Numerical Investigation of Heat Transfer Enhancement in Li-ion Battery Pack Using PCM and Ionanofluid

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Abstract. Lithium-ion (Li-ion) batteries are widely used in electric vehicles and energy storage systems. However, efficient thermal management use is essential to maintain safety, performance, and operational life of Li-ion batteries. In the current study, three-dimensional (3D) transient numerical simulations are performed to examine the cooling performance of an 18650 Li-ion battery pack with the help of commercial ANSYS Fluent® software. The cooling performance of phase-change material (PCM), pure water, pure ionic liquid [C4mim] [NTf2], and SWCNT-based ionanofluid (INF) is comparatively analyzed. The enthalpy-porosity approach is utilized for simulating the PCM material, while temperature-dependent properties are employed for ionanofluid simulations. The effect of variations of nanoparticle volumes (Φ = 0.0025 - 0.020) on temperature distribution is also examined. The results show that inclusion of nanoparticles significantly enhances effective thermal conductivity and improves convective heat transfer. For Φ≥ 0.01, the maximum temperature decreases and thermal uniformity improves. The average battery temperature decreases from 30.8°C to about 29.8°C using PCM, while temperature is uniformly maintained at 30.0°C for INF with Φ=0.020. Ionanofluid provides a more uniform temperature distribution and a lower peak temperature. The results may provide useful guidelines for the design of advanced thermal management systems using high-concentration INFs for Li-ion battery packs.

Keywords: Battery Thermal Management, Lithium-Ion (Li-ion) Battery Pack, Electric Vehicle (EV), Phase Change Material (PCM), Ionanofluid (INF), CFD.

1 Introduction

An electric vehicle is one of the good sources to reduce air pollution and can improve air quality. The rapid growth of electric vehicles has significantly increased the usage of lithium-ion batteries. A lithium-ion battery is the primary source of energy storage. A lithium-ion battery has high energy density along with a long-life cycle. Chemistry also has characteristics of electrochemical performance that are dependent on temperature [1]. During the load condition that is on charging and discharging of the

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battery, the temperature increases, which slowly reduces the capacity of the battery. As a result, internal resistance also increases, which gives rise to safety performance. The high temperature of the battery causes thermal runaway in the battery. Additionally, non-uniformity within the battery modules gives rise to uneven ageing of the cell, which makes the pack more prone to failure of the system [2].

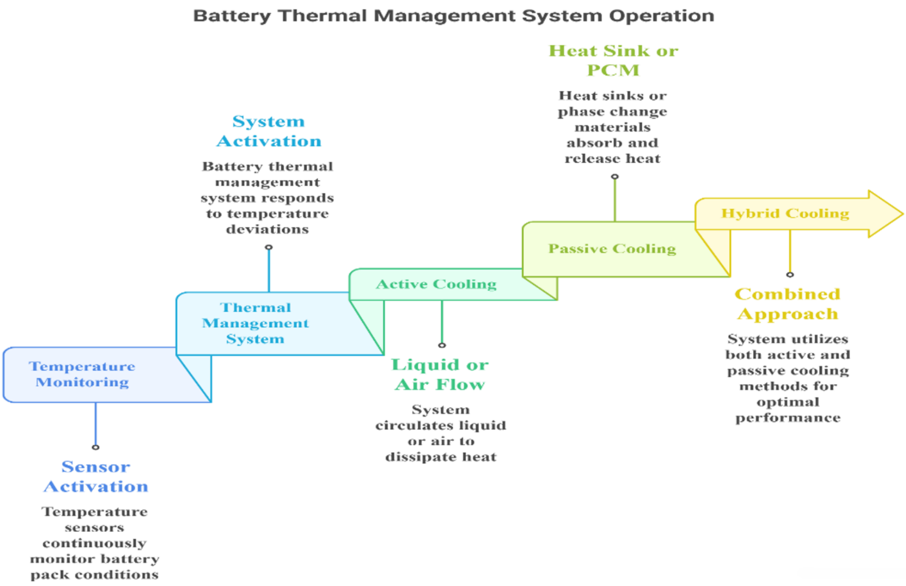


Fig. 1. Battery thermal management system (BTMS).

Figure 1 shows the flow diagram of the Battery Thermal Management System (BTMS) used in an electric vehicle. The purpose of using the BTMS is to keep the battery cell temperature within the operating range. Maintaining the required temperature of the battery is the main objective of BTMS. When the battery works in the desired range, it ensures battery safety, also efficiency increases and performance [3, 4].

The flow starts with monitoring the battery temperature by using temperature sensors in the pack. Real-time data are collected from the multiple sensors that are installed inside the battery pack. The battery thermal management system responds to the temperature differences. The system detects any abnormal heating or cooling from the data received. The BTMS continuously monitors the data. When there is any abnormality in the data, like the temperature is rising above the optimal point, the thermal management system comes in role.

At this point, the BTMS detects an abnormality and makes a decision that the temperature of the battery is rising, and it should be controlled. It also sets the best strategy for cooling the system. Researchers have done a lot of research to find the optimum way to cool the system. On this pretext, there are three broad areas of cooling the system. The systems are active cooling, where liquid or air is used to circulate the air for heat dissipation. The second method is Passive cooling. Generally, in this method, Phase Change Material (PCM) is used in solid form or liquid form to absorb and release the excess heat. One more method is hybrid cooling, where a combined approach of both active and passive cooling is used to affect heat dissipation in the system [5].

Initially, the temperature of the battery pack of an electric vehicle was controlled either by an air-based system or by a liquid-based cooling method to have the temperature of the cell within the desired range, which is around 20°- 40°C, respectively [6]. In this study, emphasis is given to the passive cooling approach.

