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# Realizing rapid cooling and latent heat recovery in the thermoelectric-based battery thermal management system at high temperatures

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# HIGHLIGHTS

• TEC helps to recover the latent heat of PCMs.

• A thermal-electric-fluid multi-physical field numerical model for the BTMS is developed.

- The integration of TEC significantly improves the cooling efficiency of the BTMS.
- The 12%EG-based PCM and 4 A TEC input current are selected as the optimal configuration.

## ARTICLE INFO

Keywords: Battery thermal management system Thermoelectric Phase change material Latent heat recovery Numerical mode

# ABSTRACT

To realize rapid cooling of the battery at high temperatures and effective latent heat recovery from phase change materials (PCMs), a thermoelectric-based battery thermal management system (BTMS) is proposed. Additionally, a transient multiphysics numerical model is developed to predict the system's thermal performance, and the concept of the latent heat recovery rate of PCMs is introduced. Results show that the introduction of thermoelectric coolers (TECs) significantly enhances the system's efficiency in cooling the battery at high temperatures (Stage 1) and recovering PCM latent heat (Stage 2). The overall thermal performance can be further improved by utilizing PCMs with a higher mass fraction of expanded graphite (EG) or increasing the TEC input current. Moreover, after the end of Stage 2, the power supply for TECs is interrupted, and the system enters Stage 3, which only relies on PCMs to control the battery temperature. The duration of Stage 3 increases with the EG mass fraction, achieving a peak of 3830 s at an EG mass fraction of 12%. Considering the thermal performance and power consumption of the system, the optimal solution is determined as an EG mass fraction of 12% and a TEC input current of 4 A. In this situation, the required time for Stage 1 and Stage 2 is 170 s and 620 s, with the latent heat recovery rate of PCMs up to 361.94 J/kg/s. The findings will provide new insights for the development of the thermoelectric-based BTMS.

#### 1. Introduction

The growing global focus on sustainable development and environmental protection has heightened interest in the advancement of electric vehicles (EVs) as a form of clean energy transportation [1]. Lithium-ion batteries, serving as essential energy components in EVs, emerge as a pivotal catalyst in advancing electric vehicle technology, attributed to their notable features such as low self-discharge rate, high energy density, and extended cycle life [2]. Nevertheless, lithium-ion battery

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Nomenclature		ρ	density, kg·m <sup><math>-3</math></sup>
		μ	dynamic viscosity, Pa·s
Symbols		β	liquid fraction
$c_p$	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$	$\sigma$	electrical conductivity, $S \cdot m^{-1}$
$ \begin{array}{c} C_{p} \\ \overrightarrow{E} \\ H \\ h \\ \Delta h \\ I \\ \overrightarrow{J} \\ k \\ Lv \\ p \\ Q \\ T \\ t \\ v \\ V \\ Greek \\ Synthetic Synthet$	specific field density vector, $V \cdot m^{-2}$ enthalpy, $J \cdot kg^{-1}$ sensible heat enthalpy, $J \cdot kg^{-1}$ phase change enthalpy, $J \cdot kg^{-1}$ current, A current density vector, $A \cdot m^{-2}$ turbulent kinetic energy, $m^2 \cdot s^{-2}$ latent heat recovery rate, $J \cdot kg^{-1} \cdot s^{-1}$ pressure, Pa heat generation power, W temperature, K time, s mass flow rate, $kg \cdot s^{-1}$ volume, mm <sup>3</sup>	o Subscrip b co l m n p pcm s Abbrevic BTMS CPCM EV EG PCM	ts battery copper electrode liquid phase material n-type thermoelectric leg p-type thermoelectric leg phase change material solid phase ttions battery thermal management system composite phase change material electric vehicle expanded graphite phase achange material
α	Seebeck coefficient, $\mu V \cdot K^{-1}$	PW	paraffin wax
λ	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$	PVV TEC	paranni wax thermoelectric cooler
γ	latent heat, $J \cdot kg^{-1}$	ILC	
ε	turbulent dissipation rate, $m^2 \cdot s^{-3}$		

performance is heavily impacted by temperature, and exposure to temperatures that are either too high or too low can result in performance degradation and an overall shortened lifespan [3]. Typically, the ideal operation temperature for lithium-ion batteries falls within the range of 293.15–323.15 K, while maintaining a temperature difference of less than 5 K among batteries is imperative [4]. Additionally, lithium-ion batteries generally enforce a temperature limit of no more than 333.15 K; Exceeding this threshold prompts a rapid decline in battery performance and a significant elevation in the risk of thermal runaway [5]. Consequently, there exists an urgent need for innovation in battery thermal management technology to control the operation temperature of the battery precisely, ensuring it reaches its optimal performance state.

