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Thermal management design optimisation for electric vehicle battery modules

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ABSTRACT

The development of batteries for Electric Vehicles (EVs) cannot be separated from the thermal management aspect. In this manuscript, various design optimisation attempts utilising Phase Change Materials (PCMs) and Vortex Generators (VGs) to improve the heat dissipation from the EV battery module are performed and analysed. Three different organic PCMs are considered, and their latent heat absorption profile suggests different potential solutions. Paraffin, one of the most popularly used PCMs, could have a better thermal performance than lauric acid and caprylone for up to a 24.9% temperature reduction, despite its considerably lower peak latent heat capacity. However, its mechanical strength is also significantly lower in a PCM–resin composite; hence, it requires a certain reinforcement material in its application. Meanwhile, the use of VGs is qualitatively analysed by means of wind tunnel smoke visualisation. A simple yet effective VG could induce streamwise vortexes that could be attributed to mass and heat transfer augmentation.

KEYWORDS Battery thermal management system; composites; electric vehicles; heat storage; latent heat; phase change materials
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1. Introduction

Electric Vehicles (EVs) have been growing rapidly in recent years due to the global aim of reaching carbon neutrality in 2050, hence ending the dependability on fossil fuel. However, EV energy management remains one of the most significant obstacles in entirely replacing conventional hydrocarbon-based vehicles. The battery is the most preferred energy source for EV because of its high energy density and long cycle life, particularly a Lithium-based one (Fang et al., 2021). However, the current energy-to-weight ratio of a battery pack is still far below gasoline, making mileage and weight limitations the major technical issues persisting since the 2000s (Chan, 2003).

For a Lithium battery pack or module, the thermal aspect still becomes the Achilles heel. In each vehicle, one aims to carry as few batteries as possible since the overall weight of the vehicle is inversely proportional to the maximum distance travelled on a single charge. However, the fewer batteries available onboard means that the load for propulsions for each battery cell is dramatically increased, resulting in more heat dissipated to its surroundings. An optimum temperature range for Lithium batteries is typically between 25 and 40 °C (Behi et al., 2020; Zhi et al., 2022). The greater the temperature, the less efficient the cell's performance becomes—dissipating more heat. Therefore, a proper cooling strategy is crucial in any battery for EV.

Various Battery Thermal Management Systems (BTMSs) have been reported and could generally be categorised into Active, Passive, or Hybrid methods depending on the energy consumption system (Arora, 2018; Kim et al., 2019). The active method relies on an additional energy source, such as a fan or pump, to drive the cooling fluid. Despite its generally superior heat transfer capability, the active system often has a more complex flow mechanism design, lower temperature uniformity, and potential coolant leakage other than an air cooling system (Huang et al., 2018; Singh et al., 2021). On the other hand, the passive method uses Phase Change Materials (PCMs) or heat sinks to remove the excess heat without an additional power source. This method could offer better temperature uniformity throughout the battery system. The most commonly used organic PCM is paraffin, owing to its abundance, non-toxicity, lightweight, low-cost, and relative ease to apply (Cui et al., 2017). Paraffin PCM can be found in various engineering applications, such as solar photovoltaics (Abdulmunem et al., 2021; Xu et al., 2018), green buildings and HVAC systems (Takudzwa Muzhanje et al., 2022), thermal switches (Wang X et al., 2017), and certainly in automotive sectors (Wang S et al., 2017). Meanwhile, the hybrid system is simply a combination of two or more of the above methods. The possible combination examples are massive that can be formed from a simple PCM with air cooling lines (Ianniciello et al., 2017; Mohammed et al., 2021; Safdari et al., 2020) and liquid coolant (Jaguemont et al., 2018) to a more complex combination thermoelectric module with heat sink and water pipe (Lyu et al., 2019), and so on. However, despite the numerous achievements reported in all three BTMS methods above, each system is often designed for a limited purpose only. A so-called ice plate could be universally effective, but the design is typically more complicated and costly (Darcovich et al., 2019). Some heat sink products might be difficult to manufacture (Liu et al., 2012). A typical organic PCM such as paraffin is known for its low thermal conductivity of less than 1 W/(m·K), making it ineffective under high thermal loads (Chang et al., 2022; Douvi et al., 2021). Although certain additives could be added to improve thermal performance, such materials are often costly or have specific safety concerns (Bianco et al., 2022).

