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GABARITO

EXAMES DE SETEMBRO DE 2024

LÍNGUA INGLESA

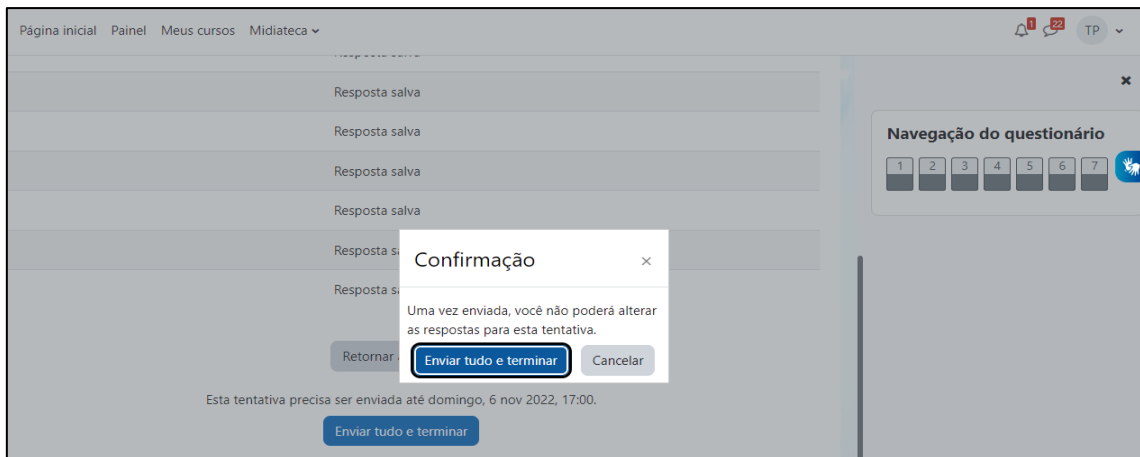
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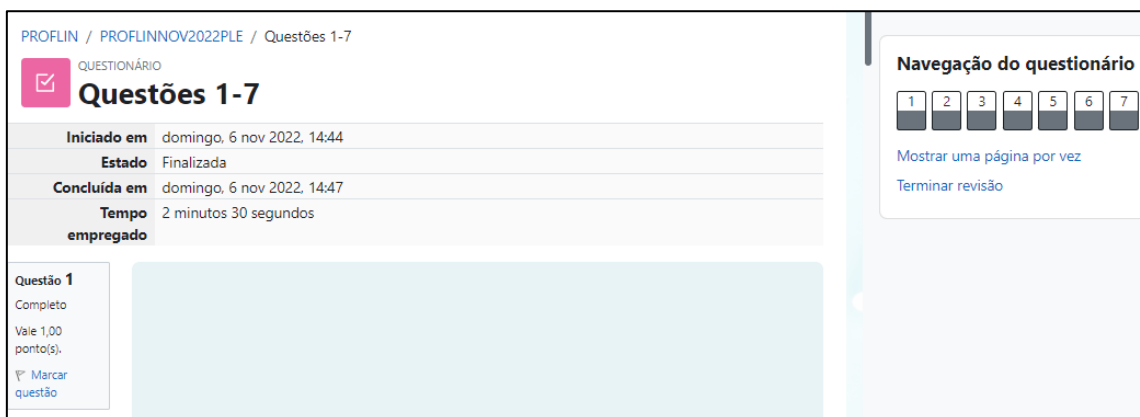
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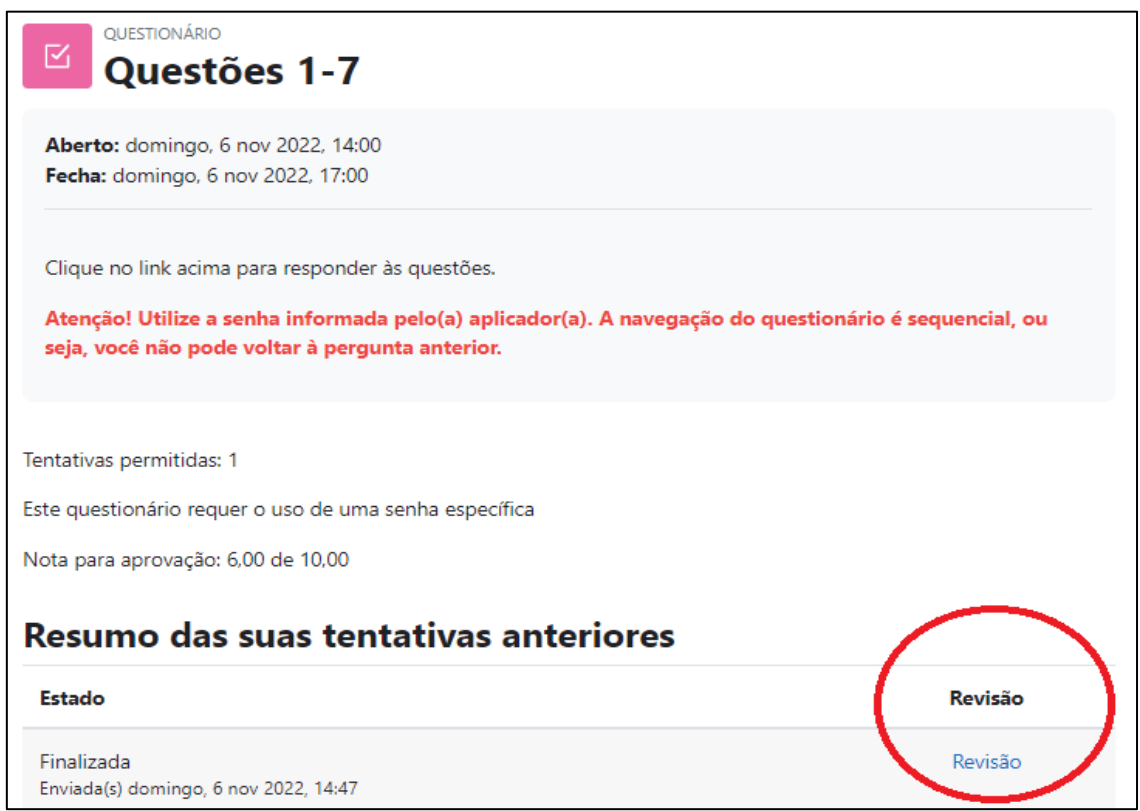
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A Hybrid Battery Thermal Management System for Electric Vehicle Operations in Cold Climates

Without proper battery thermal management, electric vehicles (EVs) suffer from significantly reduced efficiency and performance in cold climates, creating a barrier to electrifying the transportation sector. In this study, we have developed a modular, hybrid battery thermal management system that combines phase change material (PCM) with internal heating. This hybrid system uses PCM to store waste heat generated during driving, maintaining the battery temperature during shorter stops between consecutive trips. For longer stops, internal heating can reheat the battery if the latent heat of the PCM has dissipated. Moreover, by applying PCM on the outside, the proposed system is modular, requiring no structural change within the existing battery module and reducing the impact of increased thermal inertia on battery reheating time. Through both laboratory experiments and numerical simulations, we found that the proposed system could hold the battery temperature above 20 °C for around 2 h at an ambient temperature of −15 °C and achieved a battery reheating time (from 0 °C to 20 °C) of only 11 min. By reusing waste heat during short stops, this system can promote EV adoption in cold climates through improved battery efficiency, particularly for EVs making frequent stops, such as taxis and delivery vehicles. [DOI: 10.1115/1.4064712]

Keywords: electric vehicles, Li-ion batteries, low temperature, battery thermal management, battery heating, phase change materials, air conditioning, energy, heat transfer

1 Introduction

With the growth of the general public's environmental awareness, electric vehicles (EVs) are experiencing rapid growth in market share. In 2020, despite a 14% global light-duty vehicle market shrinkage due to the pandemic, global EV sales increased by about 43%, with over 3.2 million EVs being sold worldwide [1]. The state-of-the-art EV models are no longer inferior to their gasoline counterparts in terms of power and maximum range thanks to the progress in battery technology. However, range anxiety still poses an obstacle for people living in cold climates, as EVs suffer as much as a 40% range reduction at low ambient temperatures [2]. Meanwhile, more than 40% of the population in the largest EV markets, i.e., China, the United States, and Europe, live in cold-climate regions, as shown in Table 1. As a result, improving cold-climate EV performance is crucial to further promoting EV penetration.