Currently, the prevailing battery thermal management system (BTMS) incorporates phase change material (PCM) cooling, heat pipe cooling, liquid cooling, and air cooling [6]. The PCM-based BTMS has received significant attention from researchers owing to its advantages, such as the absence of energy consumption, high latent heat, recyclability, and no supercooling [7,8]. Meanwhile, the PCM exercises precise temperature control over batteries within the phase change temperature range, resulting in outstanding temperature uniformity [9]. However, the limited thermal conductivity of pure PCM makes it challenging to rapidly dissipate the heat generated by lithium-ion batteries, thereby elevating the risk of thermal management failure [10]. Therefore, the current research primarily revolves around enhancing the thermal conductivity of pure PCMs by introducing high thermal conductivity particles or metal components [11]. For example, Ma et al. [12] fabricated a composite phase change material (CPCM) by utilizing EG@Bi-MOF derived porous carbon/lauric acid for battery thermal management; The results revealed an impressive 7.35-fold increase in the thermal conductivity of the CPCM in comparison to the pure PCM, enabling effective temperature control during battery discharge. Zhang et al. [13] introduced a PCM-based BTMS, incorporating branch-type fins to augment heat transfer; The findings illustrated that with the optimal fin structure, the average temperature of batteries can be consistently maintained at 318.15 K. The aforementioned technical means can effectively address the challenge posed by the low thermal conductivity of PCMs in the realm of battery thermal management [14].

Nevertheless, the latent heat capacity of PCMs is limited, and in situations of extreme conditions, the complete depletion of PCM's latent heat prompts the rapid accumulation of heat, thereby escalating the risk of thermal runaway [15]. Simultaneously, acting as an entirely passive means of thermal regulation, the PCM is incapable of satisfying the expeditious cooling requirements when the battery is subjected to high temperatures. Therefore, the PCM usually needs to be combined with other active thermal management techniques.

Air cooling offers advantages such as a simple structure, lightweight design, cost-effectiveness, and extended lifespan [16]. Therefore, air cooling and PCMs have been integrated by some researchers to decrease the PCM melting rate [17,18]. However, the low cooling efficiency of air cooling makes it difficult to cool the interior of PCMs, resulting in uneven melting of the interior and exterior of PCMs and a low utilization rate [19]. In contrast to air cooling, liquid cooling exhibits superior thermal conductivity and specific heat, allowing for more effective temperature control of batteries and slower melting of PCMs [20]. In this field, Cao et al. [21] developed a BTMS with CPCMs and liquid cooling for the thermal management of cylindrical lithium-ion batteries; The study revealed that to uphold the cooling efficiency of the system and prevent the battery temperature from exceeding the defined limit, it is necessary to control the inlet water temperature for liquid cooling below 313.15 K. Li et al. [22] investigated the thermal performance of a BTMS with double-sided liquid cooling and CPCMs through both experiments and simulations; The findings suggested that the implementation of dual-sided liquid cooling effectively keeps the battery temperature below 310.28 K and significantly retarding the melting of PCMs. Nevertheless, the liquid cooling system exhibits intricate structures, consumes substantial energy, and entails a risk of liquid leakage [23]. Accordingly, there is a pressing need for the integration of a more efficient and secure active battery thermal management approach with PCMs.

Thermoelectric cooling, as an emerging refrigeration technology, is progressively gaining prominence in battery thermal management, recognized as one of the most promising active thermal management technologies [24]. The thermoelectric cooler (TEC)-based BTMS offers advantages such as rapid response, efficient heat dissipation, bidirectional temperature control, and precise temperature regulation [25].



Fig. 1. Schematic diagram of the three-dimensional structure of the BTMS.

However, when the TEC is affixed directly to the battery surface, the local battery temperature rapidly decreases due to its fast thermal response, resulting in a rapid expansion of the temperature difference [26]. Consequently, an intermediate heat transfer medium is typically required to optimize the placement of the TEC. Previous studies commonly employed the PCM as the intermediate heat transfer medium, with findings indicating that integrating the TEC with PCM effectively regulates battery temperature and retards the melting process of the PCM [26-28]. For example, Liu et al. [27] developed a BTMS integrating TECs with PCMs for extreme operating conditions; The study results showed that, compared to PCM alone, the combination of the TEC and PCM can prolong the time to control the battery temperature at 323.15 K to 780 s. Jiang et al. [28] designed a BTMS integrating TECs with PCMs for application in cylindrical lithium-ion batteries; The results demonstrated that, under high-rate battery discharge, compared to natural convection and liquid cooling systems, the time for the battery temperature to rise to 323.15 K is extended by 4405 s and 4060 s, respectively.

Nevertheless, the existing BTMS with integrated PCM and TEC only involves the basic encapsulation of the PCM in the structural design, and fails to address the problem of insufficient utilization of the TEC cooling power caused by the inherent low thermal conductivity of the PCM. Simultaneously, with respect to numerical models, existing studies predominantly lean towards Computational Fluid Dynamics simulations or rudimentary analyses, falling short of precise numerical models that account for the intricate multi-physical field coupling phenomenon. Furthermore, prevailing investigations in the BTMS have predominantly focused on controlling the battery temperature increase under normal temperature conditions. Under extreme operating conditions, the complete melting of PCMs may result in the battery temperature exceeding established limits, causing irreversible damage to the battery pack or even posing the risk of thermal runaway. Therefore, it is imperative to investigate the BTMS in terms of rapid cooling of batteries at high temperatures and effective recovery of the PCM latent heat, which is barely reported in the current research.

