Energy Proceedings
Vol 50, 2025
ISSN 2004-2965

Comparative analysis of passive cooling strategies for enhanced li-ion cell thermal management#

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ABSTRACT

This study addresses the critical challenges of thermal management in Li-ion batteries for electric vehicles (EVs) to ensure optimal performance. The study focuses on assessing two passive cooling methods: Phase Change Material (PCM) and passive immersion. The study compares their thermal performance against natural air cooling. The investigation involves mathematical modelling, numerical formulation, and validation of the electrothermal and PCM models, showcasing their efficacy in simulating Li-ion cell thermal dynamics. The results indicate that the PCM-based thermal management system performs better than others, achieving a remarkable temperature reduction of 11.02 °C and maintaining safe operating temperatures. Moreover, the PCM-based system demonstrates an impressive energy density of 136.88 Wh/kg, outperforming other passive immersion methods. This study contributes valuable insights for enhancing the thermal performance of Li-ion cells. It also contributes to understanding passive Li-ion cell thermal management strategies, emphasizing the pivotal role of PCM-based cooling solutions for improved safety, efficiency, and lifespan in various applications.

Keywords: Li-ion battery, Passive immersion cooling, Battery thermal management system, Phase change material

NONMENCLATURE

Abbreviations	
EV	Electric vehicles
Li-ion	Lithium-ion
PCM	Phase change material
Symbols	
g	Acceleration due to gravity, (m/s^2)
d_{cell}	Diameter of cell, (mm)
ρ	Density
I_{cell}	Discharge Current, (Ampere)
R_{int}	Discharge Internal Resistance, (Ω)
$q_{reversible}$	Entropic heating, (W)
Q_h	Heat generation, (W/m^3)
h_{cell}	Height of cell, (mm)
θ	Melt Fraction
k	Thermal conductivity, (W/m °C)
t	Time, (s)
u	Velocity vector, (m/s)
V_{batt}	Volume of cell, (m^3)
C_{mush}	Mushy zone constant

1. INTRODUCTION

The escalating global energy demand and its associated increase in fuel consumption have heightened concerns about climate change and emissions. Projections indicate a 50 % surge in world energy consumption over the next three decades, compelling a crucial shift towards sustainable energy systems, prominently featuring renewable energy and electrification. Notably, the automotive and transportation sector, responsible for approximately 30 % of the global energy consumption [1], heavily relies on fossil fuels, contributing to about 90 % of its energy needs [2–4]. To address these challenges, the electrification of road transportation emerges as a promising solution, predominantly led by the rapid expansion of electric vehicles (EVs). This strategic shift addresses environmental concerns and reduces the dependence of the transportation sector on fossil fuels. The accelerating growth of EVs globally, driven by legislative pressures, technological advancements in batteries, and the increased investments, marks a pivotal transition.

Thus, Lithium-ion (Li-ion) batteries have evolved from powering consumer electronics to becoming the

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

primary energy source for EVs and larger-scale applications. The Li-ion battery offers advantages such as high energy density, low self-discharge, and increased cycle life. However, Li-ion batteries face significant challenges related to operating temperature, necessitating effective thermal management. Despite advancements in Li-ion battery chemistry, thermal issues persist. Operating temperatures significantly influence Li-ion battery performance, with extreme conditions leading to capacity degradation, thermal runaway, and reduced cycle life [5–8]. These problems highlight the critical role of thermal management in maintaining optimal performance. Extreme temperatures (> 40 °C) can cause capacity and power degradation [9–11]. High temperatures can improve SEI formation by enhancing diffusivity and reaction kinetics, leading to thicker and more resilient SEI layers. While extreme low temperatures (< 15 °C) impacts capacity and efficiency [12,13]. These effects are primarily due to reduced electrochemical charge transfer rates and increased lithium plating. At low temperatures, the reduced Li^+ transport rate slows down electrochemical reactions, which alters the conditions under which the electrolyte decomposes. Addressing these temperature-related challenges is essential for the sustained long-term performance of Li-ion batteries, especially in EV applications.