The degraded cold-climate performance of EVs is a collective result of the temperature-sensitive components onboard and the increased energy load for cabin heating [10,11]. Among all affected

by low temperatures, the battery module is the most critical component. The widely used Lithium-ion batteries suffer from reduced capacity, reduced power output, and prolonged charging time in cold climates [12]. To mitigate this impact, researchers have developed various battery thermal management strategies, with the majority of studies focusing on battery heating [13,14]. The most widely adopted battery heating method is liquid heating, in which the working fluid in the battery cooling system is heated up by electric heaters and then circulated around battery cells [12]. Another promising solution is called internal heating, which uses special charging or discharging cycles such as onboard alternating current (AC) heating or mutual pulse heating to achieve a higher heat generation rate from the battery cells [15].

The aforementioned strategies are relatively low cost and easy to implement. However, they require electricity input in order to heat up the battery; thus, in some cases, it could be more economical to skip the battery heating process and instead save the energy to directly drive the vehicle. For example, electric taxis, rideshares, and delivery vehicles that frequently park are likely to skip the battery heating process amid their operations, leading to significant battery inefficiency [16]. On the other hand, the battery generates heat during discharging, and if this energy can be reused for thermal management, the overall system efficiency could be improved. Using phase change materials (PCMs) is one potential

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Table 1 Cold-climate area in major EV markets

Region	Definition of cold-climate area	Cold-climate area population percentage	References
United States	Region with 5400 heating degree days (65 °F basis) or more	40%	[3,4]
China	Temperature of the coldest month < 0 °C	40%	[5–7]
Europe	Temperature of the coldest month < 0 °C	47%	[8,9]

solution to store the battery's waste heat for future thermal management. The temperature of PCMs stays constant during phase changes, and therefore, they have been widely used in energy storage applications. One common PCM is paraffin, and some other examples include sugar alcohols, lipids, and salt hydrates [17,18]. PCMs can be applied to the battery module to store the waste heat generated by the battery cells as latent heat. When the vehicle is parked and the battery temperature starts to drop, the latent heat stored in the PCM is gradually transferred back to the battery, keeping it warm for several hours [19–21].

However, a purely PCM-equipped battery thermal management system can only function for a certain amount of time without the presence of a heat source. After the stored heat has depleted, this system is no longer able to perform the battery thermal management task. In addition, it is found that applying PCM to the battery cells leads to prolonged battery reheating time due to the added thermal mass, and thus, a battery module with PCM applied actually retains a lower battery temperature after a long cold soaking compared to a battery module without PCM [20,21]. Current solutions to these shortcomings include finding the optimal mass ratio of PCM to the battery [20] or adding resistance wires or heat sheets to function as an extra heat source [22,23]. Adding external heat sources enables battery reheating after the PCM has lost all of the latent heat, but it also adds weight, introduces more electrical or mechanical components, and requires a more complicated battery module design, which undermines the advantages of a PCM system being reliable and easy to implement.

In this study, we propose a hybrid battery thermal management system that uses internal heating together with PCM to enhance the system's performance in different cold-climate use cases. Compared with external heat sources in liquid heating and other battery heating methods like air heating and conductive heating, internal heating minimizes the added weight and electrical components to the battery module, preserving the advantage of PCM-based battery thermal management systems. The proposed hybrid system also features a different PCM layout that is specifically designed to achieve short battery reheating time and easier implementation. Moreover, since our hybrid system is added to the outside of the battery module, the battery cooling system, and thus the warm-climate battery cooling rate, is not affected. The cold-climate battery temperature profile and battery reheating time of the hybrid system are studied via both experimental and computational methods. Experimentally, a battery module prototype with the hybrid thermal management system was fabricated and tested in a controlled low-temperature environment. Computationally, we established a simulation model and used the experimental results to validate the modeling parameters. The validated model is then used to study the effectiveness of two further developed battery module designs with different PCM and battery cell layouts. Overall, the hybrid PCM-based battery thermal management is both effective and efficient in various use cases, thus mitigating the range anxiety of EV users in cold-climate regions and promoting worldwide transportation decarbonization.

2 Hybrid Battery Thermal Management System

2.1 System Features. A diagram of the hybrid system operation is shown in Fig. 1. The proposed hybrid system features a combination of PCM and internal heating for cold-climate battery thermal management under different scenarios. During vehicle

operation, battery cells warm up due to their own heat generation, and part of the heat is stored in the PCM as latent heat. Additional battery heating is mainly needed at the very beginning of the driving cycle and based on the duration of parking before the trip, battery conditions differ in two different scenarios: Short Parking and Long Parking. In the Short Parking scenario, the parking time between the upcoming trip and the previous trip is short enough so that the applied PCM is able to use the stored battery waste heat to keep the battery cells warm throughout the whole duration of parking. For example, this could happen when the driver goes shopping and the vehicle is parked outdoors for a couple of hours. With this hybrid battery thermal management system, the battery would remain warm until the driver returns to the vehicle, so there is no waiting time needed for battery reheating. Also, the PCM reuses the waste heat generated by battery cells, and thus, no extra electricity is needed for battery heating. It should be noted that since PCM has relatively low specific heat, it does not have a significant impact on the battery cooling rate when the temperature changes outside its phase change range. In other words, even in hot weather, applying PCM does not slow down battery cooling significantly with well-selected PCM type and optimized PCM amount. The Long Parking scenario corresponds to the cold start after a long parking, such as overnight parking. In this scenario, the heat stored in the PCM has dissipated, and the entire battery module has dropped to a low temperature at the beginning of the next trip. Without another heat source, the PCM is not able to heat up the battery under this condition. In the proposed hybrid battery thermal management system, the battery cells function as the heat source through internal heating. Common internal heating methods, such as onboard AC heating, use special charging/discharging cycles to achieve a high heat generation rate [15]. This method also leads to short heating times and high energy efficiency without the need to add much weight to the battery module, thus preserving the vehicle's performance in both cold and high-temperature environments.

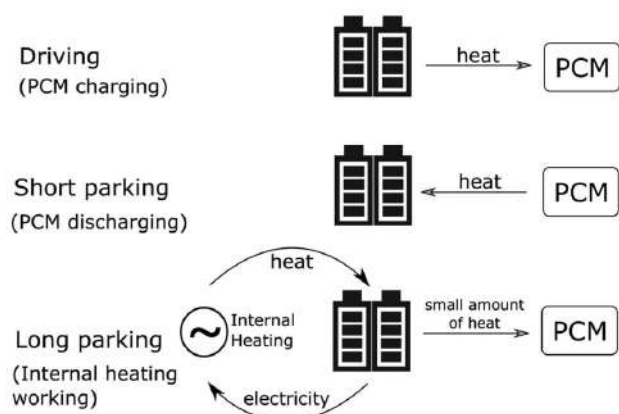


Fig. 1 Diagram of the hybrid system showing the heat transfer between battery and PCM in different scenarios. In the Short Parking scenario, the PCM uses stored waste heat to keep the battery warm for the duration of the parking cycle. In the Long Parking scenario when the PCM energy is depleted, internal heating directly warms the battery. Since the PCM layer is applied outside the battery module, it will not divert much heat during the heating process.