On this basis, a BTMS that utilizes a fin frame to optimize the heat transfer between the TEC, PCM, and battery is proposed. The developed fin frame is crafted to address the intrinsic low thermal conductivity limitation of the PCM, allowing for the full exploitation of the cooling power of the TEC to promptly cool the battery at high temperatures and recover latent heat from the PCM. Meanwhile, considering the multiphysical coupling phenomenon of the thermal, fluid, and electric fields, a numerical model is constructed to accurately analyze the system's thermal performance. To highlight the advantages of the novel system's thermal performance, the concepts of rapid temperature drop time for batteries at high temperatures and latent heat recovery rate of PCMs are defined, and the developed BTMS is also compared with other BTMS of different configurations. Finally, considering the great sensitivity of the PCM and TEC to the system's thermal performance, the effect of TEC input current and PCM properties is analyzed.

# 2. Geometric description of the novel BTMS

The three-dimensional structure of the BTMS is illustrated in Fig. 1. This system is composed of the fin frame, battery, PCM, TEC, and S-type liquid-cooled plate. Specifically, the fin frame is made up of fins, partitions, and an outer frame, featuring an overall dimension of  $178 \times 92$  $\times$  90 mm<sup>3</sup> (length  $\times$  width  $\times$  height), which is used to house the battery and encapsulate the PCM. Among others, two mutually perpendicular partitions divide the outer frame into four cavities of equal size. Four prismatic LiFeO<sub>4</sub> batteries, each measuring 70  $\times$  27  $\times$  90 mm<sup>3</sup>, are positioned in these cavities. To enhance heat transfer efficiency, identical rectangular fins, spaced 9 mm apart, are uniformly positioned on both the partitions and outer frame. Based on prior work [29], the length and width of rectangular fins are selected as the optimal sizes of 7 mm and 3 mm. Moreover, the vacant space between the battery and fin frame is filled with PCMs. TECs are evenly arranged on both sides of the fin frame in equal quantities. The TEC consists of upper and lower ceramic plates, p/n thermoelectric legs, and copper conductors, with the p/n thermoelectric leg being connected in series through the copper conductor. After the TEC is energized with current, the ceramic plate on one side cools, functioning as the cooling end, while the ceramic plate on the other side heats up, serving as the heating end. The cooling end of the TEC is securely affixed to the fin frame to cool the PCM and battery. It is crucial to emphasize that elevated temperatures at the heating end of the TEC significantly diminish its cooling efficiency. Therefore, an Stype liquid-cooled plate is implemented to regulate the temperature at the heating end. Specifically, the liquid-cooled plate is characterized by a thickness of 5 mm, a flow channel diameter of 4 mm, and water serves as the coolant in the flow channel. The thermophysical parameters for batteries [29], water, aluminum, and PCMs [30] are detailed in Table 1, while the material parameters for the TEC are available in Table 2 [31]. Here, the phase change temperature range of PCMs used is 314.15-317.15 K. For further geometric details into the BTMS, refer to both Fig. 1 and Fig. 5.

## 3. The transient multiphysics numerical model

# 3.1. Governing equations

In Fig. 2, the depicted transient numerical model for the BTMS incorporates the coupling of thermal, electric, and fluid fields, along with the governing equations specific to each field. Consistent meanings are maintained for identical variables in various equations depicted. Based on the previous work [29], the battery is set up as a heat source for uniform heat generation, and the heat generation power  $Q_b$  is 21.6 W. Upon the onset of battery discharge, heat is generated and is first transferred to the PCM, where it is stored as latent heat. In this work, the enthalpy method is employed to simulate the heat transfer mechanism within the PCM [32]. The p/n thermoelectric legs and copper conductors generate Joule heat when an electric current is applied to the TEC [24]. The Peltier heat and Thomson heat are also produced along p/nthermoelectric legs due to the thermoelectric effect [33]. These parasitic heats act as the energy source term of governing Eqs. [34]. The temperature of one ceramic plate drops to make it the cooling end, while the temperature of the other ceramic plate rises to make it the heating end, due to the synergistic effect of the parasitic heat described above [35]. The cooling power generated at the cooling end is efficiently transferred through the fin frame to cool both the PCM and battery pack. Meanwhile, the heat produced at the heating end dissipates through the fluid flow in the S-type liquid-cooled plate, guaranteeing the efficient work of the TEC. In the fluid field, the cooling water within the S-type liquidcooled plate adheres to the principles of mass, energy, and momentum conservation equations [36,37]. Simultaneously, the cooling water flows as turbulence, and the k- $\varepsilon$  turbulence model is selected to address the transport issues related to turbulent kinetic energy and dissipation [29]. Moreover, the p/n thermoelectric legs and copper conductors adhere to the principles of electric field conservation and continuity of current. Energy conservation is also applied to other unspecified solid domains. For a more detailed exposition of the numerical model, please refer to Ref. [29].

