

Using a hybrid system to improve a lithium-ion battery in the presence of phase change material and the effect of air on the battery charge and discharge

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Abstract

In this article, a numerical analysis is performed on the temperature of four plate-shaped battery cells with phase change material (PCM) chambers surrounding each one in a rectangular shape. The batteries are placed in a channel with air flow. The study is conducted transiently over a time period of ten minutes. The batteries are of lithium-ion type and the analysis is performed in two dimensions. The battery cells are arranged with two single battery cells at the beginning and end of the channel, and two battery cells in the middle of the channel. These two middle batteries are placed in parallel. By changing the distance between the two middle batteries from two to three centimeters, this study investigates the temperature of each of the four battery cells and changes in the amount of frozen PCM. Finally, the results show that the temperature of the two batteries at the beginning and the end increased continuously during the ten minutes of the study. At a distance of three centimeters between the middle batteries, the lowest temperature occurred in the first and last batteries, while at the same distance, the highest temperature occurred in the middle ones. At a distance of two centimeters between the middle batteries, the lowest amount of frozen PCM was observed, while at a distance of three centimeters, the highest amount of frozen PCM was found in the first and last batteries.

Full Text

Preamble

Using a Hybrid System to Improve Lithium-Ion Battery Performance in the Presence of Phase Change Material and the Effect of Air on Battery Charge and Discharge

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Abstract

This article presents a numerical analysis of the temperature distribution in four plate-shaped lithium-ion battery cells, each surrounded by rectangular phase change material (PCM) chambers. The batteries are positioned within an air-flow channel, and the study is conducted transiently over a ten-minute period. The analysis is performed in two dimensions. The battery cells are arranged with single cells at the beginning and end of the channel, and two parallel cells in the middle. The distance between the two middle batteries is varied from 2 cm to 3 cm to investigate the temperature of each battery cell and changes in the frozen PCM fraction. The results demonstrate that the temperatures of the first and last batteries increase continuously during the ten-minute study period. At a distance of 3 cm between the middle batteries, the lowest temperatures occur in the first and last batteries, while the highest temperatures are observed in the middle batteries. Conversely, at a distance of 2 cm, the minimum amount of frozen PCM is observed, whereas at 3 cm, the maximum frozen PCM fraction occurs around the first and last batteries.

Keywords: Battery; Phase change material; Lithium ion; Simulation

Nomenclature

Symbol	Description
A_{mush}	Mushy zone constant

Symbol	Description
C_p	Specific heat [J/(kg · K)]
DoD	Depth of discharge
g	Gravitational acceleration [m/s ²]
H	Enthalpy
h	Heat transfer coefficient [W/(m ² · K)]
j_{ECH}	Volumetric current transfer rate due to electrochemical reactions
j_{Short}	Current transfer rate due to short circuit
k	Thermal conductivity [W/(m · K)]
L	Latent heat [J/kg]
p	Pressure [Pa]
\dot{q}_{ECH}	Heat generation due to electrochemical reactions
\dot{q}_{Short}	Heat generation due to short circuit
Q_{Ah}	Total LIB capacity [Ah]
Re	Reynolds number
S	Source term
T	Temperature [K]
T_{ref}	Reference temperature [K]
U	Open-circuit potential [V]
u, v	Velocity components in x and y directions [m/s]
x, y	Cartesian coordinates [m]
Greek symbols	
α	Thermal diffusivity [m ² /s]
β	Thermal expansion coefficient [1/K]
γ	Liquid fraction
μ	Dynamic viscosity [Pa · s]
ρ	Density [kg/m ³]
σ^+, σ^-	Effective electrical conductivity of positive and negative electrodes [S/m]
ϕ^+, ϕ^-	Phase potentials of positive and negative electrodes [V]
Subscripts	
eff	Effective
l	Liquid
s	Solid
Abbreviations	
BTMS	Battery thermal management system
LIB	Lithium-ion battery
PCM	Phase change material

1. Introduction

Rechargeable batteries are now ubiquitous in electronic devices, and it is difficult to find portable electronics that do not rely on them. This dependency extends to transportation systems, where electric vehicles—encompassing both light and heavy-duty applications—require advanced battery technologies. The emergence of electric vehicles in recent years has raised expectations for replacing fossil fuel-powered vehicles, particularly with advances from companies like Tesla generating hope for global expansion of electric mobility. Energy storage batteries represent a critical component of electric vehicles, and the development of this industry is highly dependent on advances in electrical energy storage technology. One area that has attracted extensive research attention is battery thermal management (BTM), which is particularly crucial in hybrid vehicles [1-4].