Optimizing thermal management is key to supporting the adoption of EVs in a sustainable energy landscape. Battery thermal management systems (BTMS) can be classified into active, passive, and hybrid categories, depending on their energy requirements. Active systems, such as air-based and liquid cooling, rely on external power sources for operation, while passive systems, like those utilizing heat pipes or phase change materials (PCM), function without the need for additional power input. While active cooling systems have been widely studied, passive cooling methods, which dissipate heat efficiently while reducing energy consumption and costs, have garnered increasing attention. Phase change material (PCM)-based cooling and passive immersion cooling have shown promise as viable thermal management strategies.

In the context of prior research on passive cooling methods for lithium-ion batteries, this study investigates the efficacy of two distinct passive cooling methods: Phase Change Material (PCM) and passive immersion cooling. While previous studies have explored various cooling methods, including active cooling systems, there still needs to be a gap in understanding the thermal performance of PCM and passive immersion cooling with different coolant options, such as Water/Glycol, Silicone oil, and Mineral oil. Furthermore, existing literature needs comprehensive assessments of these passive cooling methods across various discharge rates. Thus, this study aims to fill this gap by evaluating the thermal characteristics of a cylindrical Li-ion cell under various discharge rates and assessing the feasibility of PCM-based and immersion cooling-based thermal management. Initially, the thermal characteristics of a cylindrical Li-ion cell are validated across discharge rates from 1 C to 3.5 C using in-house experimental data. Additionally, a comparative analysis of the thermal performance of these two passive cooling methods against traditional natural air cooling, shedding light on their potential advantages and limitations. Furthermore, the authors compared the energy density of the Li-ion cell after integrating the thermal management system, providing insights into the overall impact on battery performance. This comprehensive study validates the thermal characteristics of Li-ion cells and explores innovative passive cooling techniques, contributing to the advancement of thermal management strategies in battery systems.

2. SYSTEM DESCRIPTION AND PHYSICAL DOMAIN

The physical domain for the study is presented in Fig. 1, utilizing a 2-D model with axial symmetry to optimize computational efficiency. The setup features a spirally wound cylindrical Li-ion cell placed centrally within a cylindrical container. The cell is encased by a layer of PCM/coolant for thermal management. This PCM/coolant domain aims to stabilize the cell temperature during operation, minimizing temperature fluctuation. The cell has a diameter (d_{batt}) of 18 mm and height (h_{batt}) of 65 mm, while the PCM/coolant domain has an inner diameter (d_i) of 18 mm, an outer diameter (d_o) of 23 mm and a height identical to that of the cell.

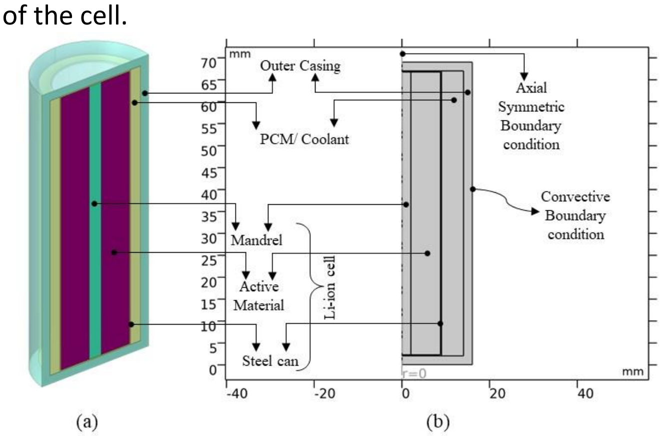

Fig. 1: Physical Domain

Table 1: Thermophysical properties of PCM and coolants

Thermal Property (Unit)	Mineral Oil [14]	Silicone Oil [14]	Water/ Glycol [14]	PCM [15–17]
Density (kg/m3)	924.1	920	1069	891.6 (ρ_s) 848.6 (ρ_l)
Specific heat capacity (kJ/(kg·K))	1.900	1.370	3.323	2.220 (c_{p_s}) 2.339 (c_{p_l})
Thermal conductivity (W/(m·K))	0.13	0.15	0.3892	0.372 (k_s) 0.153 (k_l)
Kinematic viscosity (m2/s)	5.60 x 10^{-5}	2.58 x 10^{-6}	2.58 x 10^{-6}	5.11 x 10^{-6}
Latent Heat (kJ⁄kg)	-	-	-	166.5
Solidus Temperature (K)	-	-	-	303.3
Liquidus Temperature (K)	-	-	-	306.7
Melting Temperature (K)	-	-	-	305.0

