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# Experimental and Numerical Analysis of a Hybrid Thermal Management Concept at Different Discharge Rates for a Cylindrical Li-Ion Battery Module

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**Abstract:** In this paper, an experimental and numerical study was conducted to analyze the performance of a hybrid thermal management concept for cylindrical lithium-ion battery modules at various discharge rates. The proposed concept consists of primary cooling through phase change material (PCM) and secondary cooling through vertical liquid channels between the PCM and airflow at the top of the cells. Two experimental studies were performed to obtain the temperature and heat flux profiles. In addition, the thermal performance of the battery module was obtained for 1 C, 2 C, 3 C, 5 C, and 7 C discharge rates using the numerical study. The results show that the maximum temperature was limited to ~30 °C. Additionally, the temperature uniformity in all the discharge rates was maintained below 5 °C. Finally, a meager amount of PCM was utilized during all the discharge cycles. At 1 C none of the PCM changed its phase, whereas at 2 C, 0.32%, 3 C, 0.14%, 5 C, 0.3%, and at 7 C, 0.12% of PCM changed its phase. The proposed hybrid concept can maintain the thermal environment required by the Li-ion cells for effective performance. Furthermore, this concept does not require excessive pumping fluid power and high air velocities, which reduces the energy required for the operation of the thermal management system, thereby increasing the available energy for propulsion.

**Keywords:** phase change material; hybrid cooling; liquid channels; battery thermal management; computational fluid dynamics (CFD); Li-ion cylindrical cells

# 1. Introduction

Reducing greenhouse gas emissions is one of the major challenges that the transportation industry faces. Currently, they account for 29% of the total emissions [1]. The electrification of the transportation industry is viewed as a crucial alternative to internal combustion engine vehicles, and lithium-ion (Li-ion) cells are the top contenders for creating battery packs for electric vehicles (EVs). The advantage of Li-ion cells lies in their low self-discharge rate, high energy and power density, and extended lifecycle [2–4]. However, using Li-ion cells presents its own challenges since they need a particular thermal environment for effective and safe operation [5,6]. An efficient thermal management system (TMS) is used to sustain these operating conditions, and extensive research has been conducted on TMSs [7,8].

Currently, three main primary cooling mediums are traditionally used within the TMS. These consist of air, liquid, and phase change material (PCM). The most cost-effective TMS is based on air cooling. However, the cooling capabilities are limited since air has a low thermal conductivity and heat capacity [9].

In comparison to air, fluids have improved cooling capabilities due to higher thermal conductivity and heat capacity [10]. For liquid cooling, two categories of fluids are used. The first category is electrically insulating fluids. Since these fluids do not allow the charge to pass through them, they are used in direct contact with the Li-ion cells to extract the



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heat from the surface of the cells [11–13]. However, this category of fluids usually has high viscosities, which increase the pumping power associated with fluid flow throughout the entire battery pack. In addition, to increase power requirements, battery packs that contain these fluids must be properly insulated to avoid fluid leakage, as it could result in adverse and unwanted effects on the battery pack [14]. The second category of fluids is electrically non-insulating fluids. These fluids allow the current to flow through them and cannot be placed in direct contact with the surface of the cells. A cold plate is used for these fluids and is set in direct contact with the cells. It contains liquid channels through which the fluid flows, cools the cold plate, and extracts heat from the cells. Compared to insulating fluids, these fluids have lower viscosities and, as a result, require less pumping power for the fluid flow through the battery pack. However, applying the cold plates is limited to prismatic and pouch cells because the design complexity and manufacturing difficulty are greater for cylindrical cells [15–17].

Serpentine liquid channels are utilized in battery packs with cylindrical cells to incorporate electrically non-insulating fluids and act as an alternate solution to cold plates. These channels run through the entire row of the cylindrical cells and are curved in a zig-zag manner to encapsulate the maximum amount of surface area of the cells. With these channels, a temperature non-uniformity occurs with each cell. The surface of the cell in direct contact with the channel has a lower temperature compared to the surface of the cell that is not in contact with it. Zhao et al. [18] investigated various configurations of the serpentine liquid channels. As expected, the highest temperature uniformity was achieved by increasing the direct contact surface area of the channel in the streamwise direction. This was followed by a design in which multiple serpentine channels were used, and the flow path was shortened for each channel. Rao et al. [19] attempted to develop a novel alternate solution by incorporating variable-length aluminum blocks. These blocks were placed around the surface of the cylindrical cells, and the length was changed in the streamwise direction to increase temperature uniformity. Liquid channels were placed within these aluminum blocks and effectively removed the heat from the cells and the aluminum blocks. However, the pumping power required for fluid flow through the entire battery pack can increase significantly, which reduces the energy available for the propulsion of the EV [20].