Various studies have investigated different methods for battery temperature management, which can be categorized into passive and active approaches. Active methods employ forced convection using a working fluid to manage battery temperature. While this approach requires external energy for fluid circulation and has proven effective for battery cooling, it faces challenges when energy to drive fluid circulation is unavailable. This limitation is particularly relevant in applications where consistent electrical energy access cannot be guaranteed. Passive methods, conversely, do not require external energy for thermal management and instead utilize phase change materials to control battery temperature. PCMs can store substantial thermal energy during phase transitions, but this approach remains viable only until all PCM has undergone phase change. The limited operational duration represents a significant challenge for passive methods.

Recent research in battery thermal management has explored various innovative approaches. Yang et al. [5] investigated a bionic cooling system for cylindrical lithium batteries and demonstrated performance improvements over conventional systems. Li et al. [6] conducted experimental research on an air-cooled BTMS for lithium pouch batteries, showing that dual cooling plates enhance battery performance and operating conditions. Xu and He [7] evaluated heat loss effects on lithium-ion battery cooling efficiency. Researchers have also proposed numerous methods to enhance heat transfer in thermal management systems, including nanofluids and porous materials [8-10]. PCMs have been widely applied for temperature control in various devices, including batteries [11-14]. Jilte et al. [15] assessed the effects of nanoparticle-enhanced PCMs on battery cooling, demonstrating that PCM usage can reduce battery temperature below 40°C, thereby increasing efficiency.

Hybrid systems have emerged as a promising solution for lithium-ion battery cooling. Mehrabi et al. [16] employed a hybrid system combining copper foam with PCM for the passive section and forced air convection for the active section, demonstrating that copper foam with PCM further reduces battery surface tem-

perature compared to PCM alone. Ranjbaran et al. [17] investigated the effects of different copper foam percentages on battery cooling, finding that while copper foam increases the thermal conductivity of the PCM-metal foam composite, high-percentage metallic foam negatively impacts cooling performance. Zhang et al. [18] experimentally studied a cooling system using expanded graphite and paraffin without active cooling, showing that while the system maintains safe temperature ranges during charge and discharge cycles, it produces a maximum 5°C temperature difference among cells. Although paraffin's high latent heat is valuable for passive cooling, its liquid phase lacks efficient cooling capability, particularly at high discharge rates. Consequently, high-rate and long-term operations require hybrid active-passive systems for effective temperature control.

Electrical energy storage in batteries has enabled significant advances in electronic devices, particularly portable electronics such as laptops and mobile phones [19,20]. Batteries have gained increasing importance across various research fields [21,22] and are essential components in electric vehicles and numerous electronic devices. While various active and passive methods have been proposed for battery temperature control, this article employs a hybrid approach combining both methods. The novelty of this work lies in the thermal examination of four plate battery cells arranged in a diamond pattern within a rectangular PCM casing in an air channel, investigating how battery spacing affects temperature and PCM utilization for thermal management.

2. Problem Definition

The geometry under investigation consists of four lithium-ion plate batteries positioned in an air duct at a Reynolds number of 400. The battery cells are arranged in three columns: the first and third columns each contain a single battery cell, while the second column contains two parallel battery cells. The distance between the two middle batteries is varied from 2 cm to 3 cm [Figure 1: see original paper]. Each battery cell is enclosed within a rectangular PCM chamber. The PCM properties, represented by the blue regions in the geometry, are derived from reference [23].

Airflow enters the channel at a constant velocity in a laminar state with a temperature of 283 K. The flow passes over solid surfaces under a no-slip condition and exits the channel at constant pressure equal to standard atmospheric pressure. The initial temperature of all battery components is above 303 K, and all PCM is initially in a molten state. The lateral walls are insulated, and the batteries operate throughout the 10-minute study period.

[Figure 1: see original paper] shows the configuration of four battery cells in an air duct filled with PCM. Thermophysical properties of the PCM ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$) are presented in Table 1, while battery specifications are provided in Table 2.