#### 3.2. Boundary conditions

The BTMS is geometrically modeled in this work using Solidworks 2023 software, and the numerical model is simulated through COMSOL 6.0 finite element simulation software. Considering that the geometric

structure of the BTMS is symmetrical, to save the computational cost as much as possible, only one half of the structure is selected as the research objective. Simultaneously, to appraise the effectiveness of the TEC in rapidly cooling the battery at high temperatures and recovering latent heat from the PCM, the initial temperature of batteries, PCM, and fin frame is set to 333.15 K. In this situation, the latent heat stored in the PCM is entirely exhausted, posing a potential risk of thermal runaway for the battery. For the liquid-cooled plate, the cooling water inflow surface is specified as the inlet boundary condition with a flow rate of 0.01 kg/s, while the outflow surface is designated as the outlet boundary condition with atmosphere pressure. The inlet temperature of cooling water aligns with the ambient temperature of 303.15 K. For the TEC, the normal current density boundary condition is defined for the surface of the copper conductor where the current enters, and the grounded boundary condition is designated for the surface of the copper conductor where the current exits. Moreover, the outer surface of the BTMS, interfacing with the ambient phase, is established as a boundary condition for heat loss, with a convective heat transfer coefficient of 5  $W \cdot m^{-2} \cdot K^{-1}$ .

## 3.3. Parameter definitions

For a comprehensive analysis of the BTMS, two new performance metrics are employed: the temperature drop time for batteries at high temperatures and the latent heat recovery rate for PCMs. Therefore, the investigation is split into two primary research stages: In Stage 1, the emphasis is on the time it takes for the maximum temperature of the battery pack to drop from 333.15 K (the thermal runaway limiting temperature) [38] to 323.15 K (the upper limit of the optimal operating temperature) [39]; In Stage 2, the analysis centers on the time required for the PCM to transition from complete latent heat depletion to complete recovery. Here, the maximum temperature of the battery pack is acquired through the calculation of the highest temperature across all battery surfaces, and the temperature difference is calculated by subtracting the minimum temperature from the maximum temperature of batteries. Moreover, the residual latent heat of the PCM is represented by the liquid fraction  $\beta$ . A  $\beta$  value of 1 signifies complete consumption of the latent heat of PCMs, while a  $\beta$  value of 0 indicates full recovery of the latent heat, and the precise formula for  $\beta$  is detailed in Fig. 2. The latent heat recovery rate, a measure of the average value of recovered latent heat per unit of time, facilitates a more efficient evaluation of the TEC's

#### Table 1

Details of thermophysical material parameters for batteries, aluminum, water, and PCMs.

Component	Thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$	Specific heat (J·kg <sup>-1</sup> ·K <sup>-1</sup> )	Density (kg·m <sup>-3</sup> )	latent heat (J·kg <sup>-1</sup> )
Battery [29]	x, y:15.3 z:0.9	1150	1838.20	-
Aluminum	238	900	2700	-
Water	0.6	4200	998	-
PCMs [30]:				
EG(0%)/PW(100%)	0.20	2000	800	255,000
EG(3%)/PW(97%)	0.58	1963	825	247,400
EG(6%)/PW(94%)	1.23	1926	832	239,700
EG(9%)/PW(91%)	3.50	1889	845	232,100
EG(12%)/PW(88%)	5.74	1852	897	224,400
EG(20%)/PW(80%)	10.1	1754	913	204,000

#### Table 2

Material parameters and dimensions of the TEC [31].

	Seebeck coefficient ( $\mu V \cdot K^{-1}$ )	Electrical conductivity (S $\cdot$ m <sup>-1</sup> )	Thermal conductivity ( $W \cdot m^{-1} \cdot K^{-1}$ )	Size (L $\times$ W $\times$ H mm^3)
n-type legs	$\begin{array}{l} 7.393 \times 10^{-11} T^2 - 2.500 \times 10^{-7} T \\ -8.494 \times 10^{-5} \end{array}$	$\begin{array}{c} 0.657 T^2 - 7.136 \times 10^2 T \\ + 2.463 \times 10^5 \end{array}$	$\begin{array}{c} 1.870 \times 10^{-5} \textit{T}^2 - 1.447 \times 10^{-2} \textit{T} \\ + 3.680 \end{array}$	$1.4\times1.4\times1.6$
p-type legs	$-1.593 imes 10^{-9} T^2 + 1.364 imes 10^{-6} T \ -7.062 imes 10^{-5}$	$\begin{array}{c} 1.311 T^2 - 1.364 \times 10^3 T \\ + 4.023 \times 10^5 \end{array}$	$\begin{array}{c} 1.071 T^2 - 8.295 \times 10^{-3} T \\ + 2.625 \end{array}$	$1.4\times1.4\times1.6$
copper conductors	-	$5.998  imes 10^7$	400	$3.8\times1.4\times0.4$
ceramic plates	-	-	22	$40 \times 40 \times 0.8$

proficiency in recovering latent heat from the PCM. The calculation is expressed through the following equation:

$$L\nu = \frac{(\beta_1 - \beta_2)\gamma}{t_2 - t_1} \tag{1}$$

where,  $\beta_1$  is indicative of the PCM liquid fraction at the initial time moment  $t_1$ , and  $\beta_2$  represents the PCM liquid fraction at the concluding time moment  $t_2$ . It is crucial to highlight that  $t_2$  is the moment when the PCM liquid fraction becomes 0. However, if the liquid fraction remains not 0 at the end of the discharging process,  $t_2$  serves as the discharging time, and  $\beta_2$  indicates the liquid fraction at this time. Furthermore,  $\gamma$ represents the total latent heat value of the PCM.