The third primary cooling medium used for the thermal management of batteries is PCM. It uses its latent heat during the phase change process of the PCM to remove the heat from the surface of the cells. This was initially proposed by Al-Hallaj and Selman [21], and a study by Javani et al. [22] concluded that, over the battery submodules, a high temperature uniformity could be achieved using PCM. Moreover, a composite PCM was developed by Jiang et al. [23] through the combination of paraffin and expanded graphite (EG). A higher thermal conductivity of the PCM was achieved through this composite mixture, and a maximum temperature range of 41–44 °C was obtained at a 5 C rate of cell discharge. Compared with forced air cooling, a maximum temperature of 72 °C was recorded with 1 m/s airflow velocity. In addition to improved cooling, a temperature uniformity of 1–2 °C was achieved through the composite PCM. Building upon this, He et al. [24] studied the amount of EG required in the composite PCM to achieve optimal thermal performance, and it was concluded that, through 7% of EG in the composite PCM, a temperature uniformity of 2.82 °C can be achieved. Moreover, Hussain et al. [25] developed and investigated a novel PCM by coating nickel foam with saturated graphene and paraffin. Compared to pure paraffin, this composite PCM could achieve 23 times more thermal conductivity. Ye et al. [26] also developed a novel composite PCM structure. This structure consists of two-phase change temperature sections. This allows the lower phase change temperature section to be used at regular ambient temperatures and the higher phase change temperature section to be used at higher ambient temperatures. When the lower phase change temperature section is activated, the maximum temperature stays within the range of 25.9–34.9 °C, and when the higher temperature phase change section is activated, the maximum temperature is maintained below 49.2 °C. Additionally, a novel flexible composite PCM was developed by Wu et al. [27] to increase the contact surface

area between the PCM and the surface of the cells. The results showed that, using flexible PCM, the maximum temperature can be lowered by 4 °C compared to rigid PCM. Even though the application of PCM in TMSs shows promising results, it is not widely used due to the low overall heat transfer coefficient of the PCM. Once the latent heat of the PCM is completely utilized and the PCM has completely melted, then the PCM acts as a thermal insulator, and the heat extraction process is terminated. Therefore, a secondary cooling system, either air cooling or liquid cooling, is required to extract the heat away from the PCM itself.

As discussed, there are some shortcomings in using an individual cooling medium for the TMS. Therefore, researchers have studied hybrid TMSs by combining two or more individual cooling mediums. Saw et al. [4] investigated a hybrid TMS by introducing mist into the airflow, and the results showed that to maintain the maximum temperature of the cell below 40 °C, 3% of mist was required for an airflow of 5 g/s. Wei and Agelin-Chaab [9] introduced a novel concept of a hybrid TMS by using the natural evaporation of water. The naturally evaporated vapors were introduced into the airflow by flowing the air through water channel strips. Additionally, to eliminate the pumping power of the water, the water in the channel strips was absorbed through capillary action. A 56% improvement in temperature uniformity and a 20% improvement in the cooling of the cells was achieved. Wang et al. [28] developed a hybrid TMS strategy by placing the cells on a cold plate, and air circulated through the surface of the cold plate to extract heat from it. From the results, a 3.45 °C additional cooling was achieved when compared to a non-hybrid TMS, and the temperature uniformity increased by 2.42 folds. In the authors' previous study [29], a hybrid TMS was designed by placing and joining liquid jackets to the round surface of each cylindrical cell. Since the fluid in the liquid jacket was isolated to each cell, electrically non-insulating fluids could be applied in direct contact with the cells. Additionally, jet inlets and vortex generators developed in earlier studies were added to the battery pack to improve mixing and turbulence within the airflow. The results concluded that temperature uniformity was maintained within 1.26 °C.