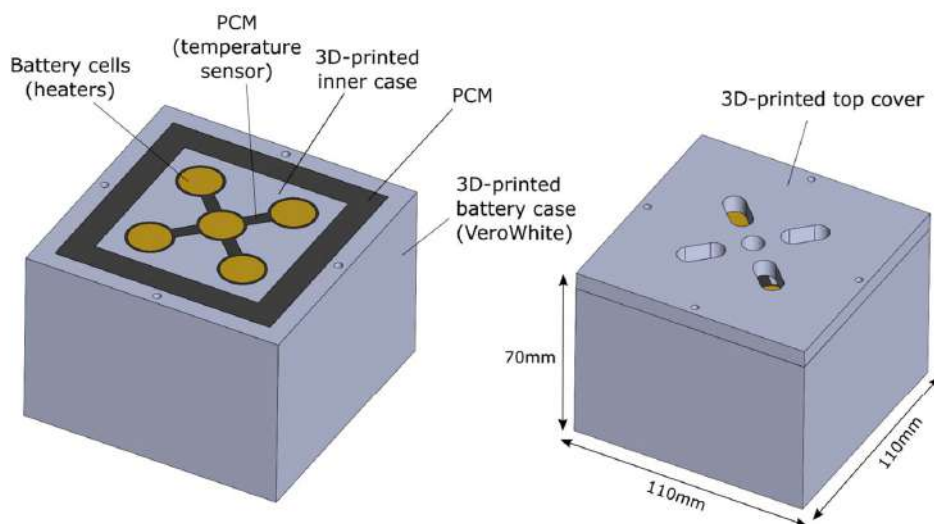


Fig. 2 Schematic of the battery module design showing the battery and the PCM layout. Five battery cells are emulated by cartridge heaters enclosed in a 3D-printed inner case. For experimental purposes, PCM is added between the heaters and the case to ensure a good thermal interface. A reservoir of PCM is located between the inner and outer cases. Holes in the top cover allow for sensor and power interfaces.

2.2 Battery Module Design. To test and illustrate the performance of the proposed thermal management system, a battery module is designed, as shown in Fig. 2. This layout is adopted in the experiment and the corresponding simulation. It also functions as the base design from which the two design variants, which will be introduced in a later section, are developed. Cylindrical 18650 Li-ion battery cells are the subject of this study, and to study battery heating in a multiple-cell scale, five cells are packed in a 3D-printed inner battery case, which represents the existing EV battery module, following a radial pattern. Outside the four side faces of the inner battery case is the PCM layer. In the base design, the thickness of the PCM layer is 11 mm, leading to a total PCM volume of 0.232 L. The outermost layer is a 3D-printed outer battery case, with a 3D-printed cover attached to the top. To accommodate the temperature sensor, there is some space between the battery cells and the inner battery case, and in the validation experiment, a small amount of PCM is filled into the space to enhance heat transfer and prevent overheat. Since internal heating is used as the extra heat source, no additional components are added to the battery module. The entire battery module has a dimension of $110 \times 110 \times 70$ mm.

The proposed battery module layout provides two main benefits. First, in the reheating process after long parking, heat is generated within the battery cells through internal heating, so having the majority of PCM segregated from the cells minimizes the heat

diverted by the PCM; thus, a short reheating time could be achieved. Second, incorporating this system does not require any changes within the inner battery case, so it should be compatible with most battery cooling system designs.

3 Experimental Approach

3.1 Experimental Setup. In the experiment, electric heaters were used to emulate Li-ion battery cells. The dimension of the electric heaters was customized to match the 18,650 Nickel Manganese Cobalt (NMC) Li-ion battery cells, with a diameter of 17 mm and a length of 65 mm. Onboard AC heating was used to represent internal heating in this study. The heating power that could be achieved by onboard AC heating at the relevant ambient temperature range, recorded by Ge et al. [24], was approximately 7 W. Based on that study, we customized the voltage and the resistance of the heaters so that when connected to a 12 V voltage supply, they output a heating power of 7 W. Initially, we used PLA (polylactic acid) as the 3D-printing material for the battery case, but it was found in the following experiment that this material led to a significant PCM leakage problem due to the high permeability to organic molecules of the PLA [25]. As a result, we tested several other materials, and in the end, a photopolymer called VeroWhite was chosen. Since few reports on the thermal properties of VeroWhite are available, this study uses the reference values of Polyamide-Nylon 6,6 (PA66) [26], which is reported to have very similar thermal properties as VeroWhite [27]. The PCM selected for this experiment is Rubitherm RT25HC, which is a paraffin-based organic material. The properties of VeroWhite and the chosen PCM are listed in Table 2. In the validation experiment, the space between the heaters and the inner battery case is also filled with a small amount of PCM to prevent the heaters from overheating by eliminating the air gap between the heaters and the surrounding material.

Figure 3 gives a diagram of the experimental setup, with some photos showing the actual experimental condition. A resistance temperature detector (RTD) (Adafruit PT100) was attached to the central electric heater in the battery module for temperature measurements. It was connected to an RTD temperature sensor amplifier (Adafruit MAX31865), which converted the resistance reading of the RTD into temperature with a resolution of 0.03 °C and an accuracy of 0.05% of full scale. The data were logged by a microcontroller (Arduino Uno) that was connected to a laptop.

Table 2 Properties of the 3D-printing material and the PCM used in the experiment (Refs. [27–30])

Properties	Value
PCM (RT25HC) solidus point (K)	295
PCM (RT25HC) liquidus point (K)	299
PCM (RT25HC) latent heat (kJ/kg)	210
PCM (RT25HC) specific heat capacity (both phases) (kJ/(kg K))	2
PCM (RT25HC) thermal conductivity (both phases) (W/(m K))	0.2
PCM (RT25HC) density (solid phase) (kg/m ³)	880
PCM (RT25HC) density (liquid phase) (kg/m ³)	770
VeroWhite specific heat capacity (kJ/kg)	1.34
VeroWhite thermal conductivity (W/(m K))	0.24
Battery specific heat capacity (kJ/(kg K))	0.96
Battery thermal conductivity (W/(m K))	19

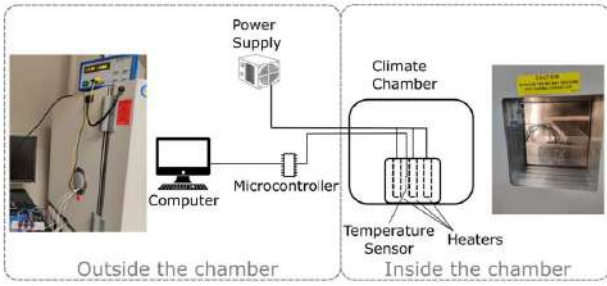


Fig. 3 Schematic of the experimental setup with photos showing the battery module inside the climate chamber and the cables connected to the power supply and the microcontroller outside the chamber

A microclimate chamber (CSZ MicroClimate) was used in the experiment to create the low ambient temperature condition. During the experiment, the battery module was placed inside the climate chamber, with wires connected to the RTD amplifier and the power supply outside through a cable hole.

3.2 Experimental Procedure. To validate the effectiveness of this hybrid system in both short parking and long parking scenarios, both cooling and heating tests are conducted in this study. When inspecting the climate chamber before the experiment, we found that when the temperature set point went lower than a certain value, the chamber could not keep the temperature stable. As a result, the testing temperature was set to -5.5°C for both the cooling and heating tests. In the cooling test, the battery module at around room temperature (23°C) was placed into the climate chamber. The cooling profile of the battery module was recorded until it cooled down to 0°C . In this experiment, the PCM was initially in a liquid state, and as its temperature dropped below its solidification point, it changed into a solid phase while releasing the latent heat to keep the battery warm. This test aims to simulate the scenario of short parking, as illustrated in Fig. 1, and the goal here is to study how long the PCM can keep the battery cells warm in such conditions.

In the heating test, the battery module at 0°C steady-state was placed inside the climate chamber that stayed at -5.5°C . As the test began, the electric heaters were switched on to simulate the internal heating of the battery cells. The time it took for the cells to reach 20°C was recorded as the battery heating time. Because the PCM that is used in this experiment has a melting point above 20°C , during the entire heating test, the PCM remained a solid state. The goal here is to study how well internal heating performs in the presence of PCM. If the battery temperature rises quickly, then it shows that the proposed hybrid battery thermal management system is able to achieve a short heating time despite the added thermal mass.