This manuscript proposes a battery module design optimisation method based on numerical and experimental investigations, with careful considerations in terms of system installation, maintenance or repair efforts, and safety concerns. Various attempts, using the application of vortex generators, PCM tubes, and PCM-resin composite casting, are thoroughly discussed and analysed. Mechanical tensile tests are also conducted and reported in order to evaluate the strength change due to the presence of PCMs.

2. Numerical and experimental setup

The governing equation for the heat generation from a single battery cell $\dot{Q}$ is:

$$\dot{Q} = \dot{Q}_{irr} + \dot{Q}_{rev} + \dot{Q}_{sr} + \dot{Q}_{mix} , \quad (1)$$

where $\dot{Q}_{irr}$, $\dot{Q}_{rev}$, $\dot{Q}_{sr}$, and $\dot{Q}_{mix}$ are the irreversible joule heat, reversible entropy change, side reactions, and the heat from the mixing process, respectively (Deng et al., 2018; Jiang et al., 2022). For a common battery arrangement, assuming that there is no internal defect or quality degradation, the last two segments are negligible; hence, the remaining equation becomes:

$$\dot{Q} = \dot{Q}_{irr} + \dot{Q}_{rev} = I(U - V) - I\left(T\frac{\partial U}{\partial T}\right) , \quad (2)$$

where $I(U - V) = I^2R$ represents the internal Ohmic resistance and $(T\ \partial U/\partial T)$ is an entropy heat coefficient, which is affected by battery surface temperature, density, and State of Charge (SOC) (Thakur et al., 2023). For the preliminary numerical simulation using the Ansys Fluent CFD package, the heat dissipation rate of 525 kW/m^3 is assumed to be constant for each battery cell (Budiman et al., 2019). The battery module consists of 12 cells resembling a 18650 battery in a rectangular, tight arrangement. Vortex Generators (VGs) with a 3 mm chevron shape are applied upstream of the module to observe the heat transfer augmentation from the battery cells, as depicted in Figure 1(a). A tetrahedral 3D mesh with 0.1–1.0 mm size range is selected. According to the grid dependence test, a total of 4.3 million mesh numbers is considered appropriate for this computational work.

The CFD analysis is considered necessary to design the optimum design of VGs, where the validation can be carried out quantitatively and qualitatively. The latter is performed by means of wind tunnel smoke flow visualisation to reflect the forced convection (air cooling) method. Various VG models are designed and fabricated using a 3D printer and placed upstream of the dummy battery module, as sketched in Figure 1(b). The air velocity is approximately 1.6±0.1 m/s, corresponding to free stream *Re* = 20000. The turbulence intensity is less than 0.4%.

The VG utilisation is limited to the active air-cooling method, which might not always be feasible in a different EV due to the volume constraint or additional complexity in designing the optimum forced airflow. In such cases, a passive cooling method relying solely on the latent heat capacity of the PCM may be preferred. The suggested passive cooling optimisation is designed by means of PCMs stored in a cylindrical tube with dimensions similar to the 18650 battery cells. Each tube consists of 7g of PCMs. The placement of such tubes is carefully designed, calculating its heat transfer effectiveness as well as repair efforts required in the case of leakage. The experimental setup and battery configurations have been previously reported (Budiman et al., 2022a). Three different organic PCMs were selected: paraffin, lauric acid, and caprylone (all purchased from Sigma Aldrich, Singapore). Their latent profiles were measured using NETZSCH DSC214 Polyma Differential Scanning Calorimetry (DSC) in a N2 atmosphere and plotted in Figure 2. The battery module was then connected to a data logger, K-type thermocouple (± [0.4% + 0.5 ◦C]; attached to the positive tab of the battery cell [Budiman et al., 2023]), and a resistive dummy load, as sketched in Figure 1(c). The load could be manually adjusted to represent 1–4 C discharge rates. The discharge rate C (sometimes also mentioned as C-rate) is defined as:

$$C = I/P , \quad (3)$$

(a) (b) (c)

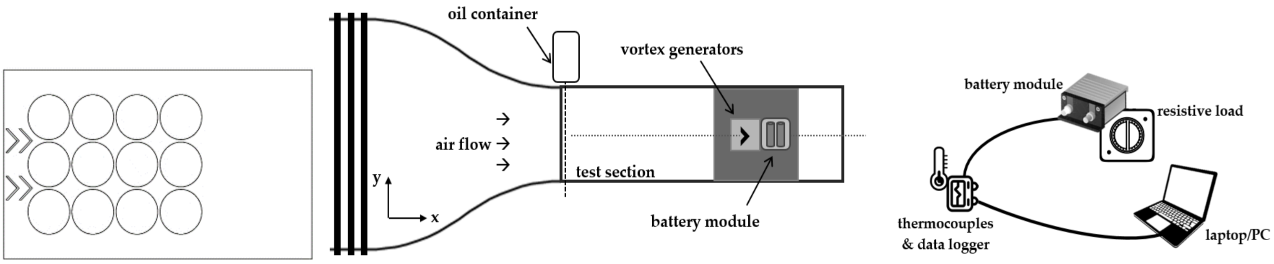


Figure 1. Numerical domain and experimental setup: (a) top view of 18650 battery module with a V-shaped VG; (b) wind tunnel and battery module; and (c) discharge test.