This paper introduces a novel hybrid thermal management concept for Li-ion battery modules. It consists of primary cooling through PCM and secondary cooling through vertical liquid channels between the PCM and airflow at the top of the cells. The fluid within the liquid channel is stationary instead of continuous flowing fluid in liquid-based TMSs in the open literature. Moreover, the natural evaporation of fluid is utilized to remove heat from the PCM material, thereby increasing the cooling capacity of the PCM. The proposed concept can be scaled up or down based on the energy requirements of the vehicle. The primary objective is to keep the temperature of the cells in the optimum range of 25–40 °C, achieve a high temperature uniformity, and utilize the least amount of PCM. In addition, a secondary objective is to significantly reduce the pumping power usually required for pumping fluids and to reduce the airflow velocity, which reduces the fan power by considering a laminar flow. Finally, environmentally friendly fluid such as water is used to improve sustainability and eliminate the emission of harmful gases and vapors into the environment.

### 2. Description of the Proposed Concept

The proposed hybrid TMS concept in this study is achieved by combining a single primary coolant and dual secondary coolants. The primary coolant is the PCM, and the secondary coolants are liquid and air. At the core, there are cylindrical Li-ion cells that are in direct contact with the PCM. In between the PCM, there are liquid channels that run vertically. The fluid in these liquid channels is stationary. An air duct is added to the top of the cells to allow for airflow, and the opening of the liquid channel is in the air duct.

The proposed concept will work in three distinct stages. Initially, the heat from the surface of the cell will be extracted through the PCM as it is in direct contact. At low temperatures, the heat will be removed through solid PCM. Once the phase change temperature of the PCM is reached, the latent heat of the PCM will be utilized to extract heat. In the next stage, the heat from the PCM will be removed using stationary fluid within the liquid channels. Through added heat from the PCM into the fluid, the natural evaporation process will accelerate, and the evaporated vapors will move into the air duct in the third stage. These evaporated vapors will then be removed from the system and into the environment through forced airflow within the air duct. Once the fluid in the liquid channel is consumed through natural evaporation and the fluid level falls, then a small pump will be required to top up the fluid. The proposed concept is shown in Figure 1 through computer-aided design (CAD) models.



**Figure 1.** (a) Isometric view, (b) top cross-section view, (c) A-A section view, and (d) B-B section view of the proposed concept.

## 3. Experimental Methodology

For this study, two different types of experiments were performed. The first experiment was performed to validate the numerical model. A battery module was developed, as shown in Figure 1, and temperature measurements of the cells were obtained and compared with the results of the numerical model. The second experiment was performed to obtain the transient heat flux values at the surface of the cylindrical Li-ion cell. These heat flux values were then used in the validated numerical model as a boundary condition to obtain the thermal performance of the battery module under different discharge C rates. The details of the setup and procedure of each experiment are provided in the following sub-sections.

#### 3.1. Experiment 1—Temperature Measurements of Battery Module

This experiment was executed to measure and obtain the temperature profile of the cells within the battery module. The setup and schematics of the experiment are shown in Figure 2. A battery module was developed using the CAD design shown in Figure 1.

The housing of the module was manufactured using wood. Nine Samsung INR18650-25R cylindrical Li-ion cells were added to the battery module and were connected in a series arrangement. The properties of the cell are provided in Table 1.



Figure 2. Experiment 1—(a) top view picture and (b) schematic of the experimental setup.

Since the cells used in battery packs do not have electrical insulation, to obtain accurate results in the temperature measurements, the electrical insulation was removed from the surface of the cell. The liquid channels were made using aluminum tubes and were filled with water after placing them in the battery module. Single T-type thermocouples were attached to each cell to measure the temperature of the cells. Paraffin wax was used as the PCM. The PCM was melted and then poured into the battery module in liquid form. Once poured, it was then allowed to solidify to capture the form of the cavity in the battery module. To force the airflow through the duct, an axial fan (GDSTIME AXIAL Fan 12038) was used, and a Proster Anemometer was used to measure the airflow velocity. A Turnigy Reaktor Quadkore charger was used to charge the lithium-ion batteries. The charger is

capable of simultaneously charging four cell groups up to 300 W and 20 A. To power the charger, a direct current (DC) power supply was used. All nine cells were discharged in series using a multi-functional load discharger (TDI RBL488). It has a maximum draining capacity of 800 W and 120 A. The measurements from the thermocouples were captured using a National Instrument (NI) data acquisition device (DAQ) NI-9211 combined with NI cDAQ-9174 chassis. Finally, LabView 2023 software was used to capture the reading from the NI-DAQ module.

