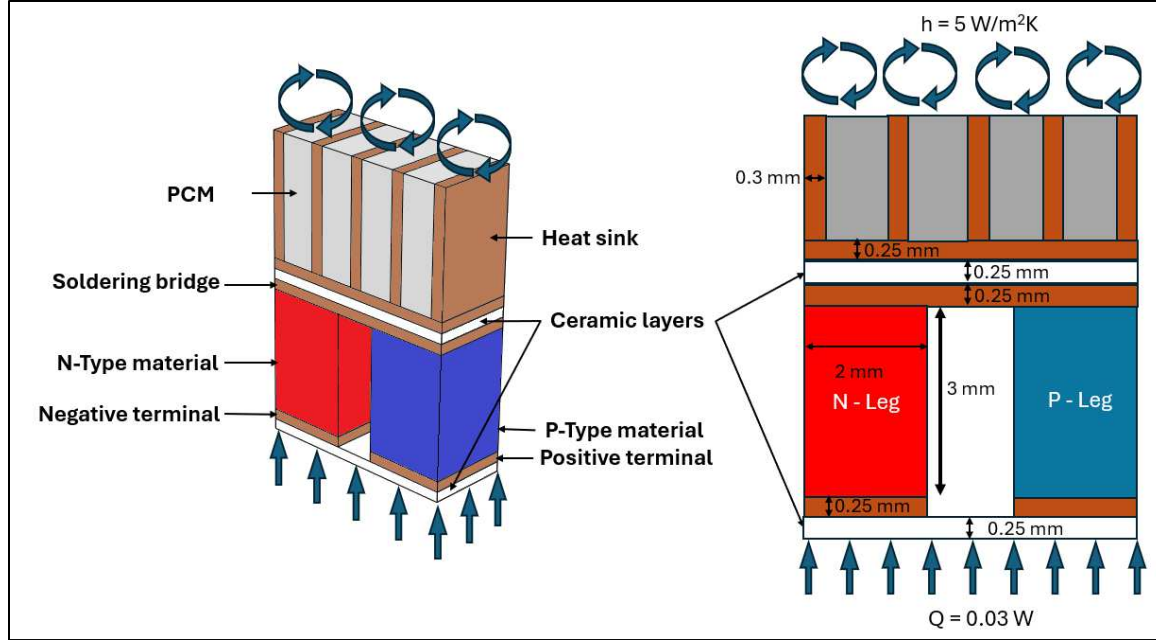


Fig. 1 A 3D schematic of the studied domain, with the geometric dimensions displayed on the right.

The TEC is operated at steady-state input currents of 1 A, 1.2 A, and 1.4 A with fins only (no PCM) and with two PCM types at 2 different heights. Table 1 summarizes the cases studied in this work. The letter “A” for the studied cases stands for Gallium as a PCM. On the other hand, the letter “B” stands for OM32 as a PCM. Throughout all setups, temperature profiles at the hot and cold sides of the TEC, as well as the liquid fraction of the PCM, are recorded. The COP is calculated for each case to quantify the enhancement provided by the different PCMs, with particular attention to the performance during phase transition periods. This methodology enables a comprehensive assessment of gallium's potential advantages over paraffin-based PCMs in TEC thermal management applications.

The Material properties for the thermoelectric elements, copper heat sink, and beryllium oxide (BeO) ceramic layer were selected from COMSOL’s built-in material database. The model assumed negligible thermal and electrical contact resistances and neglected radiation heat transfer between thermoelectric elements, focusing primarily on conduction and external convection. Additionally, temperature-dependent thermoelectric material properties were incorporated to enhance simulation accuracy.

Table 1. The conditions of the studied cases.

Case name	Current (A)	PCM height (mm)*	PCM type
A1	1	1.5	Gallium
A2	1.2		
A3	1.4		
A4	1	3	Gallium
A5	1.2		
A6	1.4		
B1	1	1.5	OM32
B2	1.2		
B3	1.4		
B4	1	3	OM32
B5	1.2		
B6	1.4		
C1	1	-	-
C2	1.2		
C3	1.4		

*The height of PCM that fills the fins cavities.

Governing equations

The governing equations used in COMSOL Multiphysics to analyze the thermoelectric cooling behavior are expressed as follows [4,19]:

The heat transfer equation in solid materials is given as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} = Q \quad (1)$$

Also, the electric current density equation in TEC components is described by the following equation:

$$\mathbf{J} = -\sigma(\nabla V + S\nabla T) \quad (2)$$

and the heat flux equation is given as:

$$\mathbf{q} = P\mathbf{J} - k\nabla T \quad (3)$$

Here, ρ represents the density of the thermoelectric material, C_p is its specific heat capacity, and q denotes the heat flux resulting from both Peltier heat and Fourier heat conduction. The electrical conductivity is given by σ , S is the Seebeck coefficient, P is the Peltier coefficient defined as $P=ST$, J is the electric current density, and $Q=J \cdot E$ represents the internal heat generation per unit volume (W/m^3).

To model the melting behavior of the PCM in geometries where natural convection is negligible, such as in narrow fin spaces, a pure conduction approach was adopted in our study. The latent heat of fusion was incorporated by modifying the specific heat capacity, $C_p(T)$, over a small temperature range around the melting point. The temperature-dependent specific heat was defined as [34], [35]:

$$C_p(T) = C_{ps} + (C_{pl} - C_{ps}) \cdot B(T) + L_f \cdot D(T) \quad (4)$$

where C_{ps} and C_{pl} are the specific heat of the solid and liquid PCM, respectively. L_f is the latent heat of fusion, $B(T)$ is a phase fraction function, and $D(T)$ is a normalized Gaussian function centered at the melting temperature. The Gaussian function is given by [35]:

$$D(T) = \frac{1}{\Delta T \sqrt{\pi}} \exp\left(-\frac{(T - T_m)^2}{\Delta T^2}\right) \quad (5)$$

where T_m is the melting temperature and ΔT is a small temperature interval around the melting temperature. Beckermann and Viskanta [36] noted that an unrealistically large ΔT (i.e. > 2 C) introduce too much artificial ‘smearing’ of the predicted interface, while a too small interval will complicate numerical calculation and require a very fine mesh. (In the present work, it is taken to be 0.5 K).

The phase fraction function $B(T)$ is defined as follows [34]:

$$B(T) = \begin{cases} 0 & T < (T_m - \Delta T) \\ \frac{T - T_m + \Delta T}{2\Delta T} & (T_m - \Delta T) < T < (T_m + \Delta T) \\ 1 & T > (T_m + \Delta T) \end{cases} \quad (6)$$

In COMSOL, $B(T)$ can be implemented using the smoothed function. The governing heat transfer equation over the PCM domain is written as:

$$\rho \cdot C_p(T) \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \quad (7)$$

where ρ is the density and k is the thermal conductivity of the PCM. This approach allows accurate modeling of PCM melting by conduction alone, making it suitable for our application.

The COP of the TEC was calculated using Eq. 8, which is given by [4], [19]:

$$COP = \frac{T_c}{T_h - T_c} \left(\frac{\sqrt{1 + ZT_m} - \frac{T_h}{T_c}}{1 + \sqrt{1 + ZT_m}} \right) \quad (8)$$

where T_h and T_c are the hot and cold side temperatures of the TEC, respectively. Z is the figure of merit of the thermoelectric material calculated from the thermoelectric properties of Bi_2Te_3

PCM Selection

The selection of the PCM was based on its melting temperature relative to the ambient temperature and the hot side temperature of the TEC. For the base case, OM32 was chosen due to its melting range of approximately 32 °C to 35 °C, which lies above the ambient temperature but below the hot side temperature of the TEC, making it suitable for effective thermal regulation [4]. To evaluate the influence of different PCMs on the TEC performance, gallium was selected as an alternative PCM for comparison. Distinct thermal properties and melting point of gallium provide a basis to analyze how varying PCM affects the heat absorption capacity and overall thermal management of the system. This comparative study enables assessment of the TEC's performance enhancement or degradation when using gallium instead of OM32, thereby guiding optimal PCM selection for improved thermal control. The thermal properties of the material used in the simulation are listed in Table 2.

Table 2. Thermophysical properties of the PCM materials used in the simulation [19], [37], [40].

Material	Melting point (C)	Latent heat (kJ/kg)	Thermal Conductivity (W/m.K)		Specific heat capacity (J/kg.K)		Density (Kg/m ³)	
			Solid	Liquid	Solid	Liquid	Solid	Liquid
OM32	32	191	0.25	0.125	3200	2800	915	880
Gallium	29.63	80.16	32	31	570	590	5774	6100

The validation of PCM melting in a heat sink

In the present study, the implemented numerical model was validated by replicating the results of “Case 4A” in reference [37], as shown in Tables 3 and 4, which involves the melting of gallium in a sink equipped with fins, under conditions where buoyancy effects are neglected. The validation focused on two critical parameters: the evolution of the liquid fraction and the temperature at the base of the sink. The comparison revealed a strong agreement between the results obtained from the COMSOL simulations and those reported in the reference study. Both the temporal progression of the liquid fraction and the temperature records at the sink base closely matched the benchmark data, confirming the accuracy and reliability of the adopted model for simulating phase change phenomena in finned geometries without buoyancy-driven flow.

Table 3. Comparison between the literature and our simulation results of the liquid fraction.

