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Comparative Numerical Study of PCM and Air-Based Cooling for Li-Ion Battery Thermal Management: A CFD Approach

Nafiz Imtiaz Rafi, Md. Rabbi*

Department of Mechanical Engineering, Chittagong University of Engineering and Technology, Chattogram, Bangladesh

ABSTRACT

Effective thermal regulation is crucial to the safety, efficiency, and longevity of lithium-ion batteries, especially for power-intensive applications, thermally efficient control is essential. A numerical simulation is performed to compare the two cooling methods for a 5x2 Li-ion battery pack: forced air cooling and phase change material (PCM) cooling utilizing n-octadecane. Gravity, the energy equation, and viscous effects were all considered when conducting the transient simulation. Solidification/melting model considered the phase transformation in the case of PCM. PCM cooling demonstrated better thermal regulation than forced air cooling techniques, producing in a 0.74 K lower peak temperature in 100 seconds and a 1.25 K lower average temperature. Effective latent heat absorption, which reaches 15% liquid fraction, is the cause of PCM's superior performance. All things considered, PCM-based cooling is an exploitable way to increase battery safety and dependability, with potential for further research and experimental verification.

Keywords: Battery Cooling, Battery Pack, PCM, n-Octadecane, Liquid Fraction.

1. Introduction

Lithium-ion battery packs are widely acknowledged for their substantial advantages over alternative battery technologies in high-energy applications, like powering electric vehicles [1], [2]. The rapid advancement of portable gadgets and electric vehicles (EVs) has heightened expectations on the performance, longevity, and safety of lithium-ion batteries. Thermal management is a crucial aspect of battery operation since high temperatures or unequal temperature distribution can cause performance degradation, hasten aging, and present safety risks including thermal runway. Maintaining ideal operating temperatures, which are normally between 20 and 40 °C, hence requires efficient battery cooling systems. The battery pack produces a lot of heat while the car is running that needs to be vented. It is increasingly difficult to reduce the produced heat and keep a stable temperature due to the rising energy consumption [3], [4].

The power battery system is a crucial component that supplies all or some of the electricity. In this study, a hybrid battery cooling system that combines PCM and forced air is modeled and optimized using ANSYS Fluent. The paper looks at how airflow rate, PCM type, and design affect transient temperature profiles using conjugate heat transfer and phase-change models. The performance of electric vehicles is directly determined by the battery system's working qualities and temperature control. A good battery thermal management system (BTMS) should have the following features: precise battery temperature monitoring; efficient heat dissipation to keep the battery temperature below 50 °C, rapid heating in subfreezing temperatures, and temperature stability within 5 °C [5], [6].

In the forced air cooling [7], heat is extracted via convective heat transfer between surface of the battery and airflow, which is easy but not efficient due to low air thermal conductivity of air. In Contrast, PCM cooling [8] operates based on the ability to absorb latent heat during melting and solidification, enabling more uniform temperature control and higher thermal capacity. However, during the discharge process, electric vehicles' large power battery modules produce a lot of heat. Because the air-cooling system is unable to remove the heat in a timely manner, the battery module's internal temperature distribution becomes uneven and rises above the 5 °C temperature differential [9]. The use of Phase Change Materials (PCMs) to collect and store large amounts of thermal energy during phase transitions with little temperature change is a promising approach to passive thermal management. The rate at which latent heat can be absorbed or released is determined by the rate of phase transition. Slow phase transition over repeated charge–discharge cycles could lead to partial solidification and decreased long-term cooling effectiveness. Hence, the selection of PCM with proper melting range and high thermal conductivity additives is essential [10].

Few comparative numerical studies have examined PCM and air-cooling under the same operating conditions and for an identical battery configuration even though there has been a wide range of research on battery cooling. This paper attempts to numerically compare and assess their thermal performance using CFD to ascertain which method offers more consistent and stable temperature management. The findings highlight how PCM-air cooling has complementing benefits, paving the way for highly efficient, reliable, and compact thermal management in advanced battery systems [10], [11].