Parameters	Specifications	
Nominal discharge capacity (mAh)	2500	
Nominal voltage (V)	3.6	
Standard charge (A)	1.25 A, (0.125 A cut-off)	
Maximum continuous discharge (A)	20	
Discharge cut-off voltage (V)	2.5	
Cell weight (g)	45	
Cell height (mm)	65	
Cell diameter (mm)	18	
Cathode material	LiNiMnCoO <sub>2</sub>	
Anode material	Graphite	

Table 1. Samsung INR18650-25R properties and specifications [30].

The experiment was initiated by charging all the cells within the battery module using the battery charger. The charging was performed under constant current (CC) and constant voltage (CV). In this, the cell was charged at a CC of 1 A until the cut-off voltage of 4.3 V for each cell was achieved (37.8 V for all the cells in series). At this point, the cells were charged at a CV of 37.8 V until the charging current was 0 A. The battery module was then kept at a room temperature of 25 °C. The fan was then turned on, and the velocity was measured at the inlet of the battery module using a Proster anemometer. Once the readings from the thermocouples were measured to be 25 °C, the discharge process was started. The cell was discharged at a CC discharging rate, and the temperatures from the thermocouples were recorded using the LabView software. The discharge process was terminated when the voltage of the battery module reached 22.5 V. The experiment was conducted at a discharge rate of 1 C. An uncertainty analysis was performed using the method suggested by Moffat [31]. Based on the uncertainty analysis, the average percentage uncertainty in the temperature measurement was estimated to be  $\pm 3.59\%$ . The properties of the different materials used for this experiment are shown in Table 2.

Table 2. Physica	l properties of materia	ls used for Experiment	1 [32–34]
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<b>Material Properties</b>	Aluminum	Wood	Air	Water	РСМ
Density (kg/m <sup>3</sup> )	2719	700	1.225	998.2	880
Specific Heat (J/kg·K)	871	2310	1006	4182	2150
Thermal Conductivity (W/m·K)	202.4	0.173	0.0242	0.6	0.21
Viscosity (kg/m·s)	-	-	0.000018	0.001003	0.00312
Pure Solvent Melting Heat (J/kg)	-	-	-	334,000	245,000
Solidus Temperature (K)	-	-	58	273.15	315.15
Liquidus Temperature (K)	-	-	61	273.15	317.15

#### 3.2. Experiment 2—Heat Flux Measurement of Single Li-Ion Cell

This experiment was performed to measure the transient heat flux at the surface of the Samsung INR18650-25R cylindrical Li-ion cell. These heat flux measurements are required to develop the numerical model. The setup and schematics of this experiment are shown in Figure 3. In this experiment, a single Li-ion cell was used to measure the heat flux. The electrical insulation of the cell was removed in this experiment as well to ensure that accurate measurements were obtained. The details of the charger, power supply, discharger,

and NI-DAQ module are provided in Section 3.1. The fan, anemometer, and battery module were not used for this experiment. Instead, an Omega HFS-5 heat flux sensor was used to measure the heat flux. This sensor was connected to the NI-DAQ module to capture the measurements using the LabView software. Additionally, the HFS-5 sensor also consists of a T-type thermocouple to measure the temperature.



Figure 3. Experiment 2—(a) top view picture and (b) schematic of the experimental setup.

The charging of the cell was performed again using the CC-CV process, described in Section 3.1. At the end of the charging process, the cell was kept at a room temperature of 25 °C. The discharge process was started once the temperature of the cell was maintained at 25 °C. The cell was discharged at a CC discharge rate until the voltage of the cell dropped to a cut-off voltage of 2.5 V. During the discharge, the measurements were recorded using the LabView software. This cycle was repeated for 1 C, 2 C, 3 C, 5 C, and 7 C discharge rates. An uncertainty analysis was performed using the method suggested by Moffat [31]. From the uncertainty analysis, the average percentage uncertainty in the heat flux measurement was estimated to be  $\pm 3.59\%$ .

## 4. Numerical Modeling Methodology

## 4.1. Governing Equations

The numerical model was developed using ANSYS Fluent by replicating the battery module and experimental conditions of Experiment 1, as described in Section 3.1. Three different models were coupled to develop the numerical model. These models include the

flow model, energy, and solidification/melting model. A turbulence model was not used in the flow model as the airflow was a laminar flow with a low velocity. The governing equations for the flow and energy models are provided below [32].