Table 1. Thermophysical properties of PCM ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$) [23]

Property	Solid Phase	Liquid Phase
Melting point ($^{\circ}\text{C}$)	29.8	29.8
Specific heat, C_p ($\text{J/g} \cdot \text{K}$)	1.42	2.10
Density, ρ (kg/m^3)	1680	1500
Thermal conductivity, k ($\text{W/m} \cdot \text{K}$)	0.626	0.540

Table 2. Lithium-ion pouch cell specifications [24]

Parameter	Value
Cathode Material	LiFePO_4
Anode Material	Graphite
Electrolyte	Carbonate based
Nominal Capacity	20.0 Ah
Nominal Voltage	3.3 V
Dimensions	7.25 mm \times 160 mm \times 227 mm

3. Governing Equations

Lithium battery operation involves potential differences and resistances between electrodes that drive electric current movement. During charging via an external source, ion movement occurs through electrochemical reactions that generate heat and thermal energy within the battery. The governing equations for the battery are presented below, derived from applying Ohm's law to electrodes and electrolytes for electric charge [19,25]:

$$\frac{\partial(\rho C_p T)}{\partial t} - \nabla \cdot (k \nabla T) = \sigma^+ |\nabla \phi^+|^2 + \sigma^- |\nabla \phi^-|^2 + \dot{q}_{ECH} + \dot{q}_{Short}$$

$$\nabla \cdot (\sigma^+ \nabla \phi^+) = -(j_{ECH} - j_{Short})$$

$$\nabla \cdot (\sigma^- \nabla \phi^-) = (j_{ECH} - j_{Short})$$

where j_{ECH} is defined as:

$$j_{ECH} = aY[U - (\phi^+ - \phi^-)]$$

The depth of discharge (DoD) is calculated using:

$$DoD = \frac{1}{3600 Q_{Ah}} \int j dt$$

$$Y = \left(\sum a_n (DoD)^n \right) \exp \left[C_1 \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right]$$

$$U = \left(\sum b_n (DoD)^n \right) - C_2 (T - T_{ref})$$

Finally, \dot{q}_{ECH} is calculated as:

$$\dot{q}_{ECH} = j_{ECH} \left[U - (\phi^+ - \phi^-) - T \frac{\partial U}{\partial T} \right]$$

The equations for PCM melting and solidification fronts are given below [26,27], including continuity, momentum, and energy conservation equations. Buoyancy forces are considered using the Boussinesq approximation in the molten PCM:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = \mu \nabla^2 \vec{u} - \nabla p + \rho \vec{g} + \vec{S}$$

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot (k \nabla T)$$

The source term \vec{S} is defined as [27]:

$$\vec{S} = A_{mush} \frac{(1 - \gamma)^2}{\gamma^3 + 0.001} \vec{u}$$

The liquid fraction γ is calculated at different temperatures using [27]:

$$\gamma = \begin{cases} 0 & \text{if } T < T_s \\ \frac{T - T_s}{T_l - T_s} & \text{if } T_s \leq T \leq T_l \\ 1 & \text{if } T > T_l \end{cases}$$

Enthalpy is estimated using [27]:

$$h = h_{ref} + \int_{T_{ref}}^T C_p dT + \Delta H$$

$$\Delta H = L_h \gamma$$

The equations for steady and transient airflow of a viscous Newtonian fluid in laminar flow are presented below, encompassing continuity, momentum, and energy conservation equations [28]:

$$\nabla \cdot (\rho \vec{V}) = 0$$

$$\frac{\partial \vec{V}}{\partial t} + \nabla \cdot (\vec{V} \vec{V}) = -\frac{1}{\rho} \nabla p + \nabla \cdot \left(\frac{\mu}{\rho} (\nabla \vec{V} + \nabla \vec{V}^T) \right) - \vec{g} \beta (T - T_0)$$

$$\frac{\partial T}{\partial t} + \nabla \cdot (\vec{V} T) = \nabla \cdot \left(\frac{k_{eff}}{\rho C_p} \nabla T \right)$$

3.1. Numerical Method and Grid Study

The finite element method is employed to solve the governing equations for airflow around the batteries and PCM phase change. Commercial software offers excellent capabilities for numerical solutions, and this study utilizes COMSOL Multiphysics for geometry drawing, meshing, solving, and results extraction. Meshing is a critical aspect of numerical simulations that requires careful implementation. An unstructured grid is generated for the geometry in this work.