Time [s]	Liquid fraction (Numerical results from literature)	Liquid fraction (Our numerical results)
0	0	0
100	0.1349	0.1211
200	0.2819	0.2602
300	0.4276	0.4101
400	0.571	0.5501
500	0.7107	0.6907
600	0.8498	0.8215
700	0.9813	0.9785
800	1	1

Table 4. Comparison between the literature and our simulation results of the recorded temperature.

Time [s]	Temperature [K] (Numerical results from literature)	Temperature [K] (Our numerical results)
0	300	300
20	303.42	303.55
40	304.62	304.56
60	305.84	305.61
80	306.81	306.67
100	307.87	307.7
120	309.22	308.74
140	310.15	309.85
160	311.13	311.01

Experimental validation of thermo-electric device performance

To further establish the credibility of the numerical model developed in COMSOL, we performed a validation study using the experimental results presented in reference [38], as shown in Table 5. The validation was performed on a case of a single PN leg with dimensions 1.4×1.4 mm (Case 1-PN-TEG #1). The comparison was carried out by evaluating the relationship between the open-circuit voltage and the temperature difference across the device.

Although the experimental data pertains to a thermoelectric generator (TEG) and our simulation targets a TEC, this does not present a fundamental issue for validation. The physical principles governing TEGs and TECs are essentially inverse processes. TEGs convert heat flow into electrical energy, while TECs use electrical energy to drive heat flow. As a result, the voltage–temperature difference characteristics are directly comparable, with the direction of energy conversion being the primary distinction.

The validation results demonstrate excellent agreement between the simulation and the experimental measurements. The voltage predicted by the COMSOL model closely follows the trend and magnitude of the experimental data across the investigated temperature differences. The consistency between the two sets of results provides confidence that the model can capture the thermoelectric behavior for both TEC and TEG scenarios.

Table 5. Comparison between the experimental and simulation results of voltage values against temperature differences.

Temperature difference [K]	Electric potential (V) (Experimental)	Electric potential (V) (Simulation)
40	0.014496	0.0126
60	0.022046	0.0205
70	0.02588	0.0246
75	0.02781	0.0266

Validation of TEC performance under the current input

To validate the thermoelectric cooler model, we replicated the setup described in reference [39]. The simulation used a single p-type element ($1 \times 1 \times 5.8$ mm) with copper electrodes (0.1 mm thick) on both ends. Boundary conditions were set to 0°C and 0 V at the base, with a 0.7 A current applied at the top electrode. All other surfaces were adiabatic. The resulting temperature distributions matched the contours reported in reference [39], as shown in Figure 2. Additionally, the produced simulation results of cold side temperature are in good agreement with the aforementioned reference results, as shown in Figure 3, confirming the accuracy of the model used.

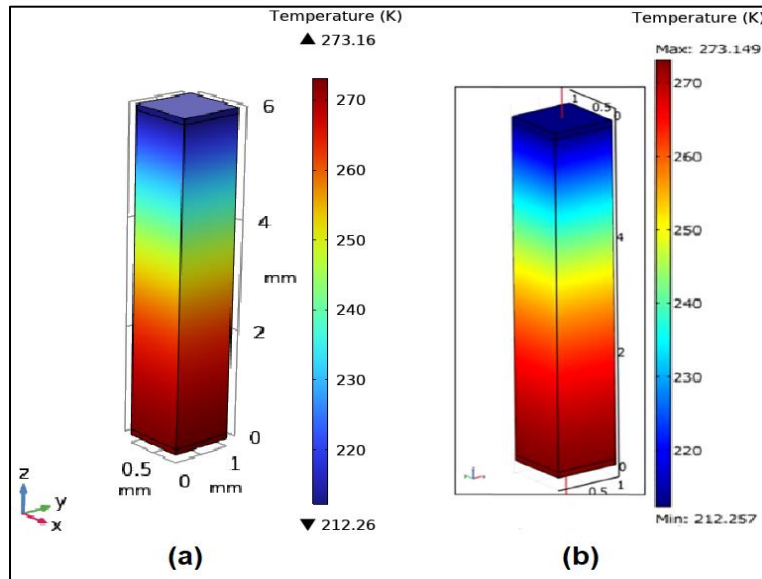


Fig. 2 The temperature contours of P-type material: a) temperature distribution taken from our simulation, b) temperature distribution from reference [39].

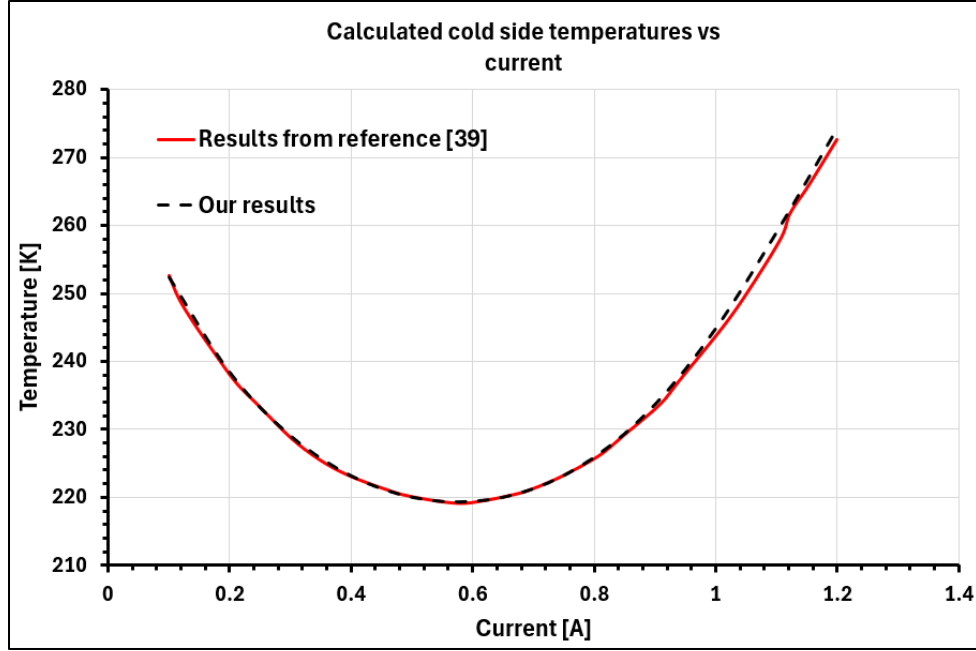


Fig. 3 Calculated cold side temperatures versus current with temperature-dependent material properties of our results against the findings of reference [39].

Results and discussion

The simulation results have been taken from COMSOL Multiphysics software. The temperature at the hot and cold sides of the TEC and the time-dependent liquid fraction of the PCM within the fin cavities were analyzed under varying operating conditions. In this section, the type of filled PCM, the effect of PCM height, the current input value, and the COP of the modeled TEC system will be discussed.

Mesh and time step sensitivity analysis

In order to confirm the reliability and the accuracy of our results, it is necessary to check different mesh and time step sizes of the studied domain. Hence, we can proceed to obtain the results for all other cases. Figure 4 shows three different meshes generated in COMSOL Multiphysics of the hot and cold side temperature of the TEC domain, categorized as fine, finer, and extra fine. The results indicate that there is no significant dependence on the mesh configuration studied, which allows us to confidently rely on the fine mesh size for the simulations.

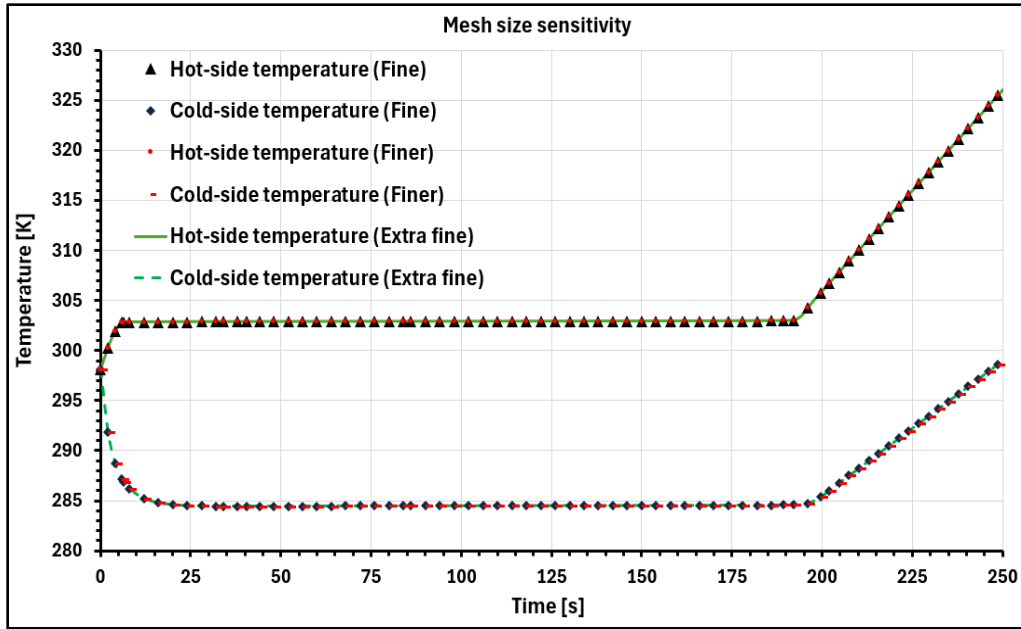


Fig. 4 Sensitivity analysis of mesh size.