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left( \rho \overrightarrow{v} \right) = S_m \tag{1}$$

Momentum Conservation Equation

$$\frac{\partial}{\partial t} \left( \rho \overrightarrow{v} \right) + \nabla \cdot \left( \rho \overrightarrow{v} \overrightarrow{v} \right) = -\nabla P + \nabla \cdot \overrightarrow{\overline{\tau}} + \rho \overrightarrow{g} + \overrightarrow{F}$$
(2)

where

$$\overline{\overline{\tau}} = \mu \left[ \left( \nabla \overrightarrow{v} + \nabla \overrightarrow{v}^T \right) - \frac{2}{3} \nabla \cdot \overrightarrow{v} U \right]$$
(3)

**Energy Equation** 

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\vec{v}(\rho E + P)\right) = \nabla \cdot \left(k_T \nabla T - \sum_j h_j \vec{J}_j + \left(\vec{\overline{\tau}}_{eff} \cdot \vec{v}\right)\right) + S_h \tag{4}$$

The solidification/melting model was only applied to the PCM region. The enthalpyporosity technique is used to model the phase change process. In this technique, the interfaces where the solid melts are not explicitly tracked. Instead, a liquid fraction ( $\beta$ ) quantity is introduced, which provides the fraction of each cell volume in liquid form. This liquid fraction is based on the enthalpy balance [32]. The enthalpy of the PCM is based on the latent heat and sensible enthalpy, as shown below [32].

$$H = h + \Delta H \tag{5}$$

where

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT \tag{6}$$

The liquid fraction is 0 if the temperature (*T*) is less than the solidification temperature ( $T_{solidus}$ ) of the PCM. Additionally, the liquid fraction is 1 if the temperature (*T*) exceeds the melting temperature ( $T_{liquidus}$ ) of the PCM. The equation for the liquid fraction during the phase change is provided below [32].

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \tag{7}$$

The latent heat equation in terms of the liquid fraction and latent heat of material (*L*) is shown below [32].

Δ.

$$H = \beta L \tag{8}$$

Therefore, the energy equation is as follows [32]:

$$\frac{\partial}{\partial T}(\rho H) + \nabla \cdot \left(\rho \vec{v} H\right) = +\nabla \cdot (k\nabla T) + S \tag{9}$$

### 4.2. Mesh Independence and Time Independence Studies

The developed mesh is shown in Figure 4. A combination of tetrahedral and hexahedral mesh was used. Inflation layers were added to the air duct walls so that the boundary layer within the airflow could be captured.



Figure 4. (a) Isometric view and (b) cross-section view at the center of the battery module mesh.

A mesh independence study was conducted to ensure that the results of the numerical model were independent of the size of the developed mesh. For this study, four meshes were developed. Each subsequent mesh had an increment of approximately 50% elements. The velocity profile at the middle of the air duct was obtained and compared, as shown in Figure 5a. An average velocity was also calculated and plotted against the number of elements, as shown in Figure 5b. The results show no significant difference beyond the mesh size of 614,024 elements; therefore, the medium mesh was selected.

Furthermore, a time independence study was performed to ensure that the results of the numerical model were independent of the size of the time step. This is required to reduce the computation power while maintaining the accuracy of the results. The result of this study is shown in Figure 5c. Based on the results, a time step size of 0.5 s was selected.

## 4.3. Boundary Conditions

Since this study incorporates PCM as the primary coolant and phase change is a time-dependent process, a transient simulation was conducted. Two different setups of the numerical simulation were developed. Setup 1 was developed for validation purposes only. For this, at the surface of the cell, a transient heat flux of a 1 C discharge rate was used as the boundary condition. The ambient condition was set to 25 °C at atmospheric pressure. The material properties from Table 2 were applied to respective materials. The velocity of the airflow at the inlet boundary was obtained using Experiment 1 as follows:

$$\vec{v_x}|_{x=0} = 1.6 \text{ m/s}$$
 (10)

$$\vec{v_y}|_{x=0} = 0 \text{ m/s}$$
 (11)

$$\vec{v}_z|_{x=0} = 0 \text{ m/s}$$
 (12)



**Figure 5.** (a) Velocity profiles at the center of the air duct for the different mesh sizes; (b) comparison of the average velocity for the various mesh sizes; (c) temporal velocities at the center of the air duct for the different time step sizes.