where I is the discharge (or charge) current and P is the nominal capacity of the battery module. The C-rate indicates how much faster the battery will empty during the discharge process (or full during charge), where 1 C equals one hour (Jilte et al., 2019). For example, 4 C means that the battery will be fully discharged (or fully charged) four times faster or in 15 minutes. The higher the C-rate, the more rapidly the temperature will increase. For comparison purposes, a hybrid system with an air-cooling feature was also prepared and tested. A fan with a maximum speed of 4.4 m/s was installed upstream of the module, which was deemed sufficient for effective convection under a certain discharge load (Bubbico et al., 2017).

The third optimisation design was achieved by means of PCM-resin composite fabrication, where the PCM is mixed with Ripoxy R-804 Vinyl Ester Resin (Justus Kimiaraya, Indonesia) and MEKP as its catalyst. Graphite powder was also added to improve its thermal conductivity. This heat-absorbing composite was moulded such that it filled the air gap between each battery cell, practically removing the convection heat transfer option and enhancing the passive BTMS method instead. Due to the existing limitations with regard to the composite mould, for this particular work, the 18650 battery cell needed to be replaced by the 21700, which also offers an increased energy density. The specifications of both battery types are tabulated in Table 1 (Alsharif et al., 2022; Budiman et al., 2022a). The mechanical strength of these composites was evaluated based on the ASTM D3039 tensile test. For comparative purposes, a carbon fibre-reinforced composite fabricated using a vacuum infusion method was also prepared.

Table 1. 18650 and 21700 battery specifications.

Parameter	18650	21700
Cell height (mm)	64.85 ± 0.15	70.30 ± 0.5
Cell diameter (mm)	18.33 ± 0.07	21.2 ± 0.2
Mass (g)	45	68
Discharge capacity (mAh)	2500	4800
Max. internal impedance (mΩ)	18	14
Charge cut-off voltage (V)	4.20 ± 0.05 (CC-CV)	4.20 ± 0.05 (CC-CV)
Nominal voltage (V)	3.6	3.7
Discharge cut-off voltage (V)	2.5	2.75
Max. continuous discharge (A)	20	10

3. Results and discussion

3.1. Vortex generators for air cooling augmentation

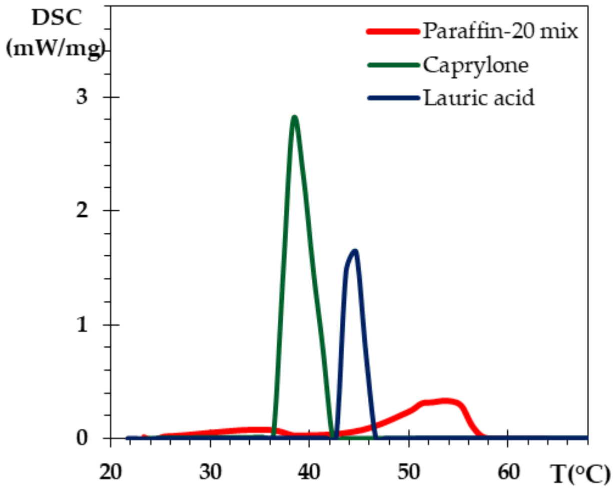


Figure 2. Latent heat profiles of three different organic PCMs used in this study.