Similarly, to ensure the accuracy and stability of the simulation results, different time step sizes were examined, namely 0.1 s, 0.01 s, and 0.001 s. As shown in Figure 5, the hot side temperature results exhibited no noticeable change once the time step was reduced to 0.01 s. Therefore, a time step size of 0.01 s was selected for all subsequent simulations.

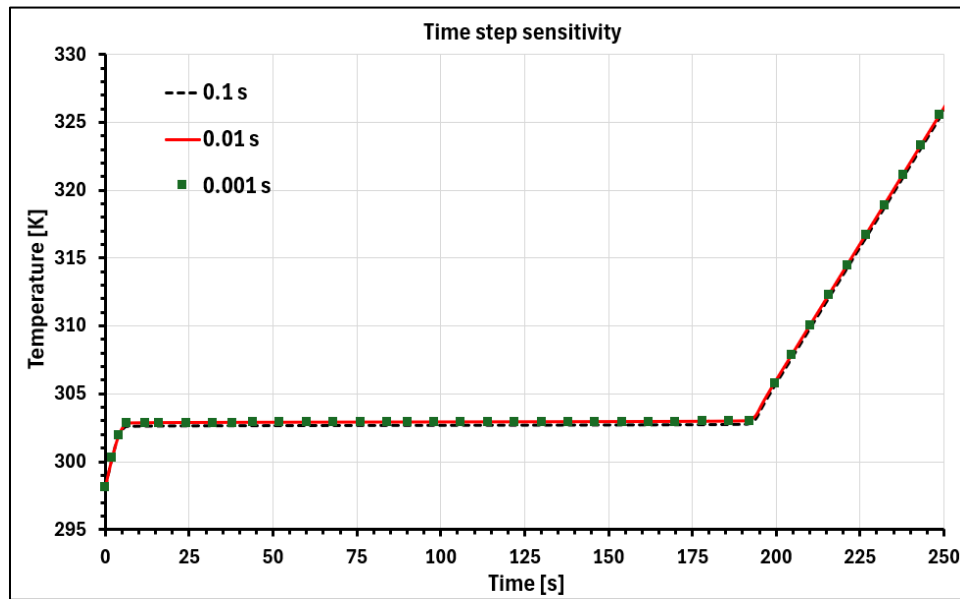


Fig. 5 Sensitivity analysis of the time step size.

The effect of PCM type

The choice of PCM plays a crucial role in determining the thermal regulation performance of the TEC system. Starting with Figure 6, which depicts the recorded data of liquid fraction and top side temperature in both A1 and B1 cases. It can be observed from Figure 6(a) that the PCM in case A1, which represents gallium as a filled PCM at a height of 1.5 mm under a current input of 1 ampere, starts melting about 2 seconds before case B1, where the melting point of gallium is less than OM32 by about 3K. Also, the time required to reach complete melting in case A1 is approximately 50 seconds more than that in its counterpart, case B1. This is attributed to the fact that case B1, which stands for OM32 as a filled PCM under the same conditions as A1, has a lower total latent heat storage capacity - which is the product of the latent heat of fusion of the PCM times the PCM's mass - compared to case A1. As a result of that, case A1 will have a chance to maintain its hot side temperature at a lower value than that in case B1. Furthermore, the high thermal conductivity of gallium prevents heat accumulation at the interface between gallium and the fin walls, causing the heat to be distributed evenly throughout the entire domain of the A1 system and resulting in nearly constant temperature records during the phase change stage, as shown in the same figure. In case A1, the temperature rapidly increases and stabilizes around 303 K between 4 seconds, where melting begins, and 95 seconds, after which it rises due to complete melting to about 330 K by 150 seconds. Conversely, the temperature of the B1 case remains steady near 305K until approximately 40 seconds, then spikes to reach nearly 335 K by 100 seconds. The same analogy is applied to A4 and B4 cases, as shown in Figure 6(b), which depicts the liquid fraction and hot side temperature of both cases under the same conditions as cases A1 and B1. The difference here is that the sink cavity is topped up with gallium and OM32 to 3 mm. Increasing PCM volume in the sink cavity will increase the time required to reach complete melting, which in turn maintains a low temperature value for a longer time before it spikes. This is evident in Figure 6(b), where OM32 and Gallium remain at their melting point range for about 90 seconds and 195 seconds, respectively.

Moving to Figure 7, which shows the temperature distribution and liquid fraction depictions placed beside each other for both A4 (gallium with 3 mm height) and B4 (OM32 with 3mm height) cases at selected times. In case A4, the melt front of gallium moves uniformly from the TEC interface and upwards across the full width of the cavity. The system maintains the temperature at the melting point of gallium, which is approximately 302 K, as shown in Figure 7(a), from 12 seconds to 190 seconds. After that, the temperature transforms to the superheated stage when complete melting is reached, as shown in Figures 7(b) and 6(b) at 200 seconds. In contrast, with case B4, when OM32 melts, the melting process begins simultaneously on all sides of the OM32 that are in direct contact with the heated fin walls. As a result, heat is pumped into the melted region before it reaches the solid phase, causing an increase in temperature. This behavior is observed in Figures 7(c) and (d) at approximately 12 seconds and 70 seconds. Then the temperature with OM32 becomes hotter at over 314 K (which is out of the legend scale range) as shown in Figure 7(c) at 100 seconds. This difference is that gallium's higher thermal conductivity and larger latent heat capacity enable better homogeneous, more uniform heat distribution compared to the OM32 case.

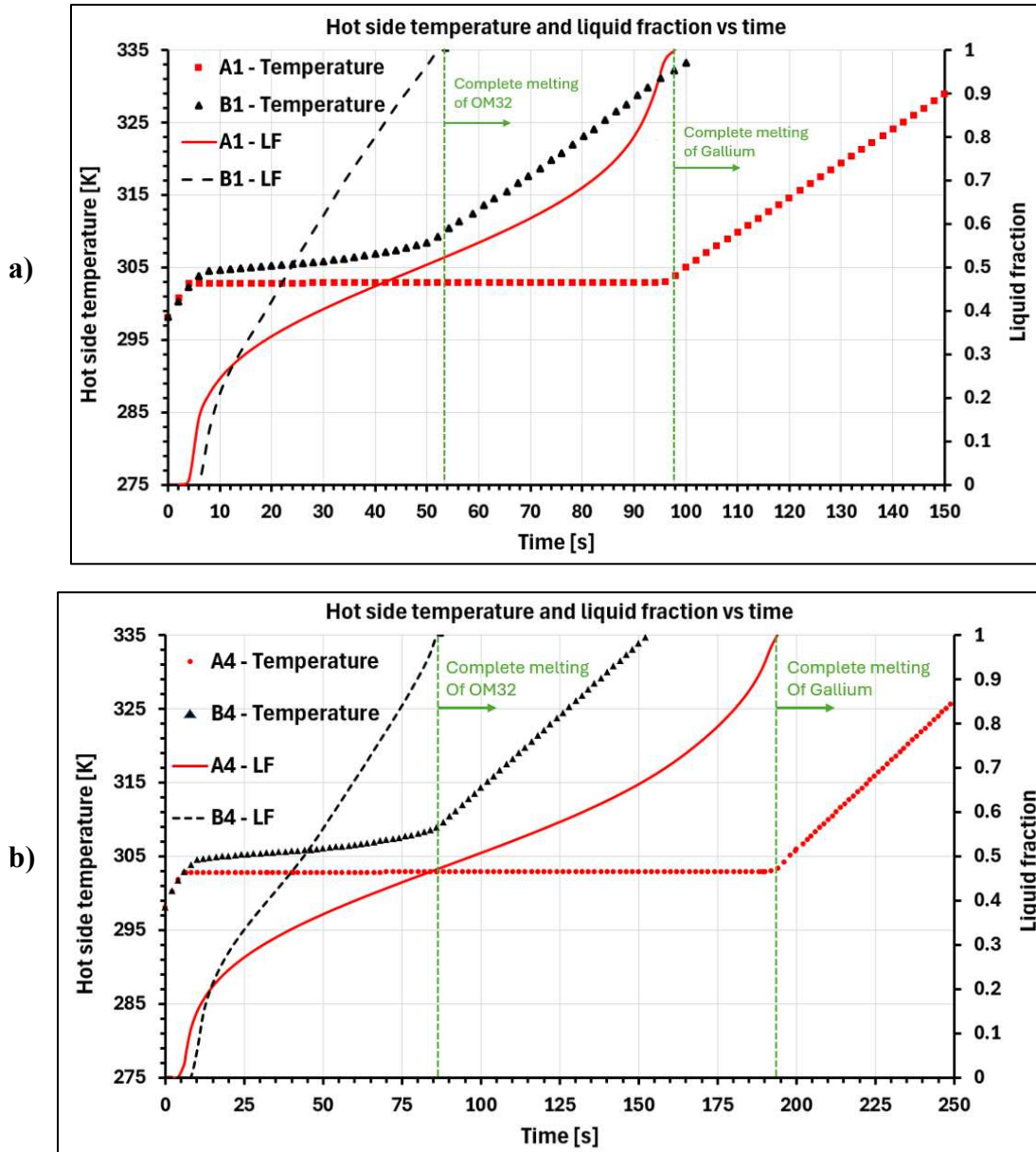


Fig. 6 Liquid fraction and hot side temperature plots; (a) The plot of A1 and B1 cases at PCM height of 1.5 mm, (b) The plot of A4 and B4 cases at PCM height of 3 mm.