2. GOVERNING EQUATIONS

The transient heat transfer is modeled through the continuity, momentum, and energy equations [12]. While the momentum equation explains fluid motion under pressure and viscous effects, the continuity equation imposes the conservation of mass. Conduction, convection, and latent heat interactions are all captured by the energy equation. PCM melting and freezing are modeled by linking liquid fraction to local enthalpy through the enthalpy–porosity technique [13]. The governing equations are as follows:

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{v}) = 0 \tag{1}$$

Momentum Equation:

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla.(\rho \mathbf{v}\mathbf{v}) = -\nabla p + \nabla.(\mu \nabla \mathbf{v}) + \rho g \tag{2}$$

Energy Equation:

$$\frac{\partial (\rho h)}{\partial t} + \nabla.(\rho \mathbf{v} h) = \nabla.(k \nabla T) + S_h \tag{3}$$

Formulation of enthalpy-porosity method (used for melting and solidification):

$$\beta = 0 \quad \text{When } T < T_{sol}$$

$$\beta = \frac{T - T_{sol}}{T_{liq} - T_{sol}} \quad \text{When } T_{sol} \leq T \leq T_{liq} \tag{4}$$

$$\beta = 1 \quad \text{When } T > T_{liq}$$

3. Methodology

3.1 Simulation Overview

The purpose of this numerical study is to examine and analyze the effectiveness of air cooling and Phase Change Material (PCM) in regulating the increase in operating temperature of a Li-ion battery pack. Maintaining optimal battery performance, prolong their service life, and avoiding overheating conditions that can hasten degradation or, worse, thermal runaway all depend on effective thermal management. Two different cooling configurations were considered:

1. PCM Cooling using n-octadecane
2. Air-Cooling using forced convection.

3.2 Geometry and Domain Setup

1. PCM Cooling: The 5×2 battery pack was surrounded by a PCM domain encapsulating the cells.
2. Air-cooling: The 5×2 battery pack was positioned in a flow domain with two inlets and two outlets to ensure constant air flow. Fig.1 and Table 1 show the geometry specifications for PCM and Air-Cooling Configurations.

Table 1 Geometry Specifications

Parameter	PCM Cooling	Air Cooling
Battery Cell arrangement	5×2	5×2
Battey Pack Length	130 mm	230 mm
Battery Pack Width	130 mm	130 mm
Battery Pack Height	65 mm	105 mm
Cell Diameter	20 mm	20 mm
Cell Height	65 mm	65 mm
Cell Spacing	5 mm	5 mm
Inlet/Outlet Cross section	---------	50mm×20mm

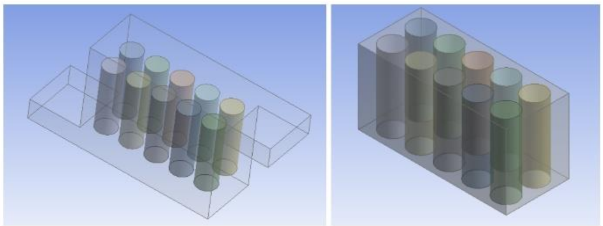

Fig. 1 Battery Pack Geometry for Forced air and PCM

3.3 Meshing

The coarse, medium, and fine meshes were used in a mesh independence investigation. The difference in average cell temperature between the medium and fine meshes was less than 1%, which shows that the meshes are independent. In order to achieve a compromise between accuracy and computational cost, default meshing parameters available in ANSYS Fluent were used in both scenarios which is shown in Fig.2. The generated mesh was fine enough to account for temperature variation within the fluid and solid phases.

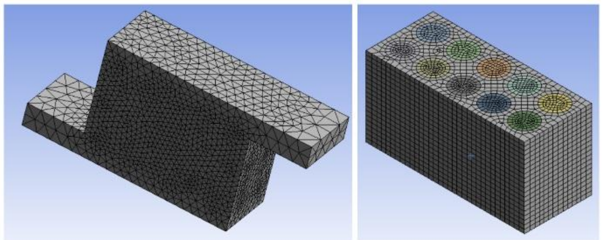

Fig. 2 Ansys default Meshing for forced air and PCM

3.4 Model

Transient simulations, with gravitational acceleration of −9.81 m/s², were performed with the energy equation activated in every case to adequately characterize the heat transfer processes. The standard k–ε turbulence model was used because it provides a good balance between accuracy and computational efficiency for the simulation of battery cooling channel turbulent flow fields. It is also extremely effective for predicting recirculation and near-wall flow behavior, which are common in forced convection systems and mixed convective flows over complex geometries. Previous Studies [10], [14] have confirmed that it is suitable for battery thermal management simulations, which makes it a suitable choice for the current project.

For the PCM case, solidification/melting model was turned on to model for the latent heat and phase transition behavior of n-octadecane while charging and discharging. Moreover, the enthalpy-porosity formulation was used to consider the movement of liquid–solid interfacial during phase change. These configurations guaranteed that the numerical results could reliably project temperature progression and thermal conductance in both PCM and air-cooled cases.