4 Numerical Approach

4.1 Governing Equations. The liquid phase of the PCM was considered unsteady, incompressible, three-dimensional, and laminar, consistent with other computational fluid dynamics modeling studies of PCM [26,30–33]. All thermo-physical properties of the PCM except for density were assumed to be constant, which is reasonable since the specific heat and thermal conductivity for both the liquid and solid phases of the PCM are the same (see Table 2). For density, the Boussinesq approximation was used such that the effects of buoyancy and natural convection within the PCM are accounted for. The velocity distribution for the PCM was obtained by solving the following continuity and momentum equations, respectively.

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \quad (1)$$

Momentum:

$$\frac{\partial}{\partial t}(\rho V) + (\rho V \cdot \nabla)V = -\nabla p + \mu \nabla^2 V + S_b + S_m \quad (2)$$

where ρ is the density of the PCM, V is the velocity of the fluid PCM, p is the pressure, μ is the dynamic viscosity of the fluid PCM, and S_b and S_m are the source terms due to buoyancy and the melting and solidification of the material. The buoyancy source term, S_b , is given by

$$S_b = \rho g \alpha (h - h_{ref}) / c_p \quad (3)$$

where α is the thermal expansion coefficient, h is the sensible specific enthalpy, h_{ref} is a reference value of the sensible specific enthalpy, and c_p is the specific heat capacity of the PCM.

To calculate the melting and solidification source term, an important parameter is the liquid fraction, β , and is defined as

$$\beta = \begin{cases} 0, & \text{if } T < T_s \\ \frac{T - T_s}{T_l - T_s}, & \text{if } T_s < T < T_l \\ 1, & \text{if } T > T_l \end{cases} \quad (4)$$

where T , T_s , and T_l represent the PCM temperature, the solidus point of the PCM, and the liquidus point of the PCM, respectively. The region in which β is between 0 and 1 is called the mushy zone, and it is modeled as a “pseudo” porous medium. When the material fully solidifies, the liquid fraction of the mushy zone decreases to 0, and when it is fully liquid, the liquid fraction is 1. The source term S_m , known as Darcy’s law damping factor, is added to the momentum equation to describe the flow in a porous medium. In the liquid phase, S_m must be zero to allow for free motion of the liquid PCM, but in the solid phase, S_m must be large to force the velocity values to near zero values. S_m is defined as

$$S_m = A(\beta)V \quad (5)$$

where $A(\beta)$ is the “porosity function” and is evaluated by

$$A(\beta) = \frac{(1 - \beta)^2}{\beta^3 + \varepsilon} A_{mush} \quad (6)$$

where ε is a small number (0.001) to prevent division by zero, and A_{mush} is the mushy zone constant, which measures how fast the fluid velocity approaches zero as it solidifies.

To study the melting and solidification of the PCM, an enthalpy porosity technique is used [34,35]. The temperature distribution is

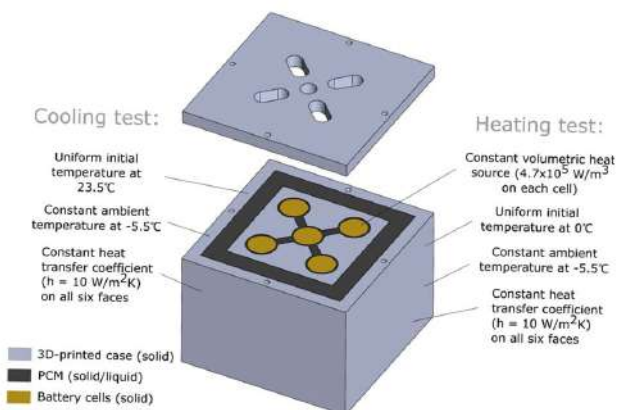


Fig. 4 The boundary and initial conditions of the cooling test and the heating test are shown on the battery module

evaluated using the energy equation:

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

where k is the thermal conductivity of the PCM, and H is the specific enthalpy. The specific enthalpy is the sum of the sensible enthalpy (h) and the latent heat (ΔH):

$$H = h + \Delta H \quad (8)$$

The latent heat is defined by

$$\Delta H = \beta L \quad (9)$$

where L is the latent heat of the PCM. The sensible heat can be obtained using Eq. (10)

$$h = h_{ref} + \int_{T_{ref}}^T c_p dT \quad (10)$$

where h_{ref} is the specific sensible enthalpy at the reference temperature T_{ref} .

To determine the temperature in the solid components of the battery module (battery, inner case, and outer case) and its thermal interaction with the PCM, the following energy equation was solved:

$$\frac{\partial}{\partial t}(\rho h_s) = \nabla \cdot (k_s \nabla T_s) + S_s \quad (11)$$

where h_s is the sensible enthalpy of the solid component, k_s is the thermal conductivity of the solid component, T_s is the temperature of the solid component, and S_s is a volumetric heat source. A volumetric heat source was applied to the battery to simulate its internal heating for the heating test scenario. The sensible enthalpy of the solid component is evaluated using the following equation:

$$h_s = h_{sref} + \int_{T_{sref}}^T c_{ps} dT \quad (12)$$

where h_{sref} is the sensible enthalpy at the solid reference temperature T_{sref} , and C_{ps} is the solid specific heat capacity. The thermal properties (C_{ps} and k_s) of the different solid components of the battery module are listed in Table 2.

4.2 Boundary and Initial Conditions. The boundary and initial conditions of the heating and cooling test simulations are illustrated in Fig. 4. For both the cooling and heating test simulations, to simulate the outer cold environment, the temperature of the ambient air outside the case was set to -5.5°C . Since the air temperature remained unchanged during the entire cooling and heating test, a constant convective heat transfer coefficient, h , of $10 \text{ W m}^{-2}\text{K}$ was set at the six outer walls of the case. This constant convective coefficient is consistent with other battery studies [28,29] and was obtained from experimental data.

There is no heat source in the cooling test, consistent with a turned-off and parked vehicle. In the heating test, to simulate the 7 W heating power on each battery cell, a constant volumetric heating rate S_{bat} was calculated by dividing the single cell heating power by its volume. This heating rate, estimated to be $4.7 \times 10^5 \text{ W m}^{-3}$, was applied to all the battery cells to simulate internal heating.

The electric heaters used in the experiment are made of steel, so the simulation used to validate the experiment adopted steel properties for the battery cell component.

Both cooling and heating processes started with a uniform initial temperature of the battery module:

$$T_{bat} = T_{PCM} = T_{case} = T_{ini} \quad (13)$$

where T_{bat} , T_{PCM} , and T_{case} are the initial temperature of the battery, PCM, and case, respectively, and T_{ini} is the set initial

Table 3 Cell temperature at the end of the cooling test for various mesh cells

Grid size	Temperature (K)
113,121	272.83
138,154	272.80
335,474	273.24

Table 4 Cell temperature at the end of the cooling test with 138,154 grid cells for different time-steps

Time-step (s)	Temperature (K)
0.5	273.25
1.0	272.80
2.0	272.72

temperature. The initial temperature T_{ini} was set to 23.5°C for the cooling test simulation and 0°C for the heating test simulation (Fig. 4).

Finally, the initial velocity of the PCM in all directions was zero. The thermal properties of the PCM, battery, and module case set in our simulations are consistent with those of the validation experiment and are listed in Table 2.

4.3 Numerical Method and Mesh Independence. ANSYS FLUENT is used for numerical modeling in this study. A tetrahedral structured grid was used in creating the mesh. Second-order discretization schemes were used for all of the governing equations. A mesh independence study was conducted to ensure that the results of the simulation were not sensitive to the mesh cell size. Table 3 shows the cell temperature using three different mesh sizes: 113,121, 138,154, and 335,474 cells. The temperature of the cell is similar for the three meshes, and in the end, a total of 138,154 cells were adopted since it is sufficient to capture the physics and the relevant cell temperature.