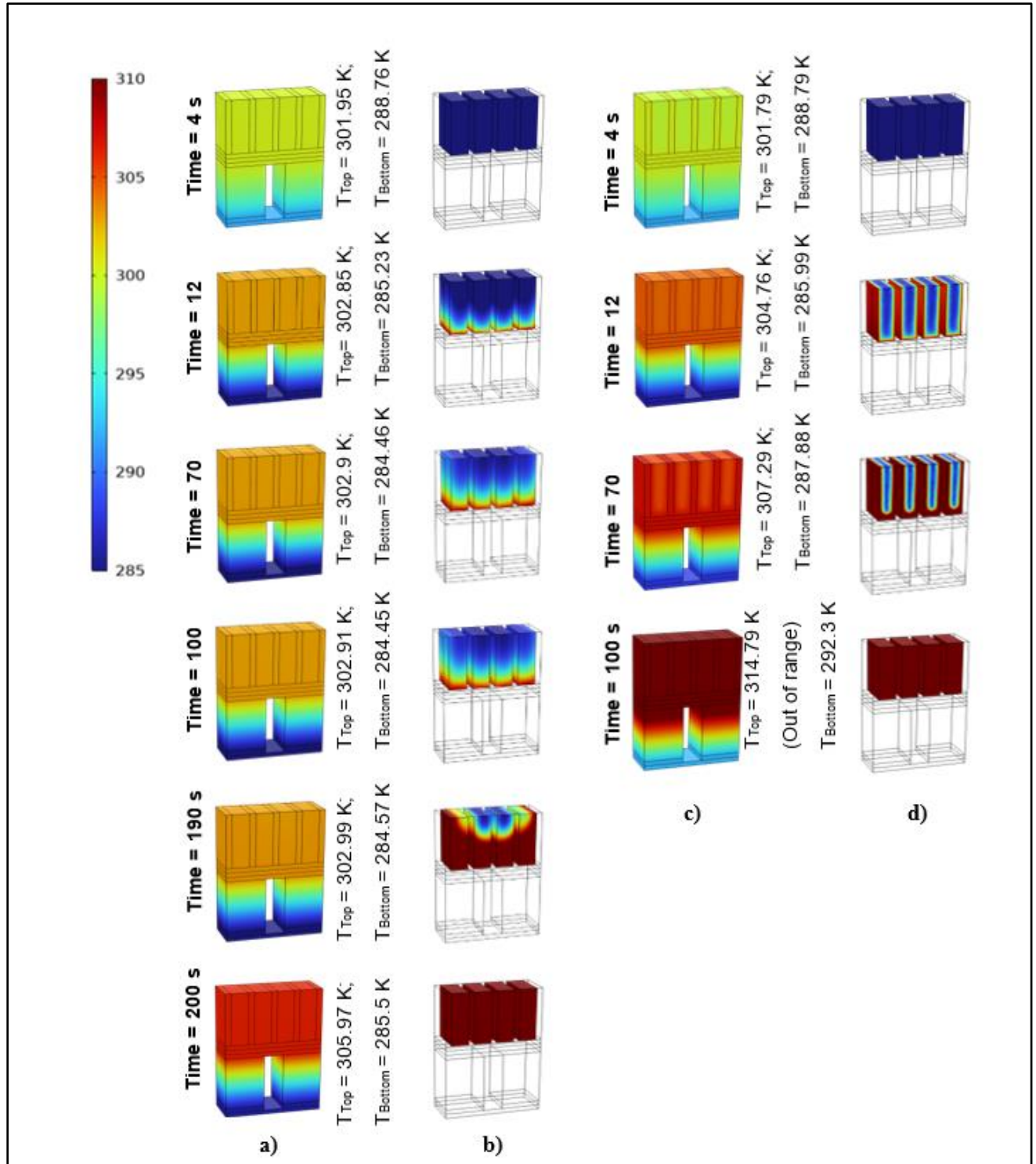


Fig. 7 Liquid fraction and temperature contours; (a) Temperature contour of case A4, (b) Liquid fraction of case A4, (c) Temperature contour of case B4, (d) Liquid fraction of case B4.

The effect of the current on the cold side temperature

One of the most important parameters to study is the current input value. The variation of currents leads to changes in the cold and hot side temperatures of the TEC device. As we mentioned earlier, the TEC-PCM finned system is subjected to heat load from the bottom, which could be heat from an electronic chip or any device that rejects heat during the operation. Effective thermal management is crucial for heat-rejecting systems to ensure stable operation and prevent performance degradation or failure. This section focuses on the role of PCM for both OM32 and Gallium in maintaining a lower cold-side temperature for extended durations under varying current levels.

Starting with cases C1, C2, and C3, and by referring to Table 1, these cases represent the TEC system with fins only and no PCM filling the cavities. For the sake of comparison, these cases will be the base cases of our study. Then we will add PCM - namely Gallium and OM32 - to investigate their influence on the thermal performance of the TEC system, especially the cold side temperature.

Figures 8(a), (b), and (c) show the cold side temperature values for the base cases against cases where PCM fills the sink cavity with a height of 1.5 mm. Each plot represents the recorded temperature values of the three cases (Base, OM32, and Gallium) at three current levels. In Figure 8, the C1, C2, and C3 cases are represented by solid lines. The initial decline observed when current is applied due to the Peltier effect, where the cold-side temperature decreases rapidly at the beginning. In case C1, with a current of 1 A, the cold-side temperature drops to approximately 288 K within 6 seconds. Whereas in the case C2, with a current of 1.2 ampere, the temperature decreases further to approximately 286 K, and in case C3, where the current is 1.4 ampere, it reaches around 284 K. After this initial cooling phase, the temperature begins to rise. This is because the top side of the TEC in these cases is only subjected to natural convection, and when the top side gets heated, the heat is not effectively removed through the fins. So, when the temperature gradients become large enough (Hot from the top side and cold at the bottom side), the heat will find another bath to flow. As a result of that, the heat will flow to the bottom side of the TEC. This leads to heating the bottom side, which in turn increases the cold side temperature for C1, C2, and C3 cases as seen in Figure 8.

Now, we will move to B1, B2, and B3 cases with current values of 1, 1.2, and 1.4 amperes, respectively. Referring to Table 1, these cases represent OM32 as a filled-in material under a height of 1.5 mm. From Figure 8(a), the cold side temperature curve of case B1 records values less than 290 K for about 50 seconds. Demonstrating improvement in maintaining low temperature values for a longer period than in case C1. This is attributed to the PCM being placed on the top side of the TEC. Having PCM placed on the hot side (top side) will help in absorbing the heat generated by the TEC through the phase change process, forcing the system to operate at a relatively constant temperature (melting temperature of OM32). This prevents a temperature rise, thereby avoiding reverse heat flow to the cold side (bottom side) of the TEC.

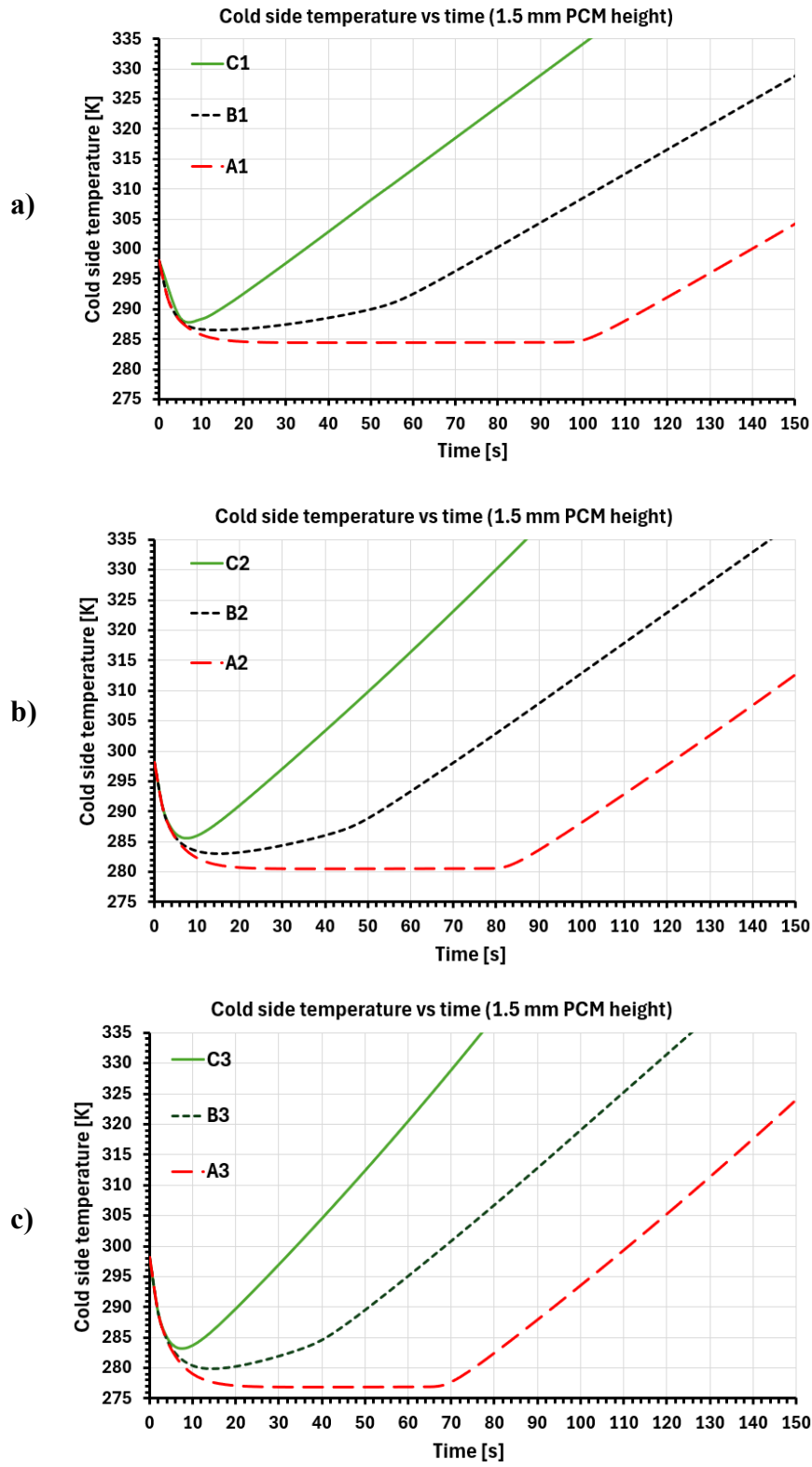


Fig. 8 Cold side temperature records of TEC with PCM at 1.5 mm height; (a) TEC under 1 ampere current, (b) TEC under 1.2 ampere current, (c) TEC under 1.4 ampere current.