3. MATHEMATICAL MODEL AND NUMERICAL FORMULATION

This study utilized COMSOL Multiphysics®, a commercial computational fluid dynamics software for numerical simulation, to numerically simulate a thermal management system for a Li-ion cell using PCM/coolant. The simulation focused on three critical physics: the Li-ion cell heat generation model, the heat transfer between the Li-ion cell and the PCM/coolant, and phase change as the PCM transitions from solid to liquid. COMSOL facilitates a comprehensive understanding and solution of these phenomena by addressing related to partial differential equations, contributing to the study's computational solutions.

3.1 Battery Electrothermal Model

The electrothermal model estimated the temperature of a Li-ion cell using a heat balance equation. The heat generation inside the Li-ion cell is governed by the Bernardi heat generation model, the reversible and irreversible processes during charging and discharging. The study integrates experimental data by surface fitting, employing COMSOL Multiphysics and the finite element method to solve the unsteady energy equation (Eq. (1)) with discretization for thermal behaviour analysis. The Bernardi heat generation equation (Eq. (2)) is applied, where density (ρ_{batt}), thermal conductivity (k_{batt}), heat capacity $\left(C_{p_{batt}}\right)$, and heat generation per unit volume (Q_h) are essential parameters.

$$\left(\rho C_p\right)_{batt}\frac{\partial T}{\partial t} = \nabla\cdot\left(k_{batt}\nabla T\right) + Q_h \qquad (1)$$

$$Q_h = \frac{1}{V_{batt}}\left[I_{cell}^2 R_{int} - I_{cell}T_{cell}\frac{\partial E}{\partial T}\right] \qquad (2)$$

To analyze the thermal behaviour of a Li-ion cell, understanding the heat generated within the cell is essential for ensuring optimal performance and safety. This heat generation is influenced by internal resistance, entropy change, and open circuit voltage (OCV), which vary with temperature and state of charge (SoC). The Li-ion cell was discharged to measure its internal resistance and OCV at different SoCs and temperatures in the experiment. A climate chamber (Weiss LC/100/40/5) maintained a consistent ambient temperature. After stabilizing the cell, electrochemical impedance spectroscopy (EIS) was used to gather data from 1000 Hz to 0.01 Hz. The impedance data highlighted high-frequency inductive performance, medium-frequency ohmic and charge transfer resistance, and low-frequency solid diffusion resistance. These parameters were curve-fitted as functions of SoC and temperature for accurate modelling of heat generation and thermal behaviour. The polynomial expressions for discharge internal resistance $(\mathrm{R_{int}})$, OCV $(\mathrm{V_{ocv}})$, and entropy change $\left(\frac{\mathrm{dV_{ocv}}}{\mathrm{dT}}\right)$ were derived to estimate the heat generation inside the Li-ion battery.

3.2 PCM model

This study addresses the mathematical modelling and numerical formulation of phase transition processes within a mushy zone, particularly melting and solidification. The apparent heat capacity (AHC) method is used for mathematical modelling. This model modified specific heat, thermal conductivity, and density based on temperature variations, accounting for the heat required for phase transitions. The numerical analysis employs a

2-D axisymmetric model with a heat source (Q_h) inside a cylindrical cavity filled with PCM/coolant, emphasizing the laminar nature of the fluid flow.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \vec{u} = 0 \quad (3)$$

Momentum equation:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla P + \nabla \cdot (\mu(\nabla \vec{u} + (\nabla \vec{u})^T) + \vec{F}_b + \vec{F}_a \quad (4)$$

Energy equation:

$$\left(\rho c_{p_{eff}}\right)_{PCM} \frac{\partial T}{\partial t} + \nabla T \cdot \left(\rho C_p \vec{u}\right)_{PCM} = \nabla \cdot ((k(T))_{PCM} \nabla T) \quad (5)$$

The momentum equation in the mushy region is modified by the source term (Eq. (7)& (9)), with parameter A (Eq. (8)) adjusting the fluid velocity. As the melt fraction (θ) increases, convective and diffusive terms gain prominence, transitioning A towards zero. The value of the constant C_{mush} impacting domain flow characteristics is crucial, typically ranging between 10^4 & 10^7, with 10^5 chosen for this analysis to avoid misleading melt front predictions and prevent delayed melting.