A similar sensitivity analysis was conducted to determine the ideal time-step size by evaluating the following three different time-steps: 0.5 s, 1 s, and 2 s. As shown in Table 4, the results are independent of the tested time-steps, and a 1 s time-step was selected as it is sufficient to capture the physics of the simulation while being computationally efficient.

5 Results and Discussion

5.1 Simulation Model Validation. The cooling test result for the battery module equipped with the hybrid battery thermal management system is shown in Fig. 5(a). To test the repeatability, a total of three cooling tests were conducted under slightly different initial temperatures, and their recorded temperature data, as well as the corresponding simulation results, are plotted on the same graph. Due to the limitation of the instrument, the experiments started at a temperature below the liquidus point of the PCM, so the PCM started as a mixture of liquid and solid. In other words, a portion of the latent heat was not able to be utilized in the test. Despite that, the hybrid battery thermal management system was able to hold the battery temperature above 0°C for around 3 h at an ambient temperature of -5.5°C . There is a good match between the simulation results and the experimental results in all three cases, showing that the model is appropriate for further simulations.

Figure 5(b) depicts the heating test results for the experiment and the simulation. With a heating power of 7 W, it took less than 5 min for the battery temperature to rise from 0°C to 20°C , and both experiments and simulations have matching results. To better

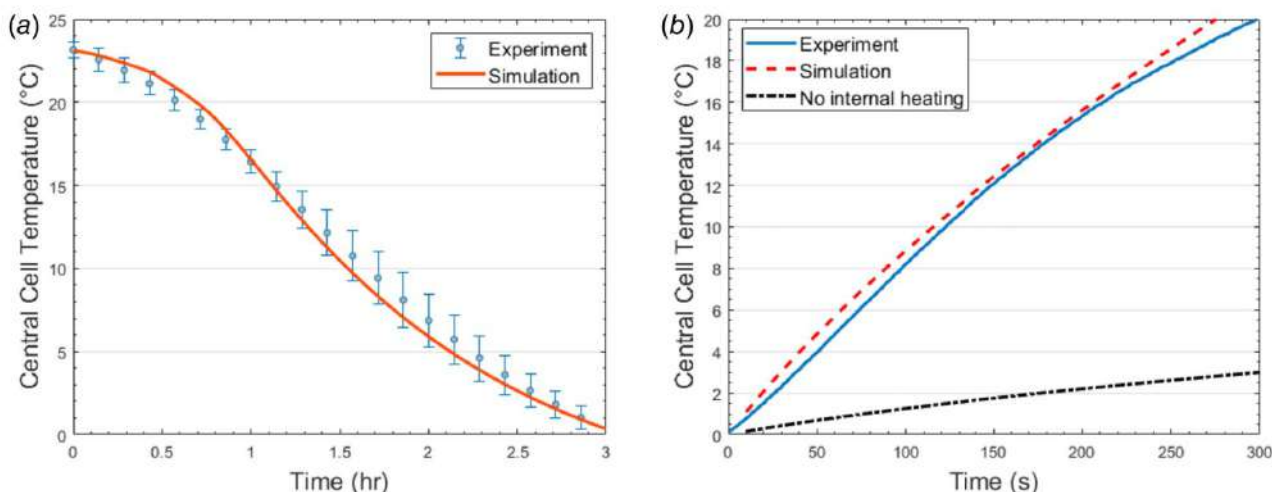


Fig. 5 Simulated battery temperature versus the measured value in (a) the cooling test and (b) the heating test. The dashed line labeled “Simulation” in (b) represents the result with a heating power of 7 W, which corresponds to an internal heating scenario and the dotted line labeled “No internal heating” represents a heating rate of 1 W, representing a scenario without internal heating.

illustrate the benefit of this hybrid system over a pure PCM system, another simulation, in which the battery heating power was reduced to 1 W, which represents the heat generation rate of Li-ion battery cells discharging at around 1C rate, is plotted on the same figure. Without the help of internal heating, battery cells could not warm themselves up effectively through discharging under normal driving conditions. It should be noted that as the temperature reaches the liquidus point of the PCM, which is around 26 °C in this experiment, the battery temperature rising rate slows down due to heat being absorbed as the latent heat. But this should not affect the effectiveness of this battery thermal management system, because 20 °C is high enough for most commercial Li-ion batteries to reach their full discharging and charging capability.

5.2 Comparison of Different Battery Module Designs.

Subject to the constraints of the instruments, in the validation

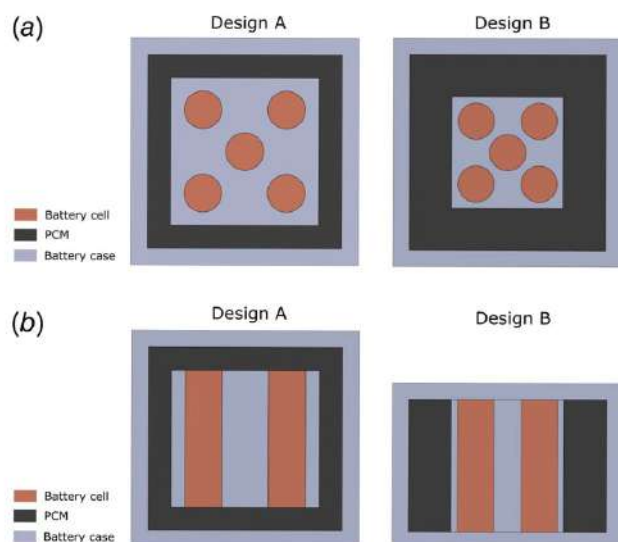


Fig. 6 Cross-sectional views of design A and design B: (a) horizontal cross sections and (b) vertical cross sections. The total amount of PCM is the same for both designs, but in design B PCM is not applied on the top and the bottom faces. Together with a smaller inner battery case, this leads to a thicker PCM layer in design B.

experiment, the ambient temperature was set at -5.5°C . This temperature is not low enough to simulate the harsh winter conditions in some cold-climate regions. As a result, a numerical study conducted under a lower ambient temperature is necessary. Then, the amount of PCM in the original battery module design could be insufficient to handle the new conditions, so some changes need to be made. Meanwhile, because applying PCM to the battery module adds extra weight, the amount of PCM added for thermal management needs to be optimized to achieve balanced vehicle performance in all conditions. As a result, two battery module design variants, shown in Fig. 6, were developed based on the original design to test the performance of the hybrid battery thermal management system under a lower ambient temperature and to study the effectiveness of different PCM layouts. Both designs keep the battery module structure the same, with five battery cells arranged diagonally in the center, and a PCM layer applied between the inner and outer battery case. In design A, the inner battery case has the same size as in the validation experiment, but the PCM is applied all around it. With the same PCM layer thickness as in the original design, the total volume of PCM is increased to 0.418 L, which adds 0.322 kg to the battery module. Design B features more closely packed battery cells, leading to a smaller inner battery case with 27% less surface area. Design B uses the same amount of PCM as design A, but the PCM is only applied on the four side faces of the smaller battery case, so a higher PCM thickness on each face is achieved.