# 3.4. Grid independence examination

To ensure computational accuracy at a minimal cost, grid independence examination is indispensable. Consequently, this work includes the selection of four sets of grid numbers that increase progressively: 526638, 986, 521, 1, 979, 880, and 2, 882, 547. It is worth noting that the boundary conditions for the grid independence examination include: a TEC input current of 3 A, pure paraffin wax (PW)-based PCM, and a coolant inlet flow rate of 0.01 kg/s. Fig. 3 illustrates the fluctuations in the maximum battery temperature among the four grid numbers. Initially, the disparity in the maximum battery temperature among different grid numbers is marginal. As the discharge continues, the maximum temperatures at grid numbers 526,638 and 986,521 significantly differ from the maximum temperature at grid number 2882547. Conversely, at grid number 1979880, the maximum temperature is already in close proximity to that at grid number 2882547. Considering the excessive computational time required for grid number 2882547, the subsequent study will utilize grid number 1979880. The details of the grid distribution of the BTMS for grid number 1979880 can be found in Fig. 2.

# 3.5. Experimental validation

To validate the accuracy of the developed numerical model, the experimental data from Ref. [28], which relates to the BTMS that includes batteries, TECs, PCMs, and liquid cooling, is employed for comparison with the numerical results. The geometric structure of the BTMS, as detailed in Ref. [28], is reconstructed, and numerical simulations are conducted using the developed numerical model. It is crucial to emphasize that the boundary conditions employed during the simulation align with the experimental conditions. Fig. 4 depicts a comparison between the numerical results and the experimental data. Notably, the values and trends of the maximum temperature and temperature difference from the numerical simulation are in good agreement with the experimental data in Ref. [28]. The average absolute errors for the maximum temperature and temperature difference are 0.849 K and 0.183 K, respectively. The outcomes reveal that the developed numerical model is proficient in accurately assessing the system's thermal performance, thereby verifying the rationality and reliability of the subsequent research efforts to a certain extent.

# 4. Results and discussion

#### 4.1. Comparison of different BTMS

To validate the effectiveness of the proposed BTMS in cooling the battery at high temperatures and recovering the PCM latent heat, four distinct cases of the BTMS are chosen for comparative analysis. Fig. 5 showcases the schematic geometry of the BTMS for the four cases. In Case 1, a combination of liquid cooling and TEC is applied; Case 2 utilizes air cooling in conjunction with TEC; Case 3 only employs liquid cooling, and Case 4 relies on air cooling alone. Additionally, the TEC operates at a current of 3 A, and the pure-PW PCMs are adopted. The liquid cooling maintains a steady inlet flow rate of 0.01 kg/s [29], and air cooling is implemented by applying a convective heat transfer



Fig. 2. Schematic of the governing equations of the transient numerical model for the BTMS.



Fig. 3. Effect of different numbers of grids on maximum battery temperature.



Fig. 4. Comparison of numerical results with experimental data.

coefficient of 50  $W \cdot m^{-2} \cdot K^{-1}$  to the heat sink [24]. Consistency with the boundary conditions elucidated in Section 3.2 is maintained for other unspecified parameters.

Figs. 6(a) and (b) present the maximum temperature of batteries and PCM liquid fraction across different cases. Owing to the delayed transfer of cooling power from the fin frame to batteries and PCMs, there is a momentary elevation in the maximum temperature initially, while the liquid fraction of the PCM remains constant, succeeded by a swift decrease in both. It is noteworthy that both Cases 1 and 2 employing TECs demonstrate superior thermal performance. Additionally, both the PCM liquid fraction and maximum temperature experienced a faster decline in Case 1 compared to Case 2, owing to the superior heat dissipation efficiency of liquid cooling compared to air cooling. In Cases 3 and 4, the PCM liquid fraction and maximum temperature reach a stable state in the later stages of battery discharge, failing to complete Stage 2, and Case 4 also fails to complete Stage 1. The variation in battery temperature difference is presented in Fig. 6(c). Cases 1 and 2, employing TECs for robust cooling, exhibit a more significant temperature difference compared to Cases 3 and 4. Moreover, in the cooling phase of the battery at high temperatures, the temperature difference of Case 1 and Case 2 surpasses the 5 K threshold. However, as the battery

discharges into the later stage, this temperature difference gradually diminishes to below 5 K. Fig. 6(d) presents the completion time for each Stage and the latent heat recovery rate of PCMs for different cases. It is apparent that Case 1 completes Stage 1 in just 530 s, outperforming Cases 2 and 3 by 220 s and 430 s, respectively. Moreover, for Stage 2, Case 1 requires only 1180 s, which is 740 s less than Case 2. Concerning the latent heat recovery rate of PCMs, Case 1 enables the highest rate of 216.10 J/kg/s, surpassing the other three cases by 62.71%, 137.95%, and 446.70%, respectively.