3.5 Materials

A 20650-type lithium-ion battery cell was selected as the pack's basis element for this study because it is widely used in electric vehicles, providing credible experimental data to utilize for validation. The thermophysical properties of the cell's component elements were supplied for accurate representation of real thermal behavior by Maleki et al. [15].For the PCM zone, n-octadecane ($C_{18}H_{38}$) was chosen as the phase change material due to its suitable melting temperature range (301‑303 K), high latent heat capacity, chemical stability and the liquid and solid properties of it were given from available literature for consistency with experimental results [16]. For the forced convection scenario, air was utilized as the cooling medium. The parameters of the air were taken straight from the ANSYS Fluent database and reflected the usual circumstances found in real-world air-cooling systems. Fig.3,4,5 shows the material properties of Li-ion battery, n-octadecane and air.

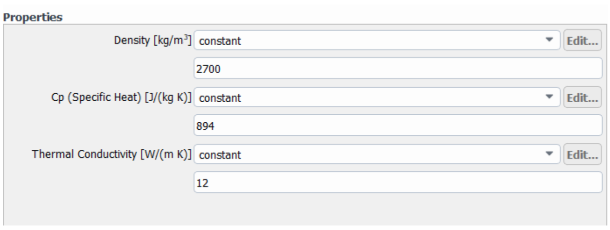

Fig. 3 Properties of Li-ion Battery

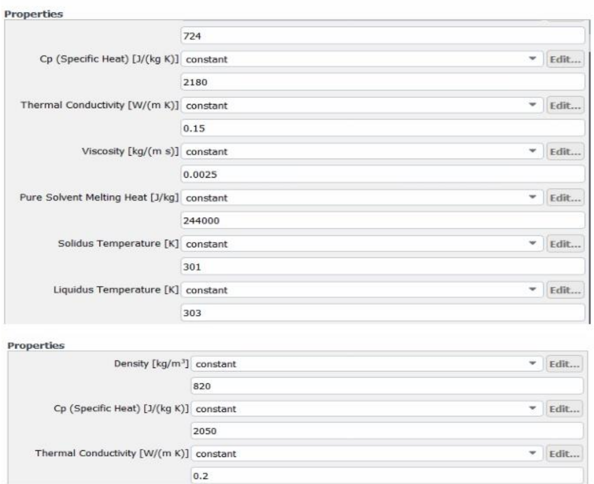

Fig. 4 Properties of n-octadecane liquid and solid

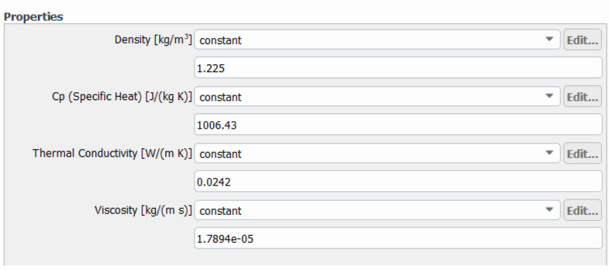

Fig. 5 Properties of Forced air

3.6 Boundary Conditions

The simulation conditions used were based on typical values observed in real electric vehicle battery pack conditions. Inlet air velocity of 1 m/s is a moderate forced convection condition most used for small battery modules. Alternatively, the 306 K initial temperature and 301 K to 303 K PCM phase change temperature range are conservative boundary conditions for charging and discharging of lithium-ion cells. The 10 $W \cdot m^{-2} \cdot K^{-1}$ heat transfer coefficient was used to model natural-to-forced convection interaction between the battery and PCM. Table 02 summarizes the boundary conditions.

Table 2 Summary of the boundary conditions

Boundary Type	Condition Applied	Value / Description
Initial Cell Wall Temperature	Constant temperature	306 K
PCM Solidus Temperature	Constant	301 K
PCM Liquidus Temperature	Constant	303 K
PCM–Battery Interface Heat Transfer Coefficient	Fixed value	10 $W \cdot m^{-2} \cdot K^{-1}$
Inlet Air Velocity (Forced Convection)	Uniform velocity inlet	1 m/s
Gravity	Applied	−9.81 m/s^2 (y-direction)

3.7 Solver Setup

In both cooling configurations, a transient solver model was used to evaluate the dynamic performances of the battery pack. The simulation was run for 100 time steps, each with 1 s to achieve the desired temporal resolution. At each time step, up to 20 iterations were performed to converge within the given residual criterion. The system thermal behavior was analyzed by extracting both the total temperature and average temperature of the battery pack over time.

In addition, temperature distribution contours were plotted to illustrate the temperature distribution in the domain for both the cases of PCM- and air-cooling. For the PCM cooling model, the solidification/melting model accounted for the phase change behavior and the liquid fraction contours are plotted to show the melting profile of n-octadecane.