Some other parameters were also changed to create a more realistic testing condition. The initial temperature of the entire battery module was changed to 30°C , with ambient temperature at -15°C to simulate a cold winter condition. The specific heat and thermal conductivity of the Li-ion battery cells were changed to the experimentally measured values of a real cell [24,36]. It should be noted that the thermal conductivity of the battery cell was assumed to be uniform in all directions. The value used in the simulation is the axial thermal conductivity, but some studies report the radial thermal conductivity to be much lower [36,37], which could lead to a higher temperature gradient among the cells that could affect battery performance. Besides the battery cells, the material of the inner battery case was changed to aluminum to emulate a real battery module and ensure a uniform temperature distribution among the cells. Furthermore, the space between the battery cells and the inner battery case was removed in design A and design B, and the battery temperature uniformity is guaranteed by the high thermal conductivity of aluminum. This change also brings another benefit. Compared with other studies in which bulk PCM is directly applied around the battery cells, this design

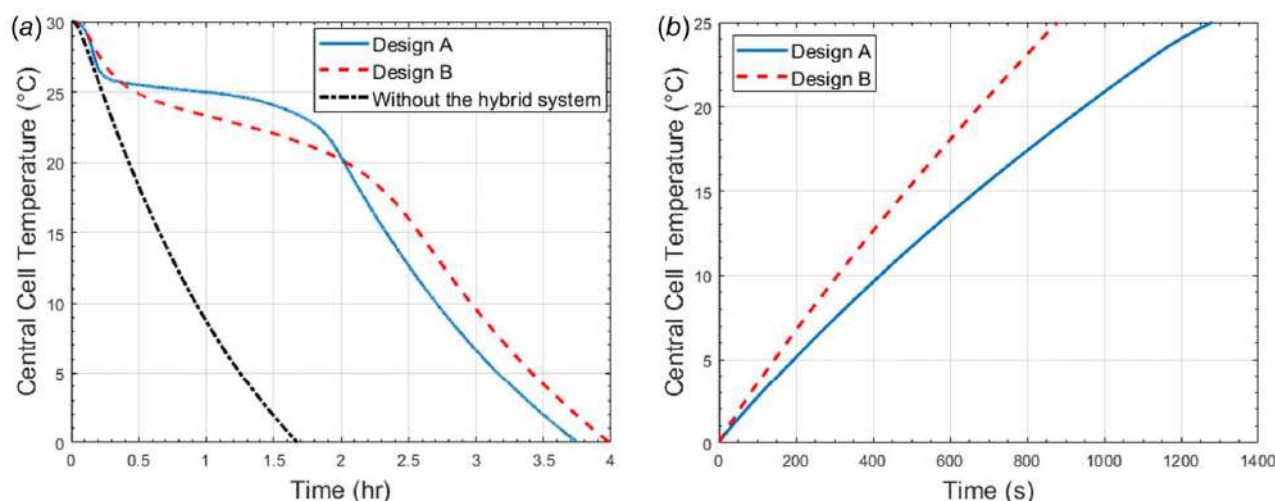


Fig. 7 Simulated battery temperature for design A and design B in the cooling test and the heating test: (a) cooling test and (b) heating test

prevents melted PCM from contacting the battery cells, eliminating the possibility of PCM-caused battery erosion.

Figure 7(a) shows the battery cooling profile of battery module design A and design B from the cooling test simulation. Another simulation that studies a battery module without the hybrid thermal management system is also presented in the figure as the control group. In the control group battery module, the same inner battery case from design A is used, but the PCM layer is removed, and the inner battery case is directly contained in the outer battery case. For both design A and design B, the hybrid system held the battery temperature above 20 °C for around 2 h, and it took 3.75 to 4 h for the battery to cool down to 0 °C, which is significantly longer compared to the battery module without the hybrid system. It can also be observed that during the first 0.2 h where the temperature was above the solidus point of the PCM, design A, design B, and the control group had similar temperature dropping rates, implying that the presence of PCM did not add any significant heat load for the cooling system.

The battery heating time of designs A and B can be read from the heating simulation results that are shown in Fig. 7(b). At an ambient temperature of −15 °C, battery module design A managed to warm up the battery to 20 °C in around 16 min. For design B, the heating time was further reduced to around 11 min.

The cooling test result shows that both designs are able to keep the battery warm for several hours without consuming extra energy. At the same time, the recorded battery heating times of design A are around 40% longer than that of design B. In other words, both designs achieve all-scenario battery thermal management in cold climates while preserving the advantages of a PCM-based system, but design B achieves shorter battery heating time. Since the weight and size of the battery module are crucial to vehicle performance and passenger comfort, the layout in design B is demonstrated to be more effective. This also implies that reducing the surface area of the inner battery case by packing the battery cells closer to each other helps minimize the amount of PCM needed, and applying PCM on the side faces is more efficient for cylindrical battery cells. It should be noted that reducing the distance between the cells also affects battery cooling. While battery cooling is not the subject of this study, the actual battery module design needs to take both aspects into consideration.

6 Conclusions

A hybrid battery thermal management system for cold-climate EV operation in which PCM is used coupled with internal heating is proposed. Both experimental and computational results show

that this hybrid system is able to maintain the battery temperature above 0 °C for several hours by reusing the waste heat generated by the battery cells. For long-time parking, internal heating offsets the impact of PCM, and a short battery heating time is achieved. This hybrid system improves EV performance at low temperatures significantly and thus has the potential to promote EV penetration in cold-climate regions. This system has added benefit for frequently stopping vehicles like taxis, rideshares, and delivery vehicles, as the battery is passively kept warm between trips.

There are two remaining questions for future studies. First, the amount of PCM applied to the battery is a key factor in the temperature-holding performance of this hybrid system, but as mentioned earlier, applying too much PCM leads to reduced dynamic performance. This study shows the potential of the proposed hybrid system, but the desirable time duration of holding battery temperature above 0 °C could vary between climate regions. Further study based on the statistics of real-life driving patterns is still needed to optimize the amount of PCM that leads to the best vehicle performance in both winter and summer driving scenarios. At the same time, for the automotive industry, standardization is important to reduce costs. Future designs could make it adaptable so that EV manufacturers can have different amounts of PCM applied for different regions without changing the standardized battery module structure. Second, in this study, cylindrical 18,650 NMC Li-ion battery cells are used to construct the battery module, but different car manufacturers adopt different battery cell geometries and chemistry. Although the concept of this hybrid battery thermal management system should be compatible with all kinds of batteries, the actual battery module design needs to be adjusted for different battery cells to ensure effectiveness and efficiency and a detailed comparative analysis on the heat transfer processes among different designs is necessary. Case studies conducted on different battery geometries and battery types are needed before implementing this hybrid system on different batteries.

Acknowledgment

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Conflict of Interest

There are no conflicts of interest.

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Concluída em sexta-feira, 30 ago. 2024, 15:00

**Tempo
empregado** 1 dia

Questão 1

Não respondido

Vale 1,00
ponto(s).

v12 (de 15)

A preocupação com a autonomia dos veículos elétricos em climas frios ainda é um obstáculo para sua penetração no mercado. Considerando o texto de Jiang et al. (2024), analise as afirmativas a seguir e identifique se são verdadeiras (V) ou falsas (F). I - As baterias de íon de lítio são sensíveis à temperatura. II - Os métodos de aquecimento de bateria são de alto custo e difíceis de se implementar. III - Um dos Materiais de Mudança de Fase (PCM) mais comum é a parafina. IV - Adicionar uma fonte extra de calor para um PCM é confiável e fácil de implementar. V - O estudo realizado sobre o sistema híbrido de controle térmico utilizou métodos experimentais e computacionais. Selecione a alternativa com a sequência correta de assertivas falsas (F) e verdadeiras (V) considerando a lista acima.

Escolha uma opção:

- ☐ V – F – V – F – V
- ☐ F – F – V – F – V
- ☐ V – F – F – V – F
- ☐ F – V – F – V – F

Questão 2

Não respondido

Vale 1,00
ponto(s).

v12 (mais recente)

O estudo de Jiang *et al.* (2024) incluiu a fabricação de um protótipo de controle térmico híbrido de bateria. Considerando o experimento realizado, analise as afirmativas a seguir:

I - O sistema híbrido de controle térmico de bateria proposto é composto de uma combinação de materiais de mudança de fase e aquecimento interno.

II - Foi utilizada uma câmara para simular o contexto de baixa temperatura externo à bateria.

III - O design proposto prevê mudança nos módulos de bateria já utilizados, pois acrescenta uma camada de PCM externa.

IV - A câmara simulou temperaturas externas estáveis abaixo de $-5,5^{\circ}\text{C}$.

V - Foram realizados testes de esfriamento e de aquecimento.

Escolha uma opção:

- ☐ Todas as afirmativas estão corretas.
- ☐ Apenas as afirmativas III e IV estão incorretas.
- ☐ Apenas a afirmativa V está incorreta.
- ☐ Apenas as afirmativas I e II estão incorretas.