The numerical results show that the presence of chevron VGs upstream of the battery module effectively reduces the overall battery surface temperature, as seen in Figure 3. Despite its relatively small size of about 4% of the battery height, the induced boundary-layer vortexes change the cooling airflow. A glance at the temperature contour shows that this indicates a heat and mass transfer augmentation near the front row of batteries (Bouremel et al., 2017). The effectiveness of the heat and mass transfer could be subjected to the presence and evolution of the vortexes. To better study this, a qualitative analysis based on experimental smoke visualisation is necessary. As can be seen in Figure 4, when two or three V-shaped VGs are aligned in the flow direction, the generated vortex looks like an umbrella or mushroom shape, with the "hats" consisting of a counter-rotating pair which makes a thicker boundary layer. However, a somewhat different structure is depicted when multiple VGs with an increasing span is used. Regardless of the visual appearances, both vortexes could be well preserved downstream of the battery module in the wind tunnel (Budiman et al., 2022b). This is in good agreement with the preliminary simulation results above, showing a potential heat transfer augmentation by means of a VG for the forced (active) cooling BTMS. In addition, the VG is relatively easy to fabricate and redesign according to the needs, and it does not require an additional power source to operate (Kuru, 2023). Other possible less complicated shapes include triangle or delta wings, concave, perforated surfaces, or dimples (Awais and Bhuiyan, 2018; Lu and Zhai, 2019; Syaiful et al., 2021; Sahin et al., 2022).

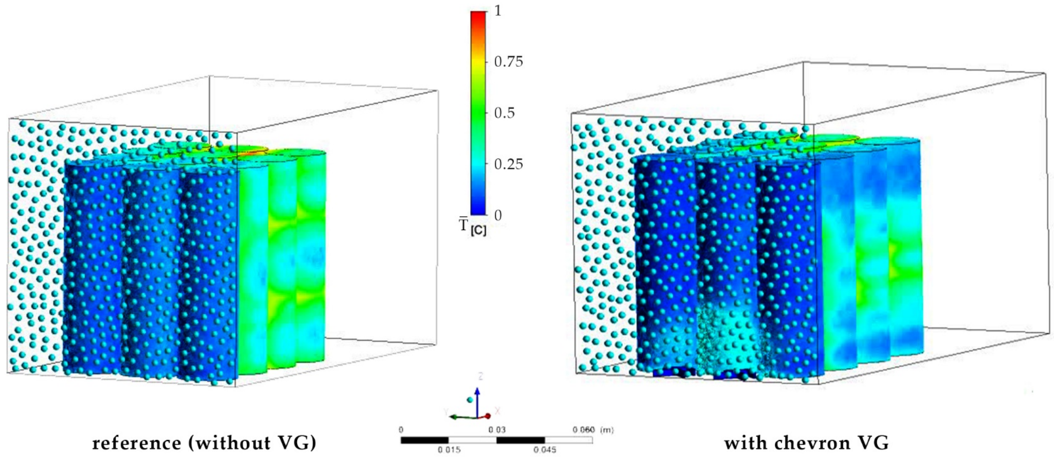
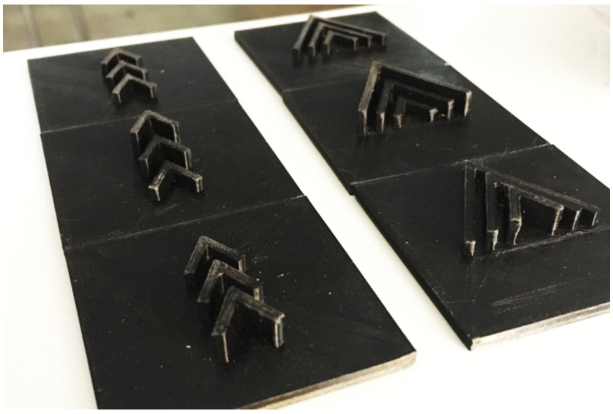


Figure 3. Simulation of VG effects shows that the overall temperature is reduced.

3.2. Heat-absorbing battery-like tubes

(a)



(b)

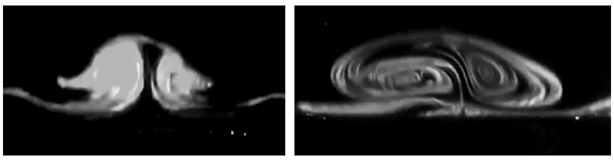


Figure 4. Photographs of the fabricated VG plates and their respective smoke visualisation of the vortexes: (a) three uniform chevron VGs; and (b) VG with increasing span size.

The following proposed method is related to a passive BTMS utilising PCMs or a hybrid method when coupled with fan cooling. A 18650-like cylinder to store the PCMs offers a strategic tube placement between the battery cells to absorb the dissipated heat and effectively protect the neighbouring cells. However, a misplacement could have an adverse effect, especially in the hybrid mode when the cooling air is blocked, causing the dissipated heat to be locally accumulated (Budiman et al., 2020). Such phenomenon can be observed in Figure 5, as some lines show a higher temperature than the reference line. The dashed lines representing the hybrid BMTS are consistently below the solid lines, characterising the passive BTMS with PCMs only. Thus, the fan cooling system could enhance heat dissipation management, although it also consumes more energy.