When complete melting was reached, which is short after 50 seconds as shown in Figure 8(a), the cold side temperature began to increase. However, comparing the temperature profiles of cases B1 and C1 reveals that the presence of PCM shifted the temperature curve downward, even during the complete melting phase. Notably, case B1 showed a nearly 20 K lower temperature than case C1 at 60 seconds.

Looking at Figure 8, we can see B2 and B3 cases have similar behavior to case B1. However, because the current is higher, the recorded temperature of these cases during the declining stage is lower than that in case B1. Increasing the current supplied to the TEC enhances the Peltier effect, which leads to a further reduction in the cold-side temperature. On the other hand, a higher current causes the hot side to become hotter, accelerating the melting rate of PCM. This reduces the time before the temperature starts to increase again. As shown in Figures 8(b) and (c), the temperature in cases B2 and B3 begins rising 10 and 20 seconds earlier, respectively, than in case B1.

Regarding A1, A2, and A3 cases, and by referring to Table 1, we can see that gallium is used as PCM under different current values. The recorded cold side temperature profile demonstrates the superior thermal regulation performance of gallium (case A1) compared to both the base case without PCM (C1) and the organic PCM (B1). Gallium achieved the lowest minimum temperature of approximately 284.5 K, which is lower than the minimum temperatures observed in B1 (~286.5 K) and C1 (~288.7 K). Furthermore, gallium maintained this minimum temperature for a significantly longer duration. The temperature in case A1 remained nearly constant around its minimum from 10 seconds up to approximately 100 seconds, effectively prolonging the cooling phase. In contrast, the temperature in B1 began to rise again at around 40 seconds, while C1 exhibited an earlier temperature increase starting near 20 seconds. This extended thermal buffering period highlights gallium's excellent heat absorption and latent heat characteristics, making it more effective in sustaining lower cold side temperatures over time compared to both OM32 and the no-PCM cases.

As we discussed in the previous section, increasing the PCM level will prolong the time needed to reach complete melting. Maintaining the temperature at a relatively constant value before it increases. Hereby, we will discuss cases (C1, A4, and B4) where the PCM (gallium and OM32) height is increased to 3 mm under 1 ampere current input.

Figure 9 illustrates the behavior of the cold-side temperature of the TEC. Among the cases, A4 containing gallium exhibited the lowest recorded temperature and maintained that temperature for the longest duration before it began to rise. This observation aligns with the conclusion drawn from the discussion of Figure 8. However, a notable difference here is that both A4 and B4 cases sustained lower temperatures for a longer period compared to A1 and B1. This suggests that increasing the quantity of gallium and OM32 enhances the system's capacity to absorb heat, thereby prolonging the phase change process.

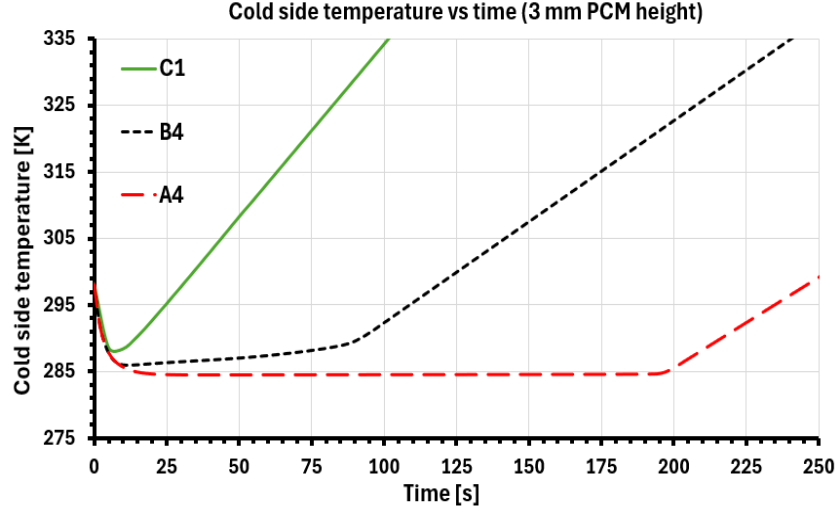


Fig. 9 Cold side temperature records of TEC with PCM at 3 mm height under 1 ampere current.

Figure 10 presents the cold-side temperature evolution for five different cases under a constant current of 1.2 ampere. These cases were chosen as a representative value to avoid redundancy, as similar trends were observed for 1 ampere and 1.4 ampere. The C2 case, which lacks any PCM, exhibits the highest temperature rise, reaching approximately 333 K within 100 seconds, indicating poor thermal regulation and rapid heat buildup. In contrast, the remaining cases (A2, A5, B2, and B5) demonstrate significantly improved thermal performance due to the integration of PCMs. The use of gallium (A2 and A5) and OM32 (B2 and B5) introduces latent heat absorption, which delays the temperature rise and results in lower cold-side temperatures. Among these, gallium outperforms OM32 in both configurations. A2, with 1.5 mm of gallium, achieves a lower minimum temperature of 281 K and maintains it for 85 s longer than B2 (~283.5 K for ~60 seconds). Similarly, A5 (gallium, 3 mm) with a temperature value of 279.5 K outperforms B5 (OM32, 3 mm), maintaining a lower temperature for a longer duration (~175 seconds). Overall, the best performance is observed in case A5, which combines the favorable properties of gallium with increased PCM volume, resulting in the lowest and most sustained cold-side temperature, highlighting its potential for enhanced thermoelectric cooling applications.

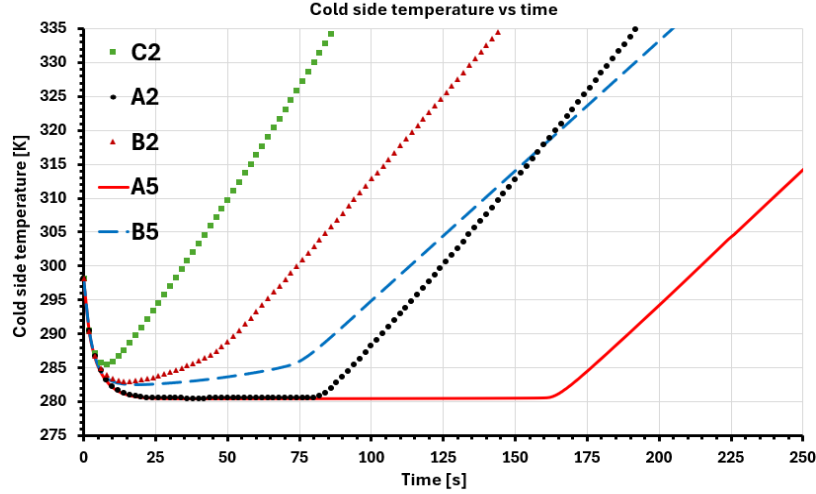


Fig. 10 Cold-side temperature evolution over time for various PCM configurations under 1.2 A current input.

COP of the TEC

The COP serves as a key metric for evaluating the efficiency of the TEC system, as it reflects the ratio of cooling capacity to the electrical power consumed. Analyzing COP under different PCM types, heights, and operating currents provides deeper insight into how these factors influence the overall energy efficiency of the system.

The effect of PCM's type and height on the COP

Figure 11 illustrates the COP of the TEC system under different PCM configurations compared to the baseline case without PCM, all operating at a constant current of 1 ampere. In the baseline case (C1), the COP exhibits a sharp decline during the initial period, after which it gradually stabilizes at about 0.85. This rapid decrease is attributed to the quick rise in cold-side temperature due to the absence of latent heat storage (refer to Figure 8(a)), which causes a sudden increase in temperature difference across the TEC and thus diminishes its COP.

In contrast, PCM-filled cases demonstrate a clear improvement in COP performance due to their ability to absorb heat through the phase change process. As we discussed before in Figure 8(a), placing PCM at the top of TEC will delay the rise in cold-side temperature. In Figure 11(a), for the 1.5 mm PCM height, A1 achieves the highest COP enhancement, reaching a peak improvement of approximately 0.23 to 0.5 above C1 for 95 seconds, then the COP begins to decline as complete melting is reached. B1 also improves performance compared to C1, with a peak improvement of about 0.25 – 0.3 above, and a duration of COP enhancement lasting around 50 seconds before it declines again to reach a COP level close to case C1.