Setup 2 was then developed by modifying Setup 1. In this, the transient heat flux at the cell's surface was changed based on the discharge rates obtained through Experiment 1. Additionally, all-aluminum housing was used rather than wood, and the PCM material was changed to paraffin with a lower phase change temperature to increase cooling and temperature uniformity. The properties of the materials used in Setup 2 are shown in Table 3.

Material Properties	РСМ	
Density (kg/m <sup>3</sup> )	880	
Specific Heat (J/kg·K)	2150	
Thermal Conductivity (W/m·K)	0.21	
Viscosity (kg/m·s)	0.00312	
Pure Solvent Melting Heat (J/kg)	245,000	
Solidus Temperature (K)	303.15	
Liquidus Temperature (K)	305.15	

Table 3. Physical properties of PCM used for Setup 2 [34].

# 5. Results and Discussion

5.1. Heat Flux Profile at Different Discharge Rates

The heat flux profile of the 18650 Li-ion cell was obtained through Experiment 2, as described in Section 3.2. The cell was discharged at 1 C (2.5 A), 2 C (5 A), 3 C (7.5 A), 5 C (12.5 A), and 7 C (17.5 A) discharge rates. The results of the experiment are provided in Figure 6. In all the discharge rates, the initial increase in the heat flux is high, and then the rate of heat flux reduces. Since there is more discharge time for 1 C, 2 C, and 3 C, the rate of heat flux increases again. However, the discharge time for 5 C and 7 C is not enough for the rate of heat flux to increase again. The maximum heat flux obtained at the end of the discharge cycle at 1 C is  $170 \text{ W/m}^2$ ; at 2 C, it is  $323 \text{ W/m}^2$ ; at 3 C, it is  $382 \text{ W/m}^2$ ; at 5 C, it is  $540 \text{ W/m}^2$ ; and at 7 C, it is  $584 \text{ W/m}^2$ . These heat flux profiles were used as the transient surface boundary condition for the numerical modeling.



Figure 6. Transient heat flux at different discharge rates.

## 5.2. Numerical Model Validation

Experiment 1 was performed as described in Section 3.1 to obtain the temperature of the cells at a 1 C discharge rate. Setup 1 of the numerical model, was developed by replicating the battery module and experimental conditions of Experiment 1. The results are compared for both the experimental and numerical studies and are provided in Figure 7. The numerical results follow the experimental results closely and stay within  $\pm 2\%$ , which is below the experimental error of  $\pm 3.59\%$ . Therefore, the results of the numerical model agree with the experimental results, and the model is considered to be thoroughly validated.



Figure 7. Numerical model validation results.

## 5.3. Thermal Analysis at Different Discharge Rates

The developed and validated numerical model was used to conduct numerical simulations for Setup 2 at different discharge rates, as described in Section 4.3. The optimal operating temperature range for the Li-ion cells is from 20 to 40 °C, and a tolerable range for the operation ranges from 40 to 50 °C. Additionally, the temperature difference between the maximum and the minimum temperature (also referred to as temperature uniformity) should be maintained within 5 °C, which is essential for the proper regulation of the electrical balance within the battery pack and to prolong the life of the cells. The maximum and minimum temperatures and temperature uniformity for all the discharge rates are shown in Figure 8.

It can be seen from Figure 8a that, at a 1 C discharge rate, the maximum temperature increase throughout the discharge cycle is up to 29.4 °C by the end of discharge. The phase change of the PCM starts at 30 °C (Table 3), and, in this case, no phase change occurs since the temperature does not reach the phase change temperature of the PCM. At the 2 C discharge rate, the maximum temperature increases up to 30 °C at 1390 s. At this point, the phase change of the PCM starts, and the maximum temperature increases to  $30.3 \,^{\circ}$ C by the end of the discharge rate. Any heat generated beyond 1390 s is extracted through the latent heat of the PCM, which maintains the maximum temperature at ~30 °C. Similarly, the maximum temperature reaches 30  $^\circ$ C for 3 C at 985 s, 5 C at 520 s, and 7 C at 405 s. There is no further increase as the maximum temperature is limited by the phase change temperature of the PCM. At higher discharge rates, the maximum temperature reaches ~30 °C quicker due to increased heat generation from the cell; however, the time it stays at this temperature reduces with increasing discharge rates. At 2 C, it remains at ~30 °C for 410 s, 3 C for 215 s, 5 C for 200 s, and 7 C for 109 s. In terms of percentage, at 2 C, the maximum temperature stays at ~30 °C for 22.8%, at 3 C, for 17.9%, at 5 C, for 27.8%, and at 7 C, for 21.2% of the total discharge time. The longer it takes for the maximum temperature to reach the phase change temperature and the less time it stays at this temperature until the completion of discharge, the more the TMS benefits, as this will result in the lowest utilization of the PCM.