Fig. 7 displays the contours of the overall BTMS temperature, battery temperature, and PCM liquid fraction at 2000 s across various cases. It is apparent that Case 1 exhibits a lower overall BTMS temperature than Case 2, despite having the same TEC input current. This is explained by the limited air cooling performance in effectively dissipating heat from the high-temperature end of the TEC, causing a considerable temperature gradient across the TEC and thus deteriorating the TEC cooling capacity. Therefore, Case 1, employing both liquid cooling and TECs, demonstrates superior heat dissipation performance, facilitating the rapid cooling of the battery at high temperatures and effective recovery of latent heat from PCMs. Furthermore, even after 2000 s, the temperature of batteries in Case 4 continues to exceed 323.15 K, exposing the battery to prolonged high temperatures that could result in irreversible damage. The contour of the PCM liquid fraction illustrates that in the central region of Cases 3 and 4, the latent heat of the PCM can not be fully recovered. This is attributed to the lack of TECs, leading to inadequate cooling power and elevated temperatures in the central part of the fin frame, impeding the recovery of PCM latent heat.

It can be concluded that utilizing the TEC is effective in cooling the battery at high temperatures and recovering latent heat from PCMs. Furthermore, the incorporation of liquid cooling at the heating end of the TEC significantly improves its cooling capacity; However, this leads to an augmented temperature difference.

# 4.2. The influence of PCMs

The thermal conductivity of PCMs plays a crucial role in determining the cooling time of the battery at high temperatures and the latent heat recovery rate of PCMs. Therefore, PCMs with different mass fractions (0%, 3%, 6%, 9%, 12%, and 20%) of expanded graphite (EG) added to pure PW are selected for investigation. Among them, the input current of the TEC is 3 A, and the inlet flow rate of the coolant is 0.01 kg/s. Simultaneously, it is discovered in Section 4.1 that once the recovery of latent heat from PCMs is completed, the continuous operation of the TEC results in significant power consumption. Furthermore, incorporating EGs into the PCM enhances thermal conductivity but concomitantly diminishes its latent heat. To select an appropriate PCM and reduce system power consumption, the PCM's capability to independently regulate battery temperature after latent heat recovery is essential. Therefore, when the recovery of latent heat from the PCM is completed (reaching a PCM liquid fraction of 0), the current input to the TEC will be discontinued. Building on this, for a visual assessment of PCM performance, Stage 3 is introduced, i.e., the time that the maximum battery temperature remains below 323.15 K after the TEC input current is cut off.

The influences of PCMs with different mass fractions of EGs on the maximum temperature of batteries and the PCM liquid fraction are shown in Figs. 8(a) and (b), respectively. An elevation in the mass fraction of EGs induces a heightened pace of decline in both the PCM liquid fraction and maximum temperature, thereby abbreviating the time required to complete Stages 1 and 2. This is attributed to the heightened thermal conductivity of the PCM resulting from the addition of EGs, thereby improving the efficiency of the TEC in cooling the PCM and battery. As the mass fraction of EGs increases from 9% to 12%, the rate of decrease in both the PCM liquid fraction and maximum temperature shows a tiny improvement, and the corresponding reduction in the time required to complete Stages 1 and 2 is not substantial.



Fig. 5. Schematic structure of the BTMS for different cases, Case 1: TEC and liquid cooling; Case 2: TEC and air cooling; Case 3: liquid cooling; Case 4: air cooling.



Fig. 6. Comparison of results for different cases. (a) Maximum temperature of batteries; (b) Liquid fraction of PCMs; (c) Maximum temperature difference of batteries; (d) Completion time of each Stage and latent heat recovery rate of PCMs.



Fig. 7. Numerical results for different cases at 2000 s. (a) Temperature contours of the overall BTMS; (b) Temperature contours of batteries; (c) Contours of the PCM liquid fraction.

Combined with Fig. 8(d), it becomes apparent that for the 0%EG-based PCM, it takes 530 s and 1180 s to complete Stages 1 and 2, respectively. Conversely, the 9%EG-based PCM exhibits a substantial time reduction, achieving Stages 1 and 2 in 190 s and 720 s, respectively. However, the improvement is less pronounced for the 20%EG-based PCM, with the time required to complete Stages 1 and 2 reduced to only 170 s and 630 s, and even experiences a faster temperature rise after Stage 2 than that of 9%EG-based PCM. Furthermore, an increase in the mass fraction of EGs leads to a decrease in the time required for latent heat recovery from the PCM.

Fig. 8(c) illustrates the influence of PCMs with different mass fractions of EGs on the temperature difference within the battery pack. The temperature difference undergoes a trend of rapid increase, followed by a decrease, and then an increase to the highest point until the completion of Stage 2. The primary factor contributing to this phenomenon is as follows: The initial battery temperature is relatively high, and the TEC rapidly cools the surface of the battery adjacent to the TEC, resulting in a rapid increase in the battery temperature difference; As the cooling energy of the TEC is conveyed to the interior of the battery pack through the fin frame, the temperature difference initiates a decline; However, the PCM latent heat near the TEC side begins to be recovered, prompting a rapid decline in the battery surface temperature, and at the same time, the PCM latent heat on the other side is not yet recovered, leaving the battery surface temperature within the phase change temperature range and causing a rapid rise in the temperature difference. Additionally, as the TEC cools the battery at high temperatures and recovers the latent heat from PCMs, the temperature difference of batteries surpasses the 5 K limit. Nevertheless, upon cutting off the TEC operating current after completing Stage 2, the temperature difference swiftly decreases below 5 K. Taking into account that the duration of PCM operating independently surpasses the time needed for the TEC to recover latent heat from the PCM, this brief episode of significant temperature differences is deemed acceptable. After the end of Stage 2 and entering Stage 3, it is evident that the reduction in battery temperature persists for a period.