In this experimental study, there was a significant temperature difference when five and ten PCM tubes were used. Therefore, it can be concluded that the more PCM tubes in the battery module, the more stable the temperature. However, it is also worth noting that there is a weight limitation to consider, as more PCMs may decrease the total mileage within a single charge.

The effect of a different latent heat profile can also be seen in the graph. With a relatively similar measured latent capacity, paraffin (k = 212 kJ/kg; labelled "P" in Figure 5) could have a lower temperature trend than lauric acid (k = 205 kJ/kg, labelled "L"). This could be attributed to the broader melting profile and lower initial phase-change temperature of paraffin, as depicted in Figure 2, especially when the PCM tubes are more evenly distributed (Budiman et al., 2021). It is evident that a gradual heat absorption by the paraffin could lead to a more stable temperature compared to lauric acid, where the module temperature had already increased drastically prior to the phase change.

3.3. PCM-resin composites

The third optimisation attempt is by means of PCM composites. Contrary to the PCM tube method, where there could be a thermal lag due to the convective heat transfer between cells and conductive heat transfer due to the tube thickness, in this case the PCM is expected to spread evenly between the battery cells. As such, the dissipated heat could be absorbed and contained locally before it reaches the neighbouring cells. As depicted in Figure 6, the PCM matrix temperatures are notably lower than the base reference case without PCMs. The average temperature decrease percentage is tabulated in Table 2.

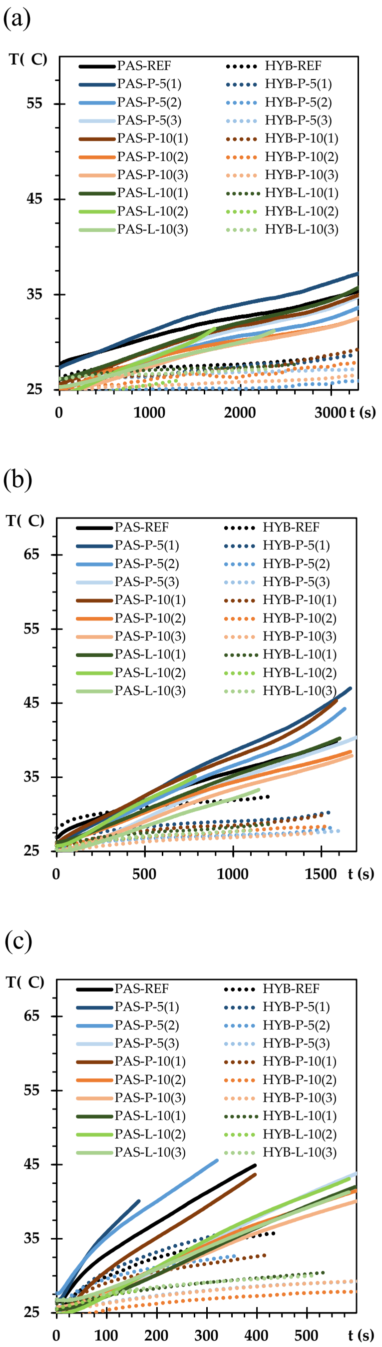


Figure 5. Plot of average battery module temperature over time for different discharge rates: (a) 1 C; (b) 2 C; and (c) 4 C. Solid and broken lines represent passive ("PAS") and hybrid ("HYB") BTMS, respectively. Black lines indicate the reference without any PCMs.

Caprylone, which has a larger phase change coefficient (k = 277 kJ/kg) and narrow melting point profile with a peak at T = 39.5 °C, produces a slightly larger temperature decrease for the 1 C discharge rate at the end of the test. However, when the load is increased dramatically, paraffin could be more suitable, with a percentage decrease of 0.8-1.2% more than caprylone.

Table 2. Maximum temperature decrease of PCM-resin composite over the discharge period.