3.8 Flow Chart

Flow Chart of the entire methodology is given in Fig.6.

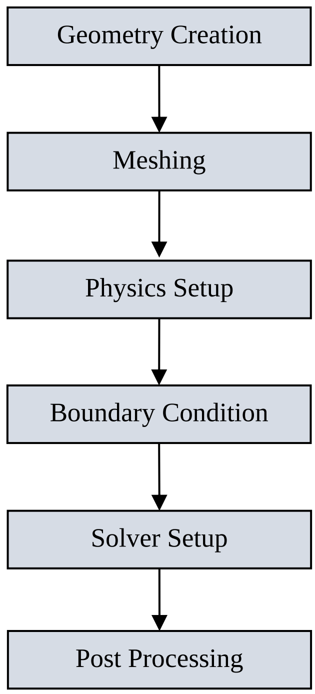

Fig. 6 Flow Chart of the Simulation

4. Results and Discussion

Cooling characteristics of the lithium-ion battery pack were investigated with an air-cooling method and a PCM-based thermal control for comparison. The results were compared in terms of overall and mean battery temperature, temperature mapping and for the PCM, the fraction of liquid during melting.

For PCM cooling condition, the simulated result of the battery temperature was lower than in the case of air cooling. Meanwhile, the overall temperature was up to 303.81 K, and the average temperature decreased to 300.4 K which is shown in Fig.7 and Fig.8.

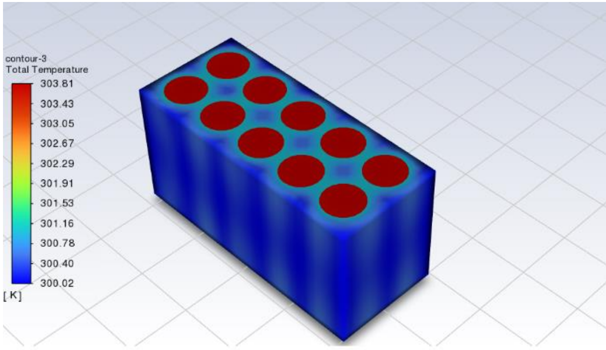

Fig. 7 Temperature distribution contour for PCM case

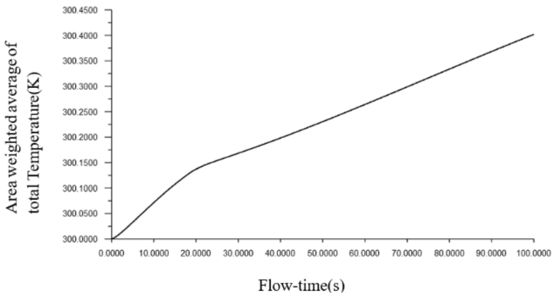

Fig. 8 Average temperature vs Flow time for PCM case

The temperature distribution lines demonstrated that the phase change material absorbed heat effectively and mitigated the hot spots at the area of the battery cells. Furthermore, the liquid fraction contour demonstrated that 15% of the PCM had melted over the course of the simulation which indicates that it served as a good heat sink that absorbed latent heat to keep cell temperature under safe operating limits. Fig.9 shows liquid fraction contour for PCM case.

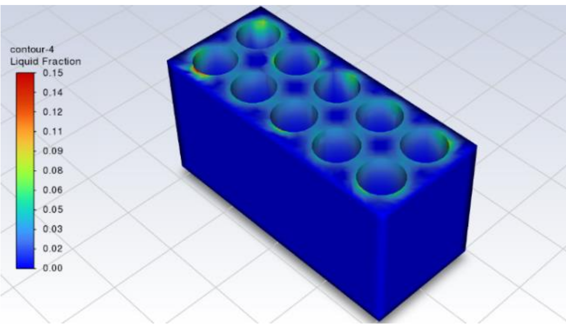

Fig. 9 Liquid fraction contour for PCM case

For the air-cooling case, the thermal response of the system was little higher. The overall temperature was up to 304.51 K, and the average temperature decreased to 301.65 K. The distribution contours in Fig.10 for temperatures indicated that although the heat over the surfaces of the battery discharged by forced convection, cooling was less uniform relative to the PCM.

The comparison of the two cases shows that PCM cooling has a steadier and more uniform thermal environment in the battery pack compared with the air cooling, due to the latent heat absorption in the process of melting.