Questão 3

Não respondido

Vale 1,00
ponto(s).

v17 (de 18)

Considerando a fase de simulação numérica da pesquisa (Jiang et al., 2024), é correto afirmar que:

Escolha uma opção:

- ☐ todas as características térmicas e físicas dos materiais de mudança de fase foram considerados constantes na simulação numérica.
- ☐ a temperatura inicial para os processos de redução de temperatura e aquecimento, na simulação numérica, foi a mesma temperatura do módulo da bateria (bateria, materiais de mudança de fase e caixa).
- ☐ a temperatura do ambiente foi constante, tanto para o teste de esfriamento quanto o de aquecimento do módulo de bateria, em 0°C.
- ☐ um teste de independência de malha foi realizado para verificar a ineficácia do tamanho das células.

Questão 4

Não respondido

Vale 1,00
ponto(s).

v4 (mais recente)

A pesquisa de Jiang *et al.* (2024) aponta que:

- ☐ a quantidade de PCM que leva ao melhor desempenho dos veículos elétricos é diferente para o uso no verão e no inverno.
- ☐ os estudos de caso conduzidos sobre os diferentes tipos de bateria foram suficientes para a implementação do sistema híbrido de controle térmico de bateria.
- ☐ o sistema híbrido de controle térmico de bateria proposto melhora de forma significativa a performance de veículos elétricos em climas de frio.
- ☐ a demanda de um benefício extra deve ser investigada para veículos que costumam ter paradas frequentes, como táxis e veículos de entrega.

Questão 5

Não respondido

Vale 3,00
ponto(s).

v11 (de 12)

Parte do calor armazenado nos Materiais de Mudança de fase (PCM) é armazenado como calor latente. Considerando o experimento apresentado por Jiang et al. (2024):

A) compare os dois diferentes cenários apresentados, curto tempo de estacionamento e longo tempo de estacionamento, e;

B) explique como se dá a transferência de calor entre a bateria e os Materiais de Mudança de fase (PCM) nos dois cenários.



Questão 6

Não respondido

Vale 3,00
ponto(s).

v10 (mais recente)

Para simular temperaturas de frio extremo, foi realizada uma simulação numérica a partir de variações do design utilizado na fase de experimento.

- A) Descreva as diferenças entre o protótipo e os designs A e B;
- B) Qual dos dois designs foi considerado mais eficaz? Por quê?





LÍNGUA INGLESA

TECNOLÓGICAS

TEXTO-BASE:

JIANG, Y.; HASHAD, K. N.; LEE, Z. E.; ZHANG, K. M. A hybrid battery thermal management system for electric vehicle operations in cold climates. *ASME Journal of Engineering for Sustainable Buildings and Cities*. vol. 5. Feb. 2024. 011004-1-011004-8.

QUESTÃO 1:

Enunciado:

A preocupação com a autonomia dos veículos elétricos em climas frios ainda é um obstáculo para sua penetração no mercado. Considerando o texto de Jiang *et al.* (2024), analise as afirmativas a seguir e identifique se são verdadeiras (V) ou falsas (F).

- I - As baterias de íon de lítio são sensíveis à temperatura.
- II - Os métodos de aquecimento de bateria são de alto custo e difíceis de se implementar.
- III - Um dos Materiais de Mudança de Fase (PCM) mais comum é a parafina.
- IV - Adicionar uma fonte extra de calor para um PCM é confiável e fácil de implementar.
- V - O estudo realizado sobre o sistema híbrido de controle térmico utilizou métodos experimentais e computacionais.

Selecione a alternativa com a sequência correta de assertivas falsas (F) e verdadeiras (V) considerando a lista acima.

Gabarito:

V – F – V – F – V

Justificativa: A alternativa está correta considerando a seção de Introdução do texto-base. A sequência é a correta, considerando explicações no quadro a seguir.

Distratores:

- 1) F – V – F – V – F
- 2) F – F – V – F – V
- 3) V – F – F – V – F

Justificativa: As sequências estão incorretas, considerando explicações no quadro a seguir.

I - VERDADEIRA	“The widely used Lithium-ion batteries suffer from reduced capacity, reduced power output, and prolonged charging time in cold climates”
II - FALSA	“The aforementioned strategies are relatively low cost and easy to implement.”
III - VERDADEIRA	“One common PCM is paraffin [...]”
IV - FALSA	“Adding external heat sources enables battery reheating after the PCM has lost all of the latent heat, but it also adds weight, introduces more electrical or mechanical components, and requires a more complicated battery module design, which undermines the advantages of a PCM system being reliable and easy to implement.”
V - VERDADEIRA	“The cold-climate battery temperature profile and battery reheating time of the hybrid system are studied via both experimental and computational methods.”

QUESTÃO 2:

Enunciado:

O estudo de Jiang *et al.* (2024) incluiu a fabricação de um protótipo de controle térmico híbrido de bateria. Considerando o experimento realizado, analise as afirmativas a seguir:

I - O sistema híbrido de controle térmico de bateria proposto é composto de uma combinação de materiais de mudança de fase e aquecimento interno.

II - Foi utilizada uma câmara para simular o contexto de baixa temperatura externo à bateria.

III - O design proposto prevê mudança nos módulos de bateria já utilizados, pois acrescenta uma camada de PCM externa.

IV - A câmara simulou temperaturas externas estáveis abaixo de $-5,5^{\circ}\text{C}$.

V - Foram realizados testes de esfriamento e de aquecimento.

Gabarito:

Apenas as afirmativas III e IV estão incorretas.

Justificativa: A resposta poderá ser encontrada na seção “Hybrid Battery Thermal Management System” e “Experimental Approach”. “Apenas as afirmativas III e IV estão incorretas.” é a correta, considerando explicações no quadro a seguir.

Distratores:

1) Todas as afirmativas estão corretas.

2) Apenas as afirmativas I e II estão incorretas.

3) Apenas a afirmativa V está incorreta.

Justificativa: As opções acima estão incorretas, considerando explicações no quadro a seguir.

I - CORRETA	“The proposed hybrid system features a combination of PCM and internal heating for cold-climate battery thermal management under different scenarios”
II - CORRETA	“A microclimate chamber (CSZ MicroClimate) was used in the experiment to create the low ambient temperature condition.”
III - INCORRETA	“Second, incorporating this system does not require any changes within the inner battery case, so it should be compatible with most battery cooling system designs.”
IV - INCORRETA	“When inspecting the climate chamber before the experiment, we found that when the temperature set point went lower than a certain value, the chamber could not keep the temperature stable. As a result, the testing temperature was set to -5.5°C for both the cooling and heating tests.”
V- CORRETA	“To validate the effectiveness of this hybrid system in both short parking and long parking scenarios, both cooling and heating tests are conducted in this study.”

QUESTÃO 3:

Enunciado:

Considerando a fase de simulação numérica da pesquisa (Jiang *et al.*, 2024), é correto afirmar que:

Gabarito:

a temperatura inicial para os processos de redução de temperatura e aquecimento, na simulação numérica, foi a mesma temperatura do módulo da bateria (bateria, materiais de mudança de fase e caixa).

Justificativa: A resposta está correta, pois, de acordo com a fórmula presente na página 011004-5 do texto, a temperatura inicial é igual à temperatura da bateria, do PCM e da caixa: “Both cooling and heating processes started with a uniform initial temperature of the battery module: $T_{bati} = T_{PCMi} = T_{casei} = T_{ini}$ where T_{bati} , T_{PCMi} , and T_{casei} are the initial temperature of the battery, PCM, and case, respectively, and T_{ini} is the set initial temperature”

Distratores:

1) todas as características térmicas e físicas dos materiais de mudança de fase foram considerados constantes na simulação numérica.

Justificativa: A resposta está incorreta, pois, há uma exceção, a densidade não foi constante, conforme o trecho: “All thermo-physical properties of the PCM except for density were assumed to be constant, which is reasonable since the specific heat and thermal conductivity for both the liquid and solid phases of the PCM are the same”

2) a temperatura do ambiente foi constante, tanto para o teste de esfriamento quanto o de aquecimento do módulo de bateria, em 0°C.