**Figure 8.** (a) Maximum temperature, (b) minimum temperature, and (c) temperature uniformity for all the discharge rates.

It can be seen from Figure 8b that, in all the discharge rates, the minimum temperature of the battery module does not reach the phase change temperature. It increases throughout the discharge and, at the end of discharge at 1 C, it reaches 27.5 °C; at 2 C, it reaches 28.6 °C; at 3 C, it reaches 28.1 °C; at 5 C, it reaches 28.2 °C, and, at 7 C, it reaches 27.7 °C. The maximum temperature increases at a higher rate compared to the increase in the minimum temperature. This difference in temperature increase rates results in a temperature non-uniformity in the battery module.

It can be seen from Figure 8c that the temperature uniformity generally reduces with an increasing discharge rate, as expected. At a 1C discharge rate, the temperature difference keeps increasing throughout the discharge cycle, and it is 1.8 °C by the end of the discharge cycle. For all the other discharge rates, the temperature uniformity reduces until the phase change temperature of the PCM is reached. Then, it increases until the end of the discharge cycle. Once the phase change temperature is reached, the maximum temperature does not increase, whereas the minimum temperature keeps increasing. This reduces the temperature difference, which then increases the temperature uniformity.

The temperature contours of all the cells at the end of the discharge cycle are shown in Figure 9. The high temperature locations are at the center of the cells, specifically the surfaces facing the neighboring cells, whereas the surfaces facing the housing of the battery module have lower temperatures. Moreover, the surfaces of the cells that are in direct contact with the top and bottom plate of the battery module have relatively lower temperatures due to heat conduction from the cell to the module housing. Compared to the surface in contact with the bottom plate, the surface of the cell in contact with the top plate exhibits the minimum temperature due to the air-cooling effect that occurs at the top plate. Therefore, the top plate cools due to air cooling, and this allows for additional conduction from the cell surface to the top plate.



**Figure 9.** Temperature contours at the end of the discharge cycle for (**a**) 1 C, (**b**) 2 C, (**c**) 3 C, (**d**) 5 C, and (**e**) 7 C discharge rates.

Moreover, the compound heating effect between the cells can be visualized in Figure 10. The temperature contours at the center of the battery module for all the different discharge rates are shown in Figure 10. Since the contours are extracted at the end of the discharge cycle, they are similar. The highest temperature of the PCM is exhibited at the contact

surface with the cells. The PCM that is in between the surfaces of the two neighboring cells has higher temperatures compared to the rest of the PCM. The effect of the liquid channel can also be seen in Figure 10. The fluid in the liquid channel acts as a heat sink for the PCM, which reduces the temperature of the PCM around the liquid channels. Additionally, the battery module also acts as a heat sink for the PCM, and the PCM near the housing of the battery module has the lowest temperatures. The housing is being cooled by the ambient temperature and the airflow within the air duct, which results in the lowest temperatures of the PCM.



**Figure 10.** Temperature contours at the center of the battery module at the end of the discharge cycle for (a) 1 C, (b) 2 C, (c) 3 C, (d) 5 C, and (e) 7 C discharge rates.

### 5.4. PCM Solidification and Melting Analysis

In the battery module, the PCM is stationary and constricted in the module housing. Once the latent heat of the PCM is completely used and all the PCM has melted, it will start to act as a thermal insulator, and further heat extraction from the cell will not occur, which can lead to safety issues for the battery module. Therefore, it is crucial to extract heat away from the PCM. As discussed previously, the secondary coolants, which are the water in liquid channels and the airflow within the air duct, have assisted in removing heat from the PCM, resulting in an increase in its heat extraction capacity. However, it is necessary to study the amount of PCM that has melted in the discharge process. This is obtained from the liquid fraction term in the solidification/melting model described in Section 4.1. At 1 C, none of the PCM was utilized as the maximum temperature was below the phase change temperature of the PCM. At 2 C, the PCM utilization was 0.32%; at 3 C, it was 0.14%; at 5 C, it was 0.3%; and at 7 C, it was 0.12%.