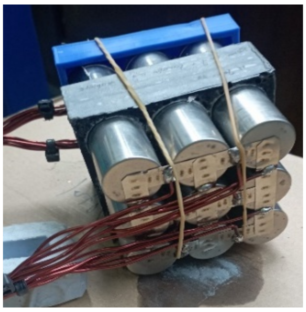
Discharge rate	Caprylone	Paraffin
1 C	13.8 %	12.6 %
2 C	13.9 %	15.1 %
4 C	24.1 %	24.9 %

The challenge of having PCMs as the filler for the battery module composite is its structural integrity. Similar to other EV core components, a battery module matrix must be able to bear mechanical stress brought on by cruise-related vibrations and volumetric change during phase changes, and provide sufficient protection against potential PCM leakage, ultraviolet radiation, electrical short circuits, and fire hazards (Kaleg et al., 2022; Liu et al., 2012). To evaluate the decrease in mechanical strength, a tensile test was carried out, and the results are tabulated in Table 3. It can be seen that the PCM-filled composite has a significantly weaker structure than the lauric composite, despite having the same mass percentage. More detailed analyses are required with respect to this issue, for example, by performing Scanning Electron Microscope (SEM) observations to study its morphology. A reinforced material such as carbon fibre could be applied to increase its mechanical strength (Azzopardi et al., 2023). From Table 3, it can be seen that the magnitude of the maximum force that the reinforced material could endure is higher than the ordinary composite. For the battery module, carbon fibre could be applied as an outer frame as a minimum. It would have been significantly better if the carbon fibre could be put inside the matrix, i.e., between the battery cells; unfortunately, the matrix fabrication would be relatively more complex.

Table 3. Tensile test results of the PCM-filled composite.

Composite	Ultimate stress (MPa)	Ultimate force (N)
Reference (no PCM)	62	604
20% lauric acid	41	402
20% paraffin	22	216
Reinforced reference	329	10,225
Reinforced 20% lauric	271	8,177
Reinforced 30% lauric	220	8,250

(a)



(b)

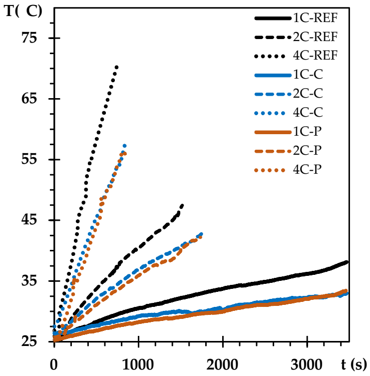


Figure 6. (a) photograph of the PCM composite battery module matrix with nine 21700 cells prepared for the discharge test; and (b) temperature plot from the discharge test, where “C” and “P” indicate caprylone and paraffin PCM, respectively.

4. Conclusion

The optimisation of the thermal management system involving Vortex Generators and Phase Change Materials in the battery module level has been performed in this work. There are at least three existing BTMS classifications, namely active, passive, and hybrid methods. For active method enhancement, a numerical observation shows the effectiveness of a small protrusion upstream of the battery module to enhance mixing and heat transfer, indicated by a surface temperature drop. Since the effect is attributed to the presence of counter-rotating vortexes, wind tunnel smoke flow visualisation was performed to study the evolution of such structures. For the augmentation of the passive or hybrid methods, various arrangements of PCM-filled tubes placed between the battery cells could be significant. However, the exact configuration is crucial, as wrong placements may lead to an adverse effect. As an alternative to these tubes, a PCM-resin composite is also proposed in this study. It is found that paraffin, although it is a considerably superior organic PCM compared to lauric acid or caprylone, weakens the resin more dramatically than the other PCMs. In this work, a properly designed BTMS utilising PCMs could lower the maximum temperature to almost 25% under different discharging conditions. To meet the vehicle standard for the battery compartment, PCM composites with reinforcement materials, such as carbon fibre, are strongly recommended.

Appendix:

Nomenclature and abbreviations

ASTM	American Society for Testing and Materials
BTMS	Battery Thermal Management Systems
CFD	Computational Fluid Dynamics
DSC	Differential Scanning Calorimetry
EV	Electric Vehicle
HVAC	Heating, Ventilation, and Air Conditioning
MEKP	Methyl ethyl ketone peroxide
PCM	Phase Change Materials
SEM	Scanning Electron Microscope
SOC	State of Charge
VG	Vortex Generator
C; C-rate	charge/discharge rate
I	electrical current (charge/discharge)
k	latent heat/phase-change capacity
P	battery nominal capacity
$\dot{Q}$	total heat generation
$\dot{Q}_{irr}$	Joule heat (irreversible)
$\dot{Q}_{rev}$	entropy change (reversible)
$\dot{Q}_{sr}$	heat generated from side reactions
$\dot{Q}_{mix}$	heat from mixing processes
R	resistance
Re	Reynolds number
T	temperature
U	open-circuit voltage
V	voltage

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