$$\vec{F}_b = \rho \ \vec{g}\beta\left(T - T_{ref}\right) \quad (6)$$

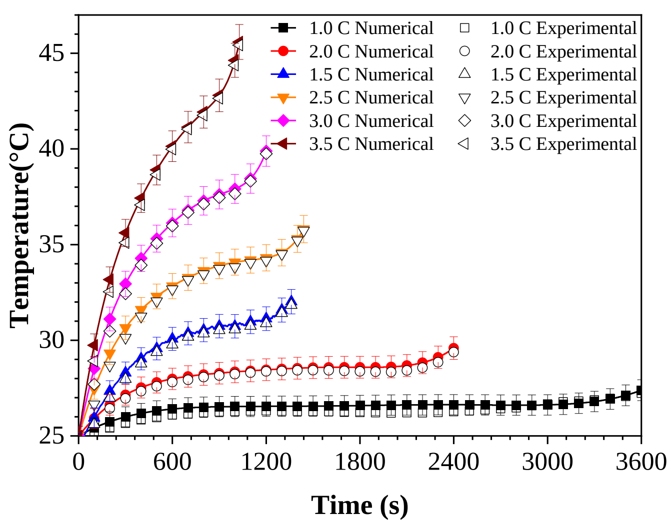

Fig. 2: Battery Model Validation

$$\vec{F}_a = -A\vec{u} \quad (7)$$

$$A = C_{mushy} \frac{(1 - \theta(T))^2}{(\theta(T))^3 + q} \quad (8)$$

$$\vec{F}_a = -C_{mushy} \frac{(1 - \theta(T))^2}{(\theta(T))^3 + q} \vec{u} \quad (9)$$

4. RESULTS

4.1 Model Validation

The electrothermal model is validated for 1C to 3.5C discharge rates for a Li-ion cell, displaying an average absolute temperature deviation of 0.257 °C to 0.353°C and an average absolute relative error of 0.982 % to 1.055 %. The model correlates well with experimental data. Similarly, the PCM model demonstrates a maximum absolute relative error of less than $\pm 5\,\%$, showing favourable agreement with experimental results. These findings underscore the model's efficacy in simulating Li-ion cell thermal dynamics and capturing PCM melting.

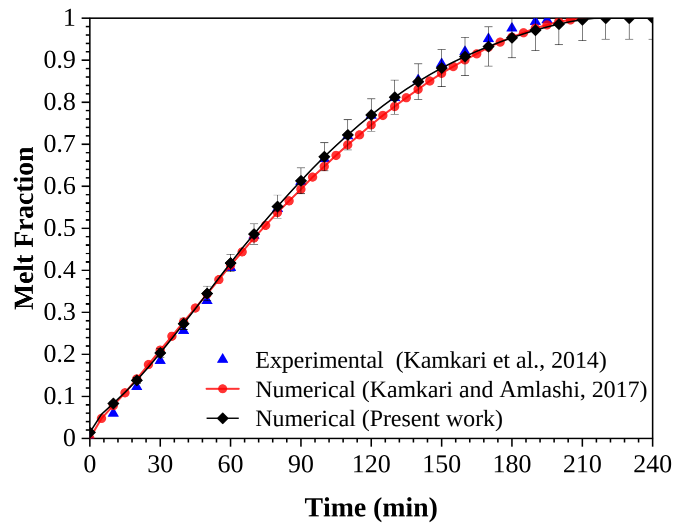

Fig. 3: PCM model validation with Kamkari et al.[18] *for PCM Melt fraction*

4.2 Thermal Performance *of Li-ion Battery*

This study compared the thermal performance of Li-ion cells employing a PCM-based cooling system with Water/Glycol, Silicone oil and Mineral oil passive immersion cooling-based thermal management alongside natural air cooling. Fig. 4 illustrated the temperature evolution of a Li-ion cell under different passive cooling methods and natural air cooling at a high discharge rate of 3.5 C. The PCM-based thermal management system outperforms others, showing a temperature of reduction of 11.02 °C. With natural air cooling, the surface temperature of the Li-ion cell reached an unsafe level of 45.59 °C, but using PCM, it drops to 34.57 °C. However, utilizing Water/Glycol, Silicone oil and Mineral oil passive immersion approaches show estimated surface temperatures of 37.45 °C, 41.75 °C and 41.20 °C, corresponding to reductions of 8.11 °C, 4.55 °C and 4.39 °C, respectively. The enhanced thermal performance of PCM compared to others is due to the active involvement of latent part, resulting in a more significant reduction in cell temperature.