Figure 11(b) shows the effect of increasing the PCM height to 3 mm. The larger PCM volume in A4 (gallium) and B4 (OM32) further extends the COP improvement window due to the larger latent heat storage capacity. A4 achieves the most significant performance, maintaining COP of 1.5 for nearly 195 seconds - almost double the duration of A1 - and exhibiting an early

peak improvement of ~ 0.18 over C1. B4 also benefits from the increased PCM volume, with an improvement of COP and a duration of approximately 85 seconds.

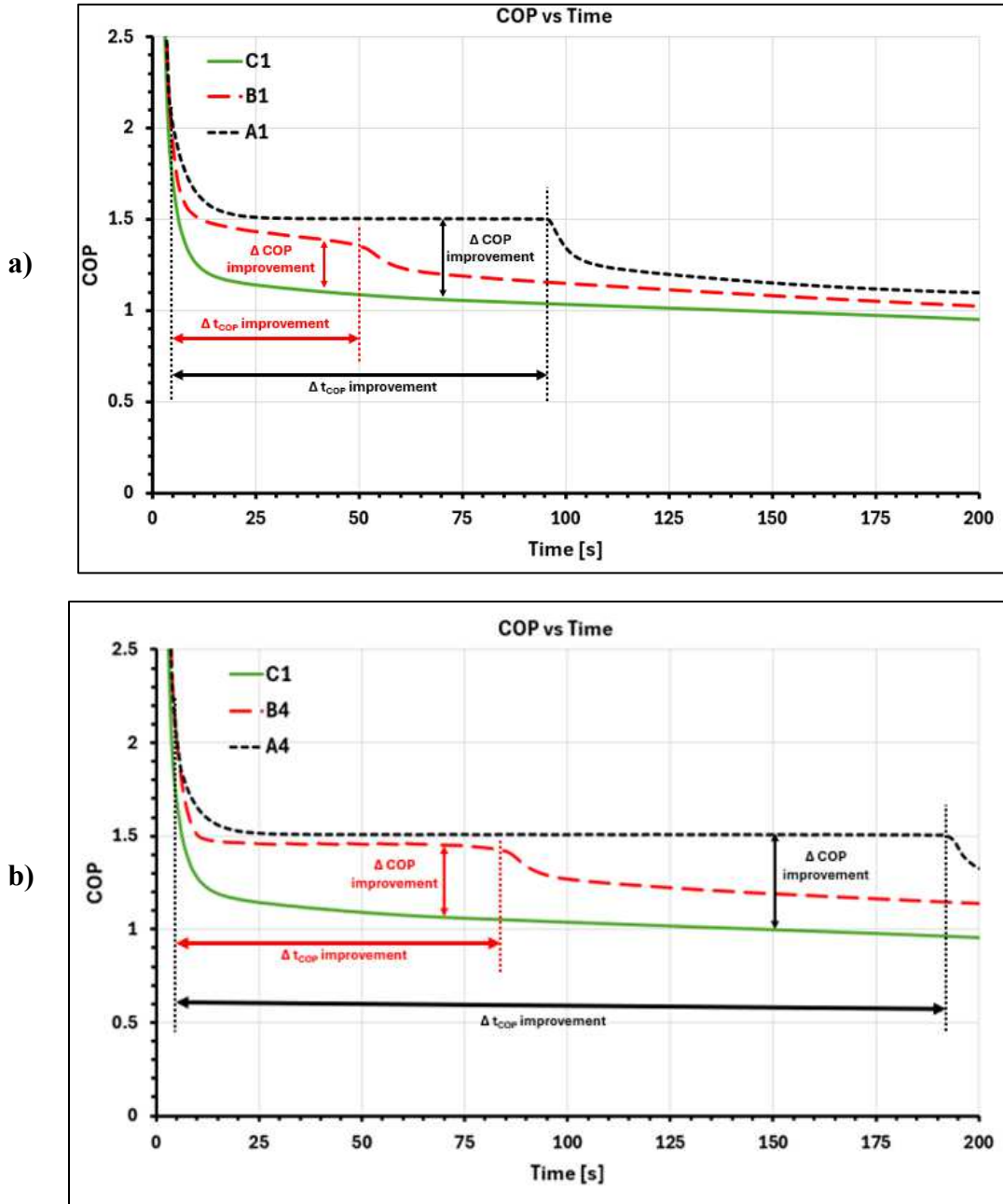


Fig. 11 COP of TEC against time under 1 A current input; (a) PCM cases with 1.5 mm height; (b) PCM cases with 3 mm height.

Overall, the results demonstrate that integrating PCM into the sink cavities significantly improves the COP of TEC systems, with both gallium and OM32 providing noticeable benefits over the base case. Gallium consistently outperforms OM32 due to its superior thermal properties,

and increasing PCM volume enhances the duration of COP improvement without a noticeable change in COP value. The A4 configuration (gallium, 3 mm) delivers the best overall performance, sustaining higher efficiency for the longest period and thus representing the most effective thermal management strategy among the tested configurations.

The effect of the input current on the COP of TEC with and without PCM

Figure 12 compares the COP evolution of 1.5 mm PCM-filled and baseline configurations at currents of 1.2 ampere and 1.4 ampere, as shown in Figures 12(a) and (b), respectively, highlighting the effect of increasing input current on TEC system efficiency. Relative to the 1.0 ampere results discussed earlier, COP values for all cases decrease noticeably as current increases, due to the combined effect of greater Joule heating and higher heat pumping rates. Higher input current values accelerate the temperature rise at the cold side and shorten the phase change period of the PCM.

In Figure 12(a), the COP of the baseline case (C2) drops rapidly to stabilize at approximately 0.78. In comparison, the gallium-filled case (A2) fell to 1.15 during the first 76 seconds and stabilized near 0.82, approaching the COP of the C1 case. While the OM32-filled case (B2) performs in between, dropping to 1.1 at 45 seconds, and stabilizing near 0.8. These results indicate that while PCMs still provide a temperature buffering effect, their COP advantage over the baseline at 1.2 ampere is reduced, and the improvement period (time above the baseline COP curve) is shorter than at 1.0 ampere - roughly 75 seconds for gallium and 45 seconds for OM32, compared to ~95 seconds and ~50 seconds, respectively, at 1.0 ampere input current as shown in Figure 11(a).

When the current is increased further to 1.4 ampere (see Figure 12(b)), the performance drop is more pronounced. The baseline case C3 falls rapidly to 0.6 within nearly 60 seconds. Gallium-filled case (A3) drops to 0.9 and stabilizes at approximately 0.68, while OM32-filled case (B3) follows a similar trend, stabilizing around 0.66. Here, the relative COP benefit of PCM filling becomes marginal because the PCM's latent heat is exhausted much faster under the higher heat load, limiting its ability to maintain a temperature differential across the TEC for extended periods. The COP improvement period is now reduced to ~65 seconds for gallium and ~40 seconds for OM32, which is less than the duration seen in A1 and B1 cases in Figure 11(a).

These results confirm that increasing the input current reduces COP for all configurations due to the dominance of heating generated and shortened PCM phase change duration. Gallium maintains a slight advantage over OM32 at all currents because of its higher thermal conductivity and more efficient heat transfer into the PCM mass. However, as current increases, the absolute benefit of PCM integration diminishes, indicating that PCM-based thermal management is most effective at operating currents where the heat load does not exceed the PCM's absorption capacity too quickly.