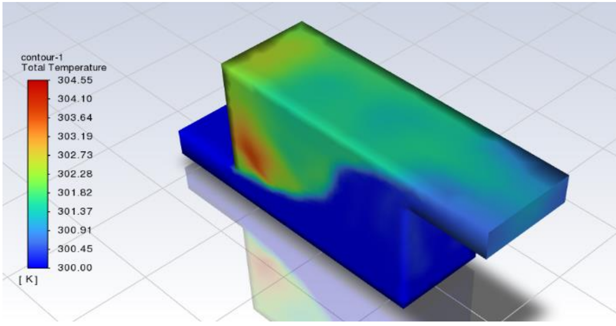

Fig. 10 Temperature distribution contour for air cooling case

In contrast, air cooling, despite being continuous and active, demonstrated less effective temperature control. These results show that the thermal management of lithium-ion cells may be significantly improved by the addition of phase change materials, such as n-octadecane. Fig.11 shows the average temperature vs Flow time for air cooling case and Table 3 summarizes the whole result section.

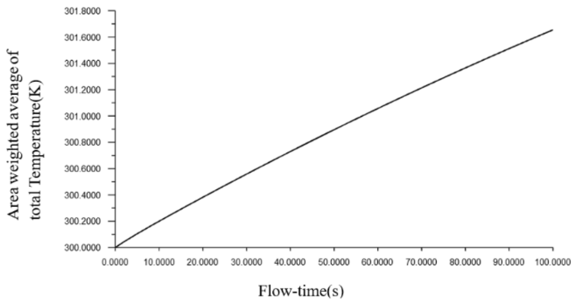

Fig.11: Average temperature vs Flow time for Air cooling case

Table 3 Summary of the simulation results

Cooling Method	Total Temperature(K)	Average Temperature (K)	PCM Liquid Fraction
PCM Cooling	303.81	300.4	0.15
Air Cooling	304.55	301.65	-----------

The highest and average temperature drops observed in this work are in line with the findings from Huynh et al. [17] and Choi et al. [11], who also found improved temperature uniformity and reduced thermal gradients for PCM-based systems. Nevertheless, the current simulations show that air cooling is still advantageous in terms of usability and continuous heat removal capacity, even though it is less effective at lowering temperature rise which is consistent with the findings of Zhao et al. [7]. In brief, the current results are compatible with previous research and offer more information about how PCM's thermal storage capabilities can improve Li-ion battery packs' long-term stability.

5. Conclusions

This work uses n-octadecane as a phase change material (PCM) to numerically explore the thermal management of a 5x2 lithium-ion battery module with forced air cooling and passive cooling. The two methods' different thermal behaviors were shown by transient simulations. Air cooling still maintained a battery temperature drop in the moderate cooling regime, the system's inhomogeneous temperature distributions even as this gave rise of localized hot spots. PCM cooling, however, was better able to regulate battery pack temperature. By utilizing n-octadecane's latent heat absorption, the PCM-based system was able to lower the mean and total temperatures to 300.4K and 303.81 K, respectively, as opposed to 301.65 K and 304.55 K in the case of air cooling. Additionally, the PCM's 15% liquid percentage shows that it may absorb heat during phase shift, hence minimizing temperature variations among battery pack cells. One discharge cycle is taken into consideration in this investigation. To assess the PCM's long-term phase stability and cooling performance degradation, future research should model several charge-discharge cycles. In conclusion, this study's results show that PCM cooling is a viable passive cooling strategy to increase battery longevity, safety, and efficiency. To improve the accuracy of the numerical predictions, a prospective study should evaluate the usage of other PCMs with higher thermal conductivity, optimize the PCM geometry, create hybrid PCM–air systems, and carry out experimental validation. Future research needs to investigate composite PCM materials exhibiting improved conductivity, carry out experiment validation, investigate hybrid PCM–air or PCM–liquid cooling systems, and model cyclic thermal fatigue to ensure enduring stability.

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7. Nomenclature

Symbol	Meaning	Unit
T	Temperature	(K)
V	Velocity Vector	(ms^{-1})
ρ	Density	(kgm^{-3})
t	Time	(s)
p	Pressure	(Pa)
μ	Dynamic Viscosity	(Pa.s)
g	Gravitational acceleration vector	($m.s^{-2}$)
h	Enthalpy	($J.kg^{-1}$)
k	Thermal conductivity	($Wm^{-1}K^{-1}$)
S_h	Volumetric heat source term	($W.m^{-3}$)
β	Liquid fraction of PCM	(Dimensi-onless)
T_{sol}	Solidus temperature of PCM	(K)
T_{liq}	Liquidus temperature of PCM	(K)