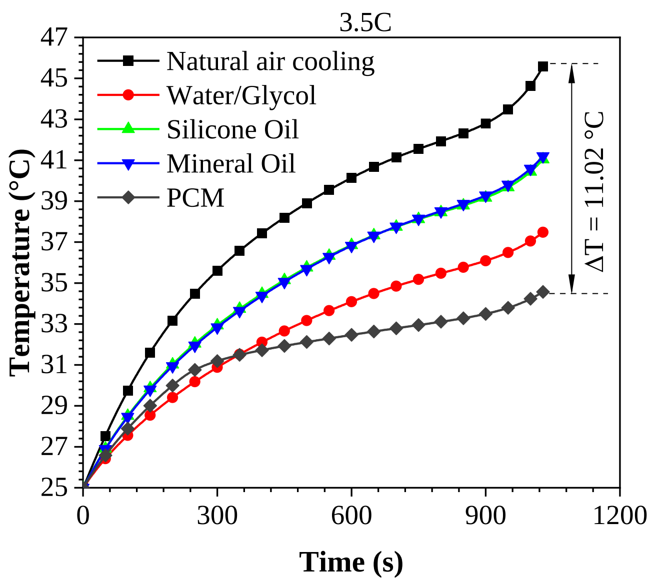

Fig. 4: Variation of Battery surface temperature evolution

In EV applications, managing thermal system's weight is critical. The PCM-based system demonstrates superior performance, achieving an energy density of 136.88 Wh/kg, with a 17.50 % reduction from original case. In comparison, Water/Glycol, Silicone oil, and Mineral oil passive immersion methods results in energy density reductions to 136.01 Wh/kg, 136.12 Wh/kg, and 132.28 Wh/kg, respectively, representing reduction of 18.02 %, 17.95 % and 20.27 %.

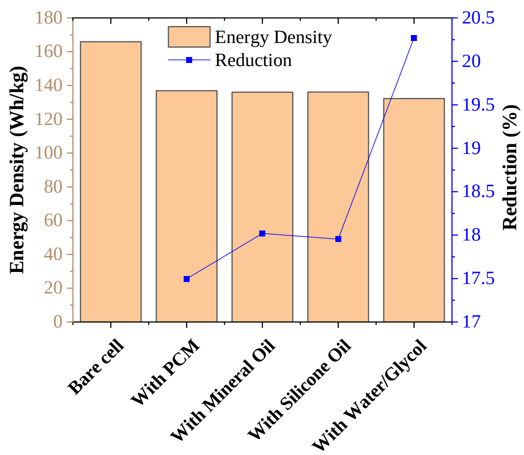

Fig. 5: Comparison of Energy Density (Wh/kg)

5. CONCLUSIONS

The study highlights that the PCM-based thermal management system significantly outperforms Water/Glycol, Silicone oil and Mineral oil passive immersion approached, demonstrating a notable temperature reduction of 11.02 K. This superior thermal performance is attributed to the active involvement of the latent part of the PCM, leading to a more substantial decrease in cell temperature. The findings revealed that PCM cooling effectively maintained the cell temperature within the safe working range of 308 K to 313 K (30 °C to 40 °C). Additionally, the PCM-based system achieves an impressive energy density of 136.88 Wh/kg.

In summary, this study offers key insights into passive thermal management strategies of Li-ion batteries. The results highlight the importance of PCM-based cooling solutions in improving cell safety, efficiency, and lifespan across diverse applications.

ACKNOWLEDGEMENT

The authors are thankful for the funding received from the Department of Science and Technology, Government of India, under the project "Different Energy Vector Integration for Storage of Energy" (Grant number TMD/CERI/MICALL19/2020/03(G)).

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