Justificativa: A resposta está incorreta, pois a temperatura inicial não foi a mesma para ambos os testes, conforme o trecho: “The initial temperature T_{ini} was set to 23.5 °C for the cooling test simulation and 0 °C for the heating test simulation”

3) um teste de independência de malha foi realizado para verificar a ineficácia do tamanho das células

Justificativa: A resposta está incorreta, pois o teste de independência de malha foi realizado para assegurar que os resultados não fossem sensíveis à malha de tamanho de células, conforme o trecho: “A mesh independence study was conducted to ensure that the results of the simulation were not sensitive to the mesh cell size.”

QUESTÃO 4:

Enunciado:

A pesquisa de Jiang *et al.* (2024) aponta que:

Gabarito:

o sistema híbrido de controle térmico de bateria proposto melhora de forma significativa a performance de veículos elétricos em climas de frio

Justificativa: A resposta está correta, conforme o trecho da conclusão: “This hybrid system improves EV performance at low temperatures significantly”

Distratores:

1) a demanda de um benefício extra deve ser investigada para veículos que costumam ter paradas frequentes, como táxis e veículos de entrega.

Justificativa: A resposta está incorreta, pois os resultados da pesquisa já apontam para o benefício extra nos casos mencionados, não sugerindo a realização de novas pesquisas, conforme o trecho: “This system has added benefit for frequently stopping vehicles like taxis, rideshares, and delivery vehicles, as the battery is passively kept warm between trips.”

2) a quantidade de PCM que leva ao melhor desempenho dos veículos elétricos é diferente para o uso no verão e no inverno.

Justificativa: A resposta está incorreta, pois o artigo sugere que sejam feitos estudos para que se consiga chegar a uma quantidade ótima para os dois cenários, conforme o trecho: “Further study based on the statistics of real-life driving patterns is still needed to optimize the amount of PCM that leads to the best vehicle performance in both winter and summer driving scenarios”

3) os estudos de caso conduzidos sobre os diferentes tipos de bateria foram suficientes para a implementação do sistema híbrido de controle térmico de bateria.

Justificativa: A resposta está incorreta, pois não foram feitos estudos de caso na pesquisa descrita no artigo, há o apontamento para a necessidade de que sejam realizados estudos de caso, conforme o trecho: “Case studies conducted on different battery geometries and battery types are needed before implementing this hybrid system on different batteries”

QUESTÃO 5:

Enunciado:

Parte do calor armazenado nos Materiais de Mudança de fase (PCM) é armazenado como calor latente. Considerando o experimento apresentado por Jiang *et al.* (2024):

- A) compare os dois diferentes cenários apresentados, curto tempo de estacionamento e longo tempo de estacionamento, e;
- B) explique como se dá a transferência de calor entre a bateria e os Materiais de Mudança de fase (PCM) nos dois cenários.

Resposta esperada:

- A) Espera-se que o candidato identifique os trechos dos textos que exemplificam cenários em que o estacionamento é feito por um curto ou um longo período de tempo, conforme é descrito na subseção: “System Features”. Uma resposta possível seria: Os veículos elétricos podem apresentar diferente desempenho no processo de aquecimento da bateria, considerando um período curto ou longo em que o VE fica estacionado. Um curto período de tempo pode se caracterizar por algumas horas em que o condutor deixa o carro parado para fazer compras ou em outros casos em que há paradas frequentes, como no caso de taxis e veículos que fazem entrega. Um caso de longo período de tempo estacionado seria quando o VE vai iniciar uma viagem depois de já ter esfriado, por exemplo, quando fica na garagem durante toda a noite.
- B) Espera-se que o candidato explique sobre a transferência de calor entre a bateria e o PCM nos dois cenários. O candidato pode utilizar a Figura 1 ou o texto que acompanha a figura. Uma resposta possível seria: Ao usar PCM, na bateria de veículos elétricos, no cenário de um curto período de tempo estacionado, não há período de aquecimento da bateria, pois o calor latente ainda existente no PCM mantém a bateria aquecida. Como o PCM reutiliza o calor não usado durante o período de condução do veículo, não há necessidade de um input elétrico para reaquecer a bateria. No caso em que houve um resfriamento da bateria devido ao longo período em que o carro ficou parado, um cenário de período longo de estacionamento, o calor armazenado no PCM já foi dispersado, portanto, será preciso utilizar uma fonte de calor, que no caso, do sistema híbrido de controle térmico de bateria proposto no texto, será o aquecimento interno.

QUESTÃO 6:

Enunciado:

Para simular temperaturas de frio extremo, foi realizada uma simulação numérica a partir de variações do design utilizado na fase de experimento.

- A) Descreva as diferenças entre o protótipo e os designs A e B;
- B) Qual dos dois designs foi considerado mais eficaz? Por quê?

Resposta esperada:

- A) Espera-se que o candidato identifique o trecho que descreve os dois designs utilizados para a simulação. O candidato pode utilizar a Figura 6 ou o seguinte trecho da seção “Comparison of Different Battery Module Designs”: “As a result, two battery module design variants, shown in Fig. 6, were developed based on the original design to test the performance of the hybrid battery thermal management system under a lower ambient temperature and to study the effectiveness of different PCM layouts. Both designs keep the battery module structure the same, with five battery cells arranged diagonally in the center, and a PCM layer applied between the inner and outer battery case. In design A, the inner battery case has the same size as in the validation experiment, but the PCM is applied all around it. With the same PCM layer thickness as in the original design, the total volume of PCM is increased to 0.418 L, which adds 0.322 kg to the battery module. Design B features more closely packed battery cells, leading to a smaller inner battery case with 27% less surface area. Design B uses the same amount of PCM as design A, but the PCM is only applied on the four side faces of the smaller battery case, so a higher PCM thickness on each face is achieved.” Uma resposta possível seria: O design A mantém o mesmo formato de organização das células de bateria que o protótipo e o mesmo tamanho da caixa interna. No entanto, o PCM foi utilizado ao redor de todos os lados da caixa interna, incluindo a parte superior e a parte inferior, aumentando o volume do PCM em comparação com o protótipo original. O design B mantém a mesma quantidade de PCM do design A, no entanto, utiliza uma caixa interna menor, o que é possível pela disposição mais próxima uma das outras das células de bateria. Além disso, a camada de PCM está nas quatro faces laterais, não incluindo o topo ou a parte de baixo da caixa interna, assim, a camada de PCM é mais grossa no design B do que no design A.
- B) Espera-se que o candidato compare os resultados dos testes realizados com os designs A e B e apresente os destaques apresentados no texto. O candidato pode utilizar as Figuras 7a e 7b e o texto que os acompanha, como: “The cooling test result shows that both designs are able to keep the battery warm for several hours without consuming extra energy. At the same time, the recorded battery heating times of design A are around 40% longer than that of design B. In other words, both designs achieve all-scenario battery thermal management in cold climates while preserving the advantages of a PCM-based system, but design B achieves shorter battery heating time. Since the weight and size of the battery module are crucial to vehicle performance and passenger comfort, the layout in design B is demonstrated to be more effective. This also implies that reducing the surface area of the inner battery case by packing the battery cells closer to each other helps minimize the amount of PCM needed, and applying PCM on the side faces is more efficient for cylindrical battery cells.” Uma resposta possível é: O design

B foi considerado mais eficaz por ter apresentado melhor desempenho no teste de aquecimento, reduzindo o tempo para aquecimento de 16 minutos (design A) para cerca de 11 minutos (design B). O design B demonstra mais eficácia por manter o mesmo peso do design A, mas oferecer melhor desempenho no processo de aquecimento. Além disso, a configuração de células de baterias mais próximas uma da outra e o uso de PCM nas quatro faces da caixa interna se revelaram como características mais eficientes para células de bateria em formato cilíndrico.