This phenomenon is attributed to the fact that after removing TEC, due to thermal inertia, the temperature of the fin frame remains lower than the temperature of the battery for a period of time.

Fig. 8(d) shows the duration of Stage 3 and the latent heat recovery rate of the PCM. As the mass fraction of EGs increases from 0% to 12%, the duration of Stage 3 increases from 1580 s to 3830 s, and at the same time, the latent heat recovery rate of the PCM increases from 216.10 J/kg/s to 334.93 J/kg/s. However, when the mass fraction of EGs increases to 20%, the maintenance time of Stage 3 and the latent heat recovery rate of the PCM both decrease to 3580 s and 323.81 J/kg/s, respectively. Therefore, an oversized increase of EG mass fraction from 12% to 20% is not preferable.

The temperature distribution contours of the overall BTMS at 500 s are depicted in Fig. 9(a). It is evident that as the mass fraction of EG increases, the temperatures of the PCM and battery decrease, whereas the temperature of the fin frame rises. This is because the increase in the mass fraction of EGs enhances the thermal conductivity of the PCM, which in turn improves the utilization of the cooling energy of the TEC and reduces the amount of cooling energy accumulated on the fin frame. Figs. 9(b) and (c) display the battery temperature and PCM liquid fraction contours, respectively. As the mass fraction of EGs increases, the temperature of the inner side of the battery pack falls within the phase change temperature range more quickly. Meanwhile, the temperature of the outer side of the battery pack keeps decreasing, causing a rise in the temperature difference with an increase in the EG mass fraction. Furthermore, the latent heat of the PCM near the TEC side is further recovered as the mass fraction of EGs increases, while the latent heat recovery of PCMs on the other side shows a slowly increasing trend.

Based on the above analysis, employing PCMs with a higher mass fraction of EGs results in a reduction in the time required to complete Stages 1 and 2. However, when the mass fraction of EGs exceeds 9%, the time required to complete these Stages is no longer notably reduced. It is worth mentioning that the use of a 12%EG-based PCM showcases prominent peaks in both the duration of Stage 3 and the latent heat



Fig. 8. Influence of PCMs with different mass fractions of EGs. (a) Maximum temperature of batteries; (b) Liquid fraction of PCMs; (c) Maximum temperature difference of batteries; (d) Completion time of each Stage and latent heat recovery rate of PCMs.

recovery rate of the PCM. Taking into consideration the time needed to accomplish rapid cooling of the battery at high temperatures, the latent heat recovery rate of the PCM, and the period during which the PCM can independently operate, the 12%EG-based PCM is identified as the optimal selection for this BTMS.

## 4.3. Influence of the TEC input current

Lower TEC input currents may deteriorate the ability to rapidly cool the battery at high temperatures and recover PCM latent heat, while excessively high TEC input currents can substantially elevate system power consumption. Therefore, six progressively increasing TEC input currents (1–6 A) are chosen for investigation. Meanwhile, the work employs the 12%EG-based PCM, with the cooling water inlet flow rate consistently maintained at 0.01 kg/s.

Figs. 10(a), (b), and (c) depict alterations in maximum temperature, PCM liquid fraction, and temperature difference over time for distinct TEC input currents. It is noticeable that with the rise in input current of the TEC from 1 A to 5 A, there is an augmented rate of decline in both PCM liquid fraction and maximum temperature, coupled with an increase in temperature difference. Nevertheless, upon elevating the input current to 6 A, there is a decline in the reduction rate of both PCM liquid

fraction and maximum temperature, coupled with a decrease in temperature difference compared to the 5 A input current scenario. The manifestation of this phenomenon stems from the predominance of Peltier heat over Joule heat at low TEC input currents. Consequently, the cooling performance of the TEC escalates proportionally with the input current. However, beyond this threshold (5 A for the given TECs), the oversized increase in Joule heat deteriorates the cooling performance of the TEC. As shown in Fig. 10(d), the low TEC input current of 1 A requires 300 s to complete Stage 1 and fails to complete Stage 2 within 1000 s. By contrast, increasing the input current from 2 A to 5 A reduces the completion time of Stage 1 and Stage 2 from 210 s and 900 s to 165 s and 580 s, respectively, and enhances the latent heat recovery rate of the PCM from 115.01 J/kg/s to 386.89 J/kg/s. Notably, as the input current of the TEC surpasses 4 A, the completion time for Stage 1 and Stage 2, along with the latent heat recovery rate of the PCM, remain insignificant changes. Additionally, when the TEC current rises to 6 A, the required time for Stage 1 and Stage 2 increases compared to the TEC input current of 5 A, and the latent heat recovery rate of the PCM decreases.