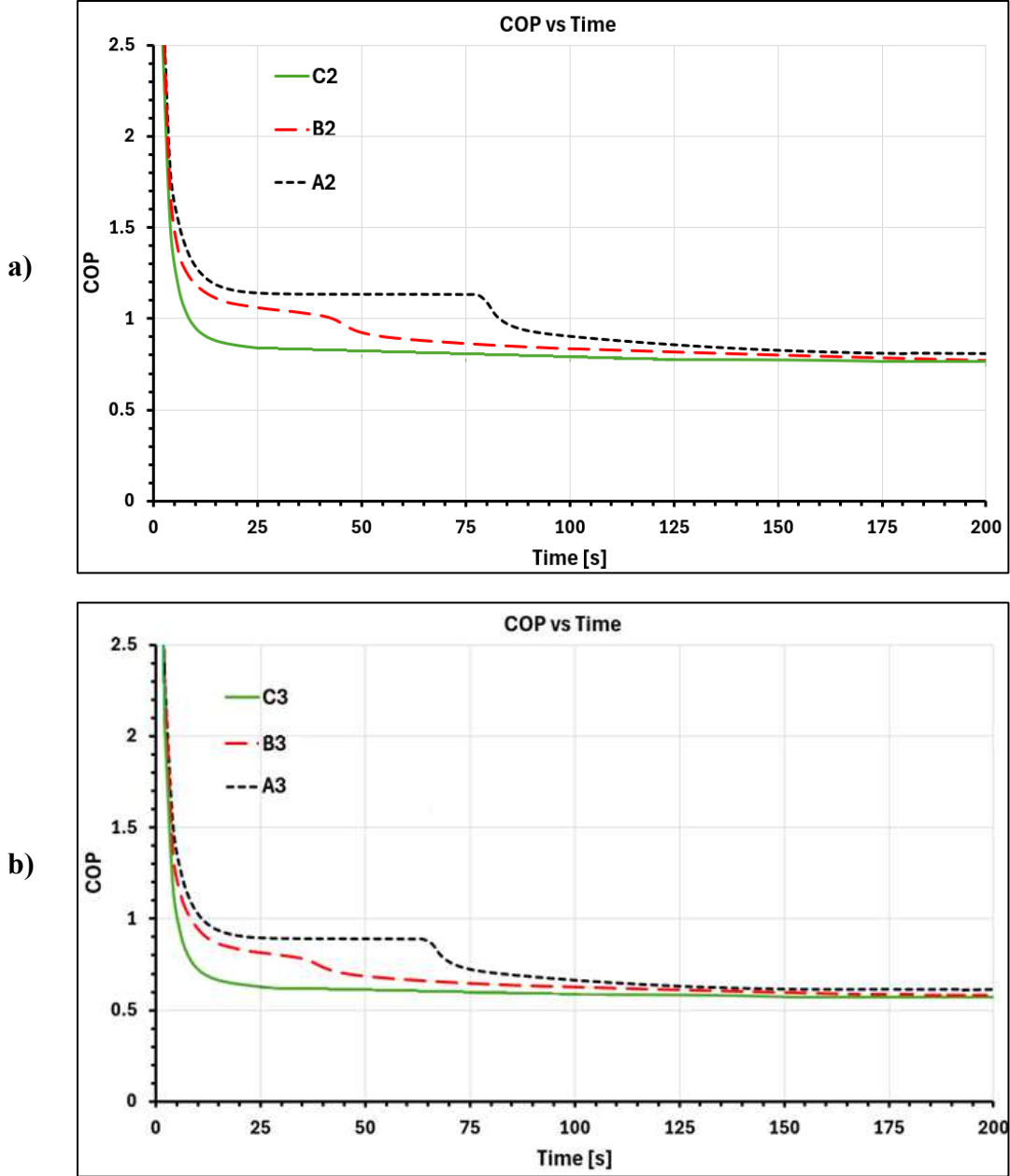


Fig. 12 COP of TEC against time under 1.5 mm PCM height and different current values; (a) TEC cases with 1.2 ampere input current; (b) TEC cases with 1.4 ampere input current.

In Figure 13, the COP improvement of the TEC system is presented for three different operating currents (1.0 ampere, 1.2 ampere, and 1.4 ampere) under three configurations (Please refer to Table 1), with a PCM height of 3 mm for the filled cases. The results indicate that the incorporation of PCM enhances the COP across all current levels when compared to the base cases without PCM (C1, C2, C3). At 1.0 ampere, A4 achieved the highest COP of approximately 1.5, followed closely by B4 at around 1.45, representing an improvement of about 50% and 45% respectively, over the no-PCM case (C1). At 1.2 ampere, the COP values decreased slightly for all cases; however, A5 and B5 still outperformed the base case (C2) by roughly 28% and 22%,

respectively. At 1.4 ampere, although the overall COP dropped further due to increased Joule heating, which decreased the phase change period, A6 maintained a COP of about 0.9 and B6 about 0.85, both showing significant gains of over 40% compared to the no-PCM case (C3). Overall, Gallium consistently delivered marginally higher COP than OM32, and the benefits of PCM were most notable at the lowest current levels, demonstrating the effectiveness of PCM in sustaining higher system efficiency under varying electrical loads and maintaining relatively high COP levels for a longer time.

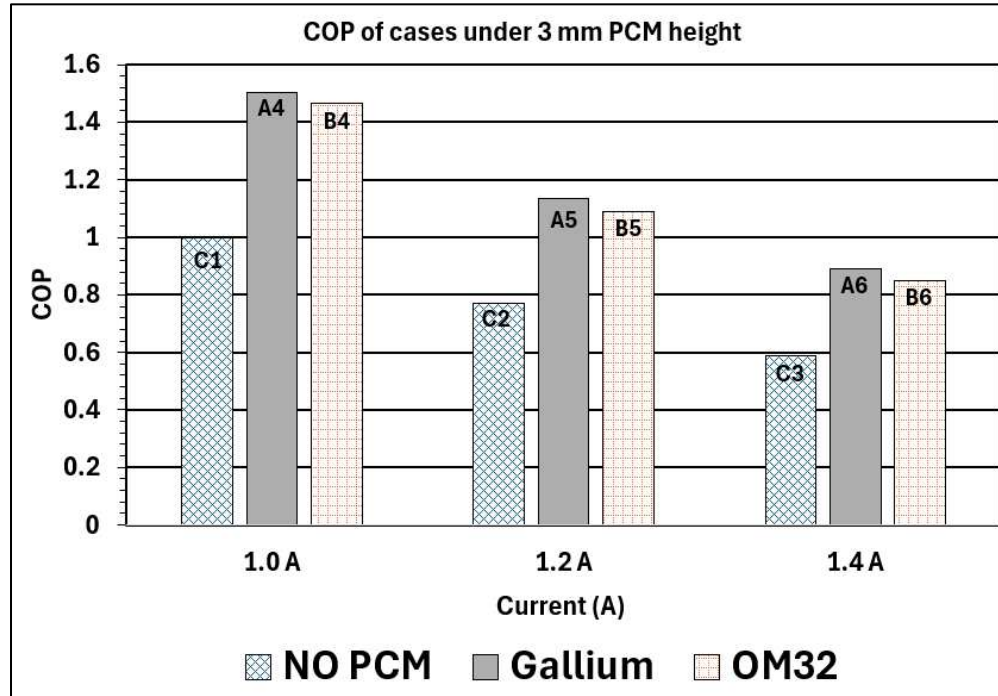


Fig. 13 COP variation of TEC system without and with PCM (Gallium and OM32) at different input currents for 3 mm PCM height.

Conclusions

The impact of PCM type, PCM height, and current input of TEC systems was systematically investigated in this study using detailed COMSOL Multiphysics simulations. The results confirmed that both gallium and OM32 PCMs enhance TEC cooling performance and COP compared to baseline fin-only configurations. Gallium consistently outperformed OM32 due to its higher thermal conductivity and larger total latent heat capacity (due to its large density), enabling more uniform heat distribution, delayed temperature rise, and prolonged phase change duration.

Increasing PCM height from 1.5 mm to 3 mm further extended the thermal buffering period for both materials, with gallium-filled systems achieving the longest low-temperature maintenance and highest COP improvements. At lower operating currents (1.0 A), the COP enhancement was most pronounced, with gallium achieving up to a 50% improvement over the baseline. While

higher currents increase Joule heating and accelerate PCM melting, which reduces overall COP, gallium still maintains a marginal advantage over OM32 at all tested conditions.

The findings demonstrate that integrating high-conductivity PCMs, particularly gallium, into TEC fin cavities is an effective passive thermal management strategy that can significantly improve cooling stability and system efficiency. This approach is beneficial under heat loads, where PCM absorption capacity can be fully utilized before complete melting.

Future work may focus on hybrid PCM configurations, encapsulation strategies, and combined active-passive cooling methods to further optimize TEC-based systems. Different heating loads at the cold side of the TEC could be studied. Also, metal foam can be used to enhance the conductivity of paraffin PCMs. Studying the TEC system's behavior under transient current input can also be investigated.

Data availability

All data generated and analyzed during this study are available on request.

References

1. Zhao, D., & Tan, G. (2014a). A review of thermoelectric cooling: Materials, modeling and applications. *Applied Thermal Engineering*, 66(1–2), 15–24. <https://doi.org/10.1016/j.applthermaleng.2014.01.074>
2. Chen, M., Rosendahl, L. A., & Condra, T. (2010). A three-dimensional numerical model of thermoelectric generators in fluid power systems. *International Journal of Heat and Mass Transfer*, 54(1–3), 345–355. <https://doi.org/10.1016/j.ijheatmasstransfer.2010.08.024>
3. Thacher, E. F., Helenbrook, B. T., Karri, M. A., & Richter, C. J. (2007). Testing of an automobile exhaust thermoelectric generator in a light truck. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering*, 221(1), 95–107. <https://doi.org/10.1243/09544070jauto51>
4. Selvam, C., Manikandan, S., Kaushik, S., Lamba, R., & Harish, S. (2019). Transient performance of a Peltier super cooler under varied electric pulse conditions with phase change material. *Energy Conversion and Management*, 198, 111822. <https://doi.org/10.1016/j.enconman.2019.111822>
5. Rowe, D. M. (2010). *Thermoelectrics Handbook*. In CRC Press eBooks. <https://doi.org/10.1201/9781420038903>
6. Bianco, V., De Rosa, M., & Vafai, K. (2022). Phase-change materials for thermal management of electronic devices. *Applied Thermal Engineering*, 214, 118839. <https://doi.org/10.1016/j.applthermaleng.2022.118839>
7. Zhang, S., Wu, Y., Hu, J., Huang, R., Zhou, Y., Bao, X., Fu, L., & Hao, J. (2014). Can Euro V heavy-duty diesel engines, diesel hybrid and alternative fuel technologies mitigate NO X emissions? New evidence from on-road tests of buses in China. *Applied Energy*, 132, 118–126. <https://doi.org/10.1016/j.apenergy.2014.07.008>