Table 3 presents the effect of element count on the average temperature of the battery pack at a 3 cm distance between the middle batteries. Based on this grid independence study, Grid 3 with 481,000 elements is selected for subsequent simulations.

Table 3. Grid independence study showing the number of elements versus average battery pack temperature at 3 cm middle battery spacing

Grid	Number of Elements	Average Battery Pack Temperature (K)
1	280,000	307.2
2	380,000	306.8
3	481,000	306.5
4	580,000	306.5

Figure 2 [Figure 2: see original paper] illustrates the mesh visualization on the computational geometry.

3.2. Validation

The current simulations are validated against the results of Mansir et al. [29] by comparing molten PCM quantities at various times and battery distances (Fig. 3 [Figure 3: see original paper]). The findings show excellent agreement,

with a maximum deviation of less than 3% between the present simulations and Mansir et al. [29], which is considered acceptable.

Given the importance of PCM phase change simulation in this study, additional validation is performed against experimental data. Figure 4 [Figure 4: see original paper] compares the volumetric fraction of molten PCM at different time intervals between the current study and the experimental work of Assis et al. [30]. The results demonstrate strong agreement, confirming the accuracy of the PCM melting front predictions.

4. Results and Discussion

Figure 5 [Figure 5: see original paper] presents velocity contours for different middle battery distances. Airflow through the batteries is highly dependent on the spacing between batteries and between the batteries and duct walls. Regions with larger flow passages experience higher air velocities, while confined spaces result in lower velocities. At 2 cm spacing, air velocity is slightly elevated in the upper and lower regions of the batteries. At 2.5 cm, considerable velocity is observed between the main batteries with moderate velocities near the battery surfaces. At 3 cm spacing, high velocity occurs in the central region between batteries with extremely low velocities on the sides.

Figure 6 [Figure 6: see original paper] shows temperature contours for different middle battery distances at 2.5, 5, 7.5, and 10 minutes. After impinging on the first battery, airflow is directed toward the middle batteries and then either toward the duct walls or the space between the two middle batteries, depending on their separation distance. The flow subsequently strikes the last battery before exiting the channel. Battery temperature is directly influenced by local air velocity, with higher velocities producing greater cooling effects. Changing the middle battery distance most significantly affects the temperatures of the last and middle batteries.

As the middle battery spacing increases from 2 to 2.5 cm, the temperature of the two center batteries decreases. The last battery temperature also drops, though the middle batteries are more strongly affected by this change. After 10 minutes, the temperature reduction in these two batteries becomes particularly pronounced. When the spacing increases from 2.5 to 3 cm, the middle battery temperature rises significantly while the last battery temperature decreases. The 3 cm spacing allows more air to pass between the middle batteries, which then directly impinges on the last battery, enhancing its cooling.

In regions with limited airflow space, the volume flow rate is lower, resulting in less effective cooling. Conversely, larger spaces facilitate higher flow rates and improved cooling. However, in some confined areas, air velocity increases to maintain mass conservation as it passes through these restrictions.

Figure 7 [Figure 7: see original paper] illustrates PCM volume fraction contours for different middle battery distances at 2.5, 5, 7.5, and 10 minutes. The ve-

locity distribution strongly influences the solidification front formation rate. At 2 cm spacing, more air passes along the battery sides, causing greater PCM solidification there while the inner regions show less solidification front growth. At 2.5 cm, the solidification front grows acceptably in both inner and outer regions. Strong airflow on both sides of the batteries accelerates the solidification process uniformly. At 3 cm spacing, the solidification front progresses rapidly inside the batteries but only slightly in the side regions due to strong central airflow and weak side airflow.

Figure 8 [Figure 8: see original paper] shows the average temperature of the first battery over 10 minutes for different middle battery distances. The first battery exhibits the smallest temperature variation due to changes in middle battery spacing, as these changes occur downstream and minimally affect the airflow reaching the first battery. The battery temperature increases rapidly during the first 10 minutes before gradually slowing. Increased distance between the middle batteries slightly reduces the first battery temperature after approximately 5 minutes by improving ventilation, though this effect is not noticeable until after the first 4 minutes. The maximum temperature reduction in the first battery is observed at 10 minutes with 3 cm spacing.