The contours of the overall BTMS temperature at 500 s are depicted in Fig. 11(a). The temperature of the liquid-cooled plate escalates as the input current increases, driven by the heightened heat production at the heating end of the TEC. Notably, with the input current exceeding 4 A,



Fig. 9. Numerical results of the system at 500 s. (a) Temperature contours of the overall BTMS; (b) Temperature contours of batteries; (c) Contours of the PCM liquid fraction.



Fig. 10. Influence of the TEC input current. (a) Maximum temperature of batteries; (b) Liquid fraction of PCMs; (c) Maximum temperature difference of batteries; (d) Completion time of each Stage and latent heat recovery rate of PCMs.



Fig. 11. Numerical results for different TEC input currents at 500 s. (a) Temperature contours for the overall BTMS; (b) Temperature contours for batteries; (c) Contours for the PCM liquid fraction.

the temperatures of the fin frame, PCM, and battery are almost the same. Figs. 11(b) and (c) display the distribution contours of the battery temperature and the PCM liquid fraction at 500 s, respectively. It can be observed that the high-temperature region of batteries and the melting region of the PCM are located in the central region of the system. With an elevation in the TEC input current, both the high-temperature region in the middle of the battery pack and the melting region of PCMs experience a rapid reduction. At 5 A, the battery temperature reaches its minimum, and the PCM is essentially solidified.

To summarize, increasing the TEC input current reduces the completion time of Stages 1 and 2, and the latent heat recovery rate of the PCM increases rapidly. However, there is a deterioration in the system's thermal performance when the input current is increased up to 6 A. As the input current reaches 4 A and above, the improvement in the system's thermal performance is insignificant. Therefore, to achieve both the effective recovery of PCM latent heat and the rapid cooling of the battery at high temperatures with minimal power consumption, a TEC input current of 4 A is considered the optimal configuration.

### 5. Conclusions

In this study, we propose a BTMS that combines the TEC, PCM, and liquid cooling to cope with the heat accumulation problem caused by the complete depletion of PCM latent heat. Additionally, by employing the fin frame structure, heat transfer between the TEC, PCM, and battery is improved, enabling the rapid cooling of the battery at high temperatures and the effective recovery of latent heat from the PCM. Meanwhile, a transient multiphysics numerical model is developed, taking into account the multiphysics coupling phenomena of thermal, fluid, and electric fields. Besides, to deeply analyze the thermal behavior of the system, two innovative performance metrics are introduced, i.e., the rapid temperature drop time of the battery at high temperatures and the latent heat recovery rate of PCMs. Based on this, the system's thermal performance is investigated from several perspectives, including the comparison of multiple cases, the selection of PCMs, and the influence of the TEC input current. The main research conclusions are as follows:

- (1) Compared with air cooling and liquid cooling, the utilization of TECs yields a substantial improvement in the temperature drop rate of the battery at high temperatures and the latent heat recovery rate of PCMs. Additionally, the use of liquid cooling at the heating end of the TEC offers an additional boost to the system's overall thermal performance when contrasted with the use of air cooling.
- (2) The utilization of PCMs with a higher mass fraction of EGs significantly accelerates the cooling of the battery at high temperatures and enhances the recovery of PCM latent heat. Specifically, compared with the 0%EG-based PCMs, the application of 12%EG-based PCMs reduces the required time of cooling the battery at high temperatures (Stage 1) and recovering PCM latent heat (Stage 2) from 530 s and 1180 s to 185 s and 670 s, respectively. Additionally, the latent heat recovery rate of PCMs escalates from 216.10 to 334.93 J/kg/s.
- (3) After fully recovering the PCM latent heat, the time for PCMs to independently control battery temperature (Stage 3) increases with the increase of EG mass fraction. With the utilization of 12% EG-based PCMs, the time of Stage 3 for the PCM reaches a maximum of 3830 s, extending 2250 s beyond that of 0%EGbased PCMs. Given that the 20%EG-based PCMs result in a reduction in both the time of Stage 3 and the latent heat recovery rate of PCMs, the EG mass fraction of 12% is chosen as the optimal solution.
- (4) Increasing the TEC input current enhances the system's thermal performance and lowers the time required for the cooling of the battery at high temperatures (Stage 1) and the recovery of the PCM latent heat (Stage 2). However, the thermal performance of the system decreases when the input current exceeds 5 A. Considering the limited improvement in the system's thermal

performance for input currents higher than 4 A, an input current of 4 A is selected as the optimal choice to minimize system power consumption.

(5) Considering the thermal performance and power consumption of the system, the optimal solution is determined as an EG mass fraction of 12% and a TEC input current of 4 A. In this situation, the time required for cooling the battery at high temperatures (Stage 1) and the recovery of the PCM latent heat (Stage 2) are 170 s and 620 s, respectively. Meanwhile, the latent heat recovery rate of the PCM reaches 361.94 J/kg/s.

# CRediT authorship contribution statement

**Ding Luo:** Writing – original draft, Supervision, Methodology, Conceptualization. **Zihao Wu:** Writing – original draft, Visualization, Validation, Investigation. **Li Jiang:** Data curation. **Yuying Yan:** Writing – review & editing. **Wei-Hsin Chen:** Writing – review & editing. **Jin Cao:** Formal analysis. **Bingyang Cao:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

#### Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

# Data availability

Data will be made available on request.

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