8. Mishra, R. K., Verma, K., Mishra, V., & Chaudhary, B. (2022). A review on carbon-based phase change materials for thermal energy storage. *Journal of Energy Storage*, 50, 104166. <https://doi.org/10.1016/j.est.2022.104166>
9. Du, K., Calautit, J., Wang, Z., Wu, Y., & Liu, H. (2018). A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges. *Applied Energy*, 220, 242–273. <https://doi.org/10.1016/j.apenergy.2018.03.005>
10. Gao, Y., Zhang, X., Xu, X., Liu, L., Zhao, Y., & Zhang, S. (2021). Application and research progress of phase change energy storage in new energy utilization. *Journal of Molecular Liquids*, 343, 117554. <https://doi.org/10.1016/j.molliq.2021.117554>
11. Tomizawa, Y., Sasaki, K., Kuroda, A., Takeda, R., & Kaito, Y. (2015). Experimental and numerical study on phase change material (PCM) for thermal management of mobile devices. *Applied Thermal Engineering*, 98, 320–329. <https://doi.org/10.1016/j.applthermaleng.2015.12.056>
12. Sharma, A., Tyagi, V., Chen, C., & Buddhi, D. (2008). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews*, 13(2), 318–345. <https://doi.org/10.1016/j.rser.2007.10.005>
13. Ling, Z., Zhang, Z., Shi, G., Fang, X., Wang, L., Gao, X., Fang, Y., Xu, T., Wang, S., & Liu, X. (2014). Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules. *Renewable and Sustainable Energy Reviews*, 31, 427–438. <https://doi.org/10.1016/j.rser.2013.12.017>
14. Xia, Z., Cao, W., Sun, X., Ding, Q., Zhu, Z., Zhou, W., Yan, S., Hou, Y., & Wang, Z. (2025). Performance Study of Wearable Thermoelectric Cooler with Phase-Change Composite Heat Sink. *Materials*, 18(7), 1576. <https://doi.org/10.3390/ma18071576>
15. Zhao, D., & Tan, G. (2014). Experimental evaluation of a prototype thermoelectric system integrated with PCM (phase change material) for space cooling. *Energy*, 68, 658–666. <https://doi.org/10.1016/j.energy.2014.01.090>
16. Venkatesan, K., & Venkataramanan, M. (2020). Experimental and Simulation studies on Thermoelectric Cooler: A Performance Study approach. *International Journal of Thermophysics*, 41(4). <https://doi.org/10.1007/s10765-020-2613-2>
17. Xu, Y., Wang, J., & Li, T. (2022). Thermal performance of low melting point metal-based heat sinks for high-power airborne equipment. *Energy Reports*, 8, 8907–8917. <https://doi.org/10.1016/j.egy.2022.07.014>
18. Yang, X., Tan, S., & Liu, J. (2016). Numerical investigation of the phase change process of low melting point metal. *International Journal of Heat and Mass Transfer*, 100, 899–907. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.04.109>
19. Manikandan, S., Selvam, C., Praful, P. P. S., Lamba, R., Kaushik, S. C., Zhao, D., & Yang, R. (2019). A novel technique to enhance thermal performance of a thermoelectric cooler using phase-change materials. *Journal of Thermal Analysis and Calorimetry*, 140(3), 1003–1014. <https://doi.org/10.1007/s10973-019-08353-y>
20. Hodes, M., Weinstein, R. D., Pence, S. J., Piccini, J. M., Manzione, L., & Chen, C. (2002). Transient thermal management of a handset using phase change material (PCM). *Journal of Electronic Packaging*, 124(4), 419–426. <https://doi.org/10.1115/1.1523061>

21. Saha, S. K., Srinivasan, K., & Dutta, P. (2008). Studies on optimum distribution of fins in heat sinks filled with phase change materials. *Journal of Heat Transfer*, 130(3). <https://doi.org/10.1115/1.2804948>
22. Qiu, L., Ouyang, Y., Feng, Y., & Zhang, X. (2019). Review on micro/nano phase change materials for solar thermal applications. *Renewable Energy*, 140, 513–538. <https://doi.org/10.1016/j.renene.2019.03.088>
23. Wang, X., Xu, J., Zhang, F., & Du, S. (2007). Phase change materials at the cold/hot sides of thermoelectric cooler for temperature control. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*, 6423, 642318. <https://doi.org/10.1117/12.779364>
24. Caroff, T., Mitova, R., Wunderle, B., & Simon, J. (2013). Transient cooling of power electronic devices using thermoelectric coolers coupled with phase change materials (pp. 262–267). <https://doi.org/10.1109/therminic.2013.6675252>
25. Dong, K., Kawaguchi, T., Shimizu, Y., Sakai, H., & Nomura, T. (2022). Optimized preparation of a Low-Working-Temperature Gallium Metal-Based microencapsulated phase change material. *ACS Omega*, 7(32), 28313–28323. <https://doi.org/10.1021/acsomega.2c02801>
26. Yang, X., Tan, S., He, Z., & Liu, J. (2018). Finned heat pipe assisted low melting point metal PCM heat sink against extremely high power thermal shock. *Energy Conversion and Management*, 160, 467–476. <https://doi.org/10.1016/j.enconman.2018.01.056>
27. Peng, H., Guo, W., Li, M., & Feng, S. (2021). Melting behavior and heat transfer performance of gallium for spacecraft thermal energy storage application. *Energy*, 228, 120575. <https://doi.org/10.1016/j.energy.2021.120575>
28. Ben-David, O., Levy, A., Mikhailovich, B., & Azulay, A. (2013). 3D numerical and experimental study of gallium melting in a rectangular container. *International Journal of Heat and Mass Transfer*, 67, 260–271. <https://doi.org/10.1016/j.ijheatmasstransfer.2013.07.058>
29. Park, C. Y., Kim, S., Song, C., Kim, J., & Lee, J. (2025). Gallium-in-Glycerol Phase Change Material Emulsions (PCMEs) with Superior Latent Heat Capacity and Thermal Conductivity. *Materials Advances*. <https://doi.org/10.1039/d5ma00152h>
30. Wang, H., Chen, S., Zhu, X., Yuan, B., Sun, X., Zhang, J., Yang, X., Wei, Y., & Liu, J. (2022). Phase transition science and engineering of gallium-based liquid metal. *Matter*, 5(7), 2054–2085. <https://doi.org/10.1016/j.matt.2022.05.031>
31. Xu, Z., Li, X., Zhu, Z., Wang, Q., Chen, Y., & Ma, T. (2020). Experimental study on the heat transfer performance of a gallium heat sink. *Energy Conversion and Management*, 213, 112853. <https://doi.org/10.1016/j.enconman.2020.112853>
32. Qasem, M. S. (n.d.). Heat sink integrating phase change materials (pcms) for cooling high power electronic devices. *Scholarworks@UAEU*. https://scholarworks.uaeu.ac.ae/all_theses/1178?utm_source=scholarworks.uaeu.ac.ae%2Fall_theses%2F1178&utm_medium=PDF&utm_campaign=PDFCoverPages
33. Ki, S., Shin, S., Cho, S., Bang, S., Choi, D., & Nam, Y. (2024). Sustainable thermal regulation of electronics via mitigated supercooling of porous Gallium-Based phase change materials. *Advanced Science*, 11(23). <https://doi.org/10.1002/advs.202310185>

34. Samara, F., Groulx, D., & Biwole, P. H. (2012). Natural Convection Driven Melting of Phase Change Material: Comparison of Two Methods. In COMSOL Conference (pp. 1–8).
35. Ben-David, O., Levy, A., Mikhailovich, B., & Azulay, A. (2013b). 3D numerical and experimental study of gallium melting in a rectangular container. *International Journal of Heat and Mass Transfer*, 67, 260–271. <https://doi.org/10.1016/j.ijheatmasstransfer.2013.07.058>
36. Beckermann, C., & Viskanta, R. (1988). Natural convection solid/liquid phase change in porous media. *International Journal of Heat and Mass Transfer*, 31(1), 35–46. [https://doi.org/10.1016/0017-9310\(88\)90220-7](https://doi.org/10.1016/0017-9310(88)90220-7)
37. Al-Omari, S. a. B., Qureshi, Z. A., Elnajjar, E., & Mahmoud, F. (2021). A heat sink integrating fins within high thermal conductivity phase change material to cool high heat-flux heat sources. *International Journal of Thermal Sciences*, 172, 107190. <https://doi.org/10.1016/j.ijthermalsci.2021.107190>
38. Zhao, T., Li, K., Zhu, Y., Jia, L., Hou, X., Wang, S., & Kaita, M. (2021). An experimental method for fast evaluating thermoelectric generators using one pair of P- and N-Type legs. *Journal of Energy Resources Technology*, 143(10). <https://doi.org/10.1115/1.4050574>
39. Jaegle, M. (2008) Multiphysics Simulation of Thermoelectric Systems—Modeling of Peltier-Cooling and Thermoelectric Generation. COMSOL Conference, Hannover, 2008.
40. Wang, X., Repaka, D. V. M., Suwardi, A., Zhu, Q., Wu, J., & Xu, J. (2023). Thermal and electrical properties of liquid metal gallium during phase transition. *Transactions of Tianjin University*, 29(3), 209–215. <https://doi.org/10.1007/s12209-023-00357-y>

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Contributions

The contributions of the authors to this paper are as follows: Mohammad Qasem: methodology, conceptualization, result compilation and analysis, writing—original draft, and supervision. Dana Alshamaileh: methodology, result validation, writing—review & editing, supervision. All authors reviewed the results and approved the final version of the manuscript.

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Ethics declarations**Consent to publication**

The authors permit the Discover Materials Journal to publish their work.

Informed consent

No informed consent is required for this type of study.

Human, animal, and plant ethical

This article does not contain any studies with human participants or animals or plants by any of the authors.

Competing interests

The authors declare no competing interests.

Clinical trial

Not applicable.