Figure 9 [Figure 9: see original paper] presents the average temperature of the middle batteries over 10 minutes for three different spacings. Generally, the temperature of these two batteries increases for 5-7 minutes before decreasing. The timing of this temperature peak varies with spacing, with the maximum duration of temperature increase occurring at 3 cm spacing and the shortest at 2.5 cm spacing. The maximum temperature difference between these two batteries exceeds 0.5°C for different spacings. The highest and lowest temperature increases occur at 3 cm and 2.5 cm spacings, respectively. Airflow distribution around the batteries significantly affects their temperature. At 2 cm spacing, less air passes between the batteries while more flows along the duct sides. At 3 cm spacing, the opposite occurs, with substantial airflow between the batteries and less along the sides. The side receiving more airflow cools more effectively, while the side with less airflow remains warmer. At 2.5 cm spacing, balanced airflow on both sides enables uniform heat transfer, resulting in lower overall temperatures.

Figure 10 [Figure 10: see original paper] shows the last battery temperature over 10 minutes for different middle battery spacings. Compared to the first battery, the last battery is more sensitive to changes in middle battery distance. Its temperature increases continuously throughout the 10-minute period. The temperature rise varies from 305.3 K to 306.4 K depending on spacing, making this the hottest cell in the battery pack. Increased distance between the middle batteries helps reduce the last battery temperature, particularly over extended periods. Greater spacing allows more air to flow between the middle batteries, which then directly impinges on the last battery. At smaller spacings, airflow is directed above and below the batteries, reducing heat transfer and increasing temperature. The 3 cm spacing provides the most effective cooling for the last

battery through direct air contact.

Figure 11 [Figure 11: see original paper] displays the average temperature of all four battery cells over 10 minutes for different middle battery spacings. The average temperature increases for 6-9 minutes depending on spacing, then decreases. The maximum average temperature occurs at 2 cm spacing due to high temperatures in the middle batteries. The minimum temperature increase occurs at 2.5 cm spacing, where the middle batteries maintain lower temperatures, resulting in a lower overall average. The average temperature transitions from maximum to minimum most rapidly at this spacing. The longest duration of temperature increase corresponds to the 3 cm spacing.

Figure 12 [Figure 12: see original paper] presents the frozen PCM fraction around the first battery over 10 minutes for different spacings. The frozen PCM fraction continuously decreases throughout the period, with the rate of reduction varying according to middle battery distance. Although the first battery temperature is not significantly affected by spacing changes, the molten PCM fraction around it is substantially impacted. PCM solidification around the first battery accelerates as the middle battery distance increases, with the maximum solidified PCM occurring at 3 cm spacing. Increased spacing allows more air to pass through the first battery, enhancing heat transfer and increasing the solidified PCM fraction.

Figure 13 [Figure 13: see original paper] illustrates the frozen PCM fraction around the middle batteries over 10 minutes. The maximum PCM phase change occurs around these batteries, with the frozen fraction varying significantly with spacing. The minimum phase change occurs at 3 cm spacing, while the maximum solidified PCM at various times is observed at 2.5 cm spacing. At this distance, the PCM phase change slope is also steepest due to balanced airflow through and around both batteries, enabling proper solidification around both cells. The 2 cm and 3 cm spacings create asymmetric solidification processes, with high frozen fractions remaining in one battery due to strongly asymmetric airflow.

Figure 14 [Figure 14: see original paper] shows the frozen PCM fraction around the last battery over 10 minutes. The maximum frozen PCM occurs at 2 cm spacing, while the minimum occurs at 3 cm spacing. The 2.5 cm spacing produces intermediate results. At 3 cm spacing, increased airflow through the batteries passes around the last battery, enhancing heat transfer and increasing the frozen PCM fraction.

Figure 15 [Figure 15: see original paper] presents the average frozen PCM fraction around all batteries over 10 minutes. At 3 cm spacing, the frozen PCM fraction around the first and last batteries decreases, while the amount around the middle batteries changes minimally. The maximum solidified PCM at various times occurs at 2.5 cm spacing, while the minimum corresponds to 2 cm spacing.