The initial intuition is that the PCM utilization should be monotonic, and as the discharge rate increases, the PCM utilization should increase as well. However, this is not always the case, as shown through this study. The PCM utilization depends on the discharge rate, the time interval percentage of maximum temperature at the phase change temperature, and the amount of heat flux increase during the interval, as shown in Table 4. It can be seen that the highest PCM utilization is at 1 C, which has the highest increase in the heat flux of 89.76 W/m<sup>2</sup>, and the lowest utilization is at 7 C, which has the lowest heat flux increase of 68.22 W/m<sup>2</sup> during the interval.

Discharge Rate	Time Interval of Maximum Temperature at ~30 $^\circ C$ (s)	Heat Flux Increase During Interval (W/m <sup>2</sup> )	PCM Utilization (%)
1 C	0 (0.0%)	-	0.00
2 C	410 (22.8%)	89.76	0.32
3 C	215 (17.9%)	76.97	0.14
5 C	200 (27.8%)	85.58	0.30
7 C	109 (21.2%)	68.22	0.12

Table 4. PCM utilization summary.

## 5.5. Airflow Analysis for the Proposed Concept

A final analysis was conducted for the airflow. The airflow profiles are similar for all the discharge rates; therefore, the worst-case scenario of 7 C was considered. Figure 11 provides the velocity and temperature of the airflow within the air duct. This is a laminar flow, and it can be seen that the flow develops as it passes through the air duct. The flow near the wall is stationary, and the boundary layer develops at the top surface and the bottom surface of the air duct. Additionally, it can be seen from Figure 11b that the airflow extracts heat from the aluminum enclosure and fluid in liquid channels, as discussed previously. However, a large portion of airflow is in between with the lowest temperatures. This portion of the airflow is completely unused as it does not extract any form of heat. Therefore, a system is required that is capable of introducing turbulence within the airflow, which can improve mixing and allow the air to extract more heat from the system and remove the losses of unused air.



Figure 11. Airflow (a) velocity and (b) temperature streamlines at the end of the 7 C discharge rate.

# 6. Conclusions

In this paper, experimental and numerical studies were conducted to analyze the performance of a hybrid thermal management concept for Li-ion battery modules at various discharge rates. The proposed hybrid concept consists of cylindrical 18650 Li-ion cells. The cells are directly in contact with the PCM, which is the primary coolant. Liquid channels containing water run vertically through the PCM. The fluid in these channels is stationary. Finally, there is an air duct placed at the top of the battery module, and the liquid channels open into the air duct. The proposed concept works in three distinct stages. Initially, the heat from the surface of the cells is extracted through the PCM as they are in direct contact. In the second stage, the heat from the PCM is removed by the stationary fluid within the liquid channels. Through added heat from the PCM into the fluid, the natural evaporation process accelerates, and the evaporated fluid moves into the air duct in the third stage. The vapor is then removed from the system into the environment through forced airflow within the air duct. Two experiments were conducted for this study. In the first experiment, the proposed battery module was manufactured, and temperature profiles were obtained to validate the numerical model. In the second experiment, the heat flux of the Li-ion cell was obtained, which was used as boundary conditions for the numerical simulations. Using the numerical method, the thermal performance of the battery module was obtained for 1 C, 2 C, 3 C, 5 C, and 7 C discharge rates. Based on the numerical results, the maximum temperatures were limited to ~30 °C, and at that point, the phase change of the PCM and any additional heat from the cell is extracted using the latent heat of the PCM. Additionally, the temperature uniformity in all the discharge rates was maintained below 5 °C. Finally, a low amount of PCM was utilized during all the discharge cycles. This shows that, due to the secondary cooling, the amount of PCM that changes phase is low, and it can extract additional heat energy from the cells. Therefore, it can be concluded that the proposed concept can maintain the thermal environment required by the Li-ion cells for effective performance. Furthermore, this concept does not require excessive pumping fluid power and high air velocities, which reduces the energy required for the operation of the TMS, thereby increasing the available energy for propulsion.

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