5. Conclusions

This study employs numerical simulation to investigate heat transfer in four lithium-ion plate battery cells positioned in an air duct and enclosed within PCM containers. Two batteries are placed parallel to each other between single batteries at the channel inlet and outlet. By varying the distance between the two middle batteries from 2 to 3 cm, the temperature of each cell and the frozen PCM fraction around each cell are measured. The key findings are as follows:

1. The temperatures of the first and last batteries increase continuously throughout the 10-minute study period. In contrast, the middle battery temperature initially increases then decreases after a certain time that depends on the spacing between the middle batteries.
2. The lowest temperatures in the first and last batteries occur at a 3 cm spacing, while the highest middle battery temperatures occur at this same distance. The minimum middle battery temperature is achieved at 2.5 cm spacing.
3. The minimum and maximum solidified PCM fractions around the first and last batteries correspond to 2 cm and 3 cm spacings, respectively.
4. The minimum and maximum solidified PCM fractions around the middle batteries occur at 3 cm and 2.5 cm spacings, respectively.
5. The 2 cm spacing produces the highest average battery temperature and smallest solidified PCM fraction, while the 2.5 cm spacing yields the lowest average temperature and maximum crystallized PCM fraction.

Author Declarations

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References

- [1] T. Jin, G. Singer, K. Liang, Y. Yang, Structural batteries: Advances, challenges and perspectives, *Materials Today*, 2021.
- [2] O. Sadeghian, A. Moradzadeh, B. Mohammadi-Ivatloo, M. Abapour, A. Anvari-Moghaddam, J. Shiun Lim, F.P. Garcia Marquez, A comprehensive review on energy saving options and saving potential in low voltage electricity

distribution networks: Building and public lighting, *Sustainable Cities and Society*, 72 (2021) 103064.

[3] A.V. Vykhotsev, D. Jang, Q. Wang, W. Rosehart, H. Zareipour, A review of modelling approaches to characterize lithium-ion battery energy storage systems in techno-economic analyses of power systems, *Renewable and Sustainable Energy Reviews*, 166 (2022) 112584.

[4] H. Wang, S.A. Pourmousavi, W.L. Soong, X. Zhang, N. Ertugrul, Battery and energy management system for vanadium redox flow battery: A critical review and recommendations, *Journal of Energy Storage*, 58 (2023) 106384.

[5] W. Yang, F. Zhou, H. Zhou, Y. Liu, Thermal performance of axial air cooling system with bionic surface structure for cylindrical lithium-ion battery module, *International Journal of Heat and Mass Transfer*, 161 (2020) 120307.

[6] X. Li, F. He, G. Zhang, Q. Huang, D. Zhou, Experiment and simulation for pouch battery with silica cooling plates and copper mesh based air cooling thermal management system, *Applied Thermal Engineering*, 146 (2019) 866-880.

[7] X.M. Xu, R. He, Research on the heat dissipation performance of battery pack based on forced air cooling, *Journal of Power Sources*, 24 (2020) 227-238.

[8] P. Kumar, D. Chaudhary, P. Varshney, U. Varshney, S.M. Yahya, Y. Rafat, Critical review on battery thermal management and role of nanomaterial in heat transfer enhancement for electrical vehicle application, *Journal of Energy Storage*, 32 (2020) 33-41.

[9] D.M. Weragoda, G. Tian, A. Burkitbayev, K.-H. Lo, T. Zhang, A comprehensive review on heat pipe based battery thermal management systems, *Applied Thermal Engineering*, 202 (2023) 118887.

[10] R. Kumar, A. Mitra, T. Srinivas, Role of nano-additives in the thermal management of lithium-ion batteries: A review, *Journal of Energy Storage*, 48 (2022) 104059.

[11] J. Luo, D. Zou, Y. Wang, S. Wang, L. Huang, Battery thermal management systems (BTMS) based on phase change material (PCM): A comprehensive review, *Chemical Engineering Journal*, 430 (2022) 132741.

[12] Y. Liu, R. Zheng, J. Li, High latent heat phase change materials (PCMs) with low melting temperature for thermal management and storage of electronic devices and power batteries: Critical review, *Renewable and Sustainable Energy Reviews*, 168 (2022) 112783.

[13] J. Liu, Y. Fan, Q. Xie, An experimental study on the thermal performance of mixed phase change materials-based battery cooling system, *Journal of Energy Storage*, 46 (2022) 103839.

[14] Lee, W. Yang, J. Wang, X. Yang, Safety issue on PCM-based battery thermal management: Material thermal stability and system hazard mitigation,

Energy Storage Materials, 53 (2022) 118-130.

[15] R. Jilte, A. Afzal, S. Panchal, A novel battery thermal management system using nano-enhanced phase change materials, Energy, 219 (2021) 119564.

[16] M. Mehrabi-Kermani, E. Houshfar, M. Ashjaee, A novel hybrid thermal management for Li-ion batteries using phase change materials embedded in copper foams combined with forced-air convection, International Journal of Thermal Sciences, 141 (2019) 47-61.

[17] Y.S. Ranjbaran, S.J. Haghparast, M. Shojaeefard, G. Molaeimanesh, Numerical evaluation of a thermal management system consisting PCM and porous metal foam for Li-ion batteries, Journal of Thermal Analysis and Calorimetry, 141 (2020) 1717-1739.

[18] J. Zhang, X. Li, F. He, J. He, Z. Zhong, G. Zhang, Experimental investigation on thermal management of electric vehicle battery module with paraffin/expanded graphite composite phase change material, International Journal of Photoenergy, 2017 (2017) 1-10.

[19] W. Jiang, J. Zhao, Z. Rao, Thermal performance enhancement and prediction of narrow liquid cooling channel for battery thermal management, International Journal of Thermal Sciences, 171 (2022) 107250.

[20] Y. Zhuang, T. Chen, J. Chen, J. Li, M. Guan, Y. Chen, Thermal uniformity performance of a hybrid battery thermal management system using phase change material and cooling plates arrayed in the manner of honeycomb, Thermal Science and Engineering Progress, 26 (2021) 101098.

[21] X. Yang, Z. Zhao, Y. Liu, R. Xing, Y. Sun, Simulation of nanofluid-cooled lithium-ion battery during charging: A battery connected to a solar cell, International Journal of Mechanical Sciences, 212 (2021) 106836.

[22] S. Gungor, E. Cetkin, S. Lorente, Canopy-to-canopy liquid cooling for the thermal management of lithium-ion batteries, a constructal approach, International Journal of Heat and Mass Transfer, 182 (2022) 121918.

[23] K. Kant, A. Shukla, A. Sharma, P. Henry Biwole, Heat transfer study of phase change materials with graphene nano particle for thermal energy storage, Solar Energy, 146 (2017) 453-462.

[24] S. Panchal, R. Khasow, I. Dincer, M. Agelin-Chaab, R. Fraser, M. Fowler, Thermal design and simulation of mini-channel cold plate for water cooled large sized prismatic lithium-ion battery, Applied Thermal Engineering, 122 (2017) 80-90.

[25] F. Chen, J. Wang, X. Yang, Topology optimization design and numerical analysis on cold plates for lithium-ion battery thermal management, International Journal of Heat and Mass Transfer, 183 (2022) 122087.

[26] A.V. Arasu, A.S. Mujumdar, Numerical study on melting of paraffin wax with Al_2O_3 in a square enclosure, International Communications in Heat and

Mass Transfer, 39 (2012) 8-16.

[27] M.-W. Tian, G.F. Smaism, S.-R. Yan, S.M. Sajadi, M.Z. Mahmoud, H.Ş. Aybar, A.M. Abed, Economic cost and efficiency analysis of a lithium-ion battery pack with the circular and elliptical cavities filled with phase change materials, *Journal of Energy Storage*, 52 (2022) 104997.

[28] M.N. Ajour, N.H. Abu-Hamdeh, O.K. Nusier, S.M. Sajadi, Developing a control program to reduce the energy consumption of nine cylindrical lithium-ion battery pack connected to a solar system by changing the distance between the batteries and the inlet and outlet of the air stream, *Journal of Energy Storage*, 49 (2022) 103997.

[29] I.B. Mansir, N. Sinaga, N. Farouk, U.F. Alqsair, C. Diyoke, D.D. Nguyen, Assessment of the effect of distance between lithium-ion batteries with a number of triangular blades, on the thermal management of the battery pack in a chamber full of phase change material, *Journal of Energy Storage*, 51 (2022) 104391.

[30] E. Assis, L. Katsman, G. Ziskind, R. Letan, Numerical and experimental study of melting in a spherical shell, *International Journal of Heat and Mass Transfer*, 50 (2007) 1790-1804.

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