Among this two-methods liquid-based cooling system is more capable of heat dissipation from the cell. In return, the electric vehicle's performance improves a lot. But conventional air and liquid flow methods are not effective enough for heat dissipation. So, this restriction has made researchers explore more advanced materials as a coolant for thermal management systems. In this framework, Phase change material (PCM) has gained attention that has more capability to absorb more latent heat on melting while providing a temporary solution of heat dissipation to the battery [7].

Conventional Battery Thermal Management Systems (BTMS) regulate the temperature of electric vehicle battery packs by employing either air-based or liquid-based cooling methods to keep the cells within a safe operating window, generally between 20°C and 40°C, respectively [6]. But conventional air and liquid cooling techniques often struggle to maintain temperature within the narrow optimal operating range in the battery during charging and discharging, particularly under high power demand.

The aforementioned limitation has motivated for exploring of advanced thermal management strategies that combine passive and active cooling mechanisms for better cooling of the battery. In this context, Phase change materials (PCMs) have gained attention for their ability to absorb large amounts of latent heat when they melt, providing temporary thermal stabilization in the battery [8], while nanofluids (nanoparticles in regular fluids) and ionanofluid (nanoparticles in ionic liquids) offer enhanced thermal conductivity and convective heat transfer suspending nano-sized particles in the battery packs [4, 9].

The objective of this paper is to present a structured computational framework for analyzing PCM and ionanofluid with emphasis on physical modelling, numerical formulation, and design implications. A three-dimensional transient numerical simulation was carried out to examine the thermal management of an 18650 Li-ion battery pack utilizing PCM, pure water, pure ionic liquid [C4mim] [NTf2], and SWCNT-based ionanofluid with various nanoparticle volumes (Φ = 0.0025, 0.0050, 0.010, 0.015 and 0.020≤). The three-dimensional transient conjugate heat transport problem is solved with ANSYS Fluent® using the finite volume method. The simulation is also performed for a water-based battery pack under similar operating and boundary conditions for the purpose of comparison of results.

2 Numerical Methodology

2.1 Computational Model and Procedure

In the present paper, the three-dimensional (3D) computational geometry of a lithium-ion (Li-ion) battery pack consists of eight vertical cylindrical cells and a cooling medium enclosed in a rectangular enclosure. The individual cell is based on standard 18650 specifications with a diameter of 18 mm and a height of 65 mm. The cells are arranged and enclosed within the polyvinyl chloride (PVC) to ensure an adiabatic wall boundary condition. Such specifications are commonly used for EV applications. Fig. 1 illustrates the 3D model of such an arrangement with dimensions.

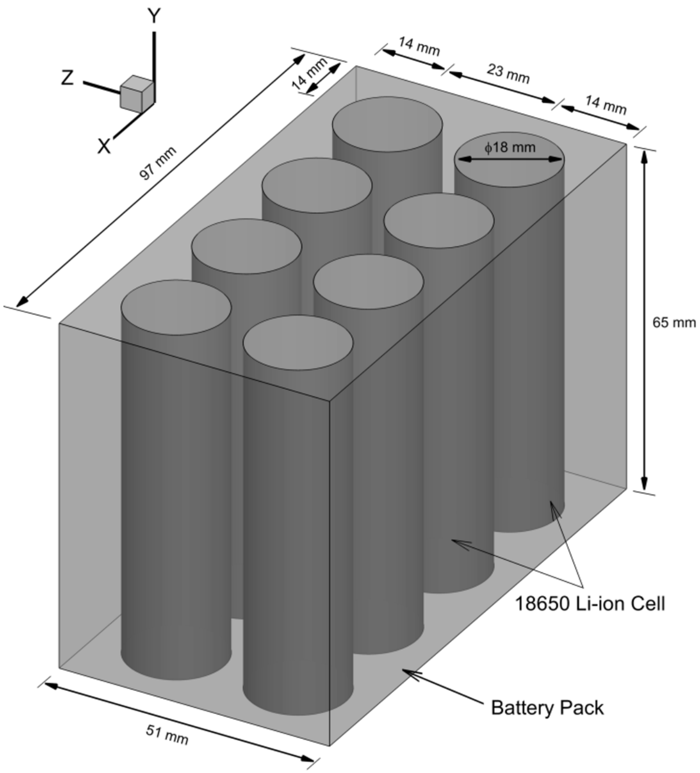


Fig. 2. Three-dimensional geometry of battery pack comprising eight 18650 Li-ion cells.

The center distance between consecutive cells is 23 mm, while the cells are located 14 mm away from the casing wall along X and Z directions. The length of the casing along the X-axis of the battery pack is 97 mm, and its depth along the Z-axis is 51 mm. The present battery configuration consists of four different cooling media, such as phase change material (PCM), ionic liquid (IL), ionanofluid (INF) and water, which are utilized to fill the empty space surrounding the cells within the rectangular enclosure.

The present simulations are carried out by employing individual cooling media surrounding the cells under identical operating situations and boundary conditions. N-octadecane is utilized as a PCM material to absorb heat directly from the cell surfaces through latent heat storage. While the INF is comprised of single-walled carbon nanotubes (SWCNTs) being dispersed in 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide ([C4mim] [NTf2]) ionic liquid (IL) for passive cooling thermal management of a Li-ion battery pack model. Pure water is used for comparison purposes. Both water and INF are modeled as quiescent fluid so that heat transfer occurs due to natural convection and conduction. The maximum temperature of each cell is limited to 30.85 °C (304 K) for PCM, INF and water-based battery cooling configurations, which is in the range of 30-35 °C [10, 11]. While the ambient temperature is set to 28.85 °C (302 K).

A computational grid comprising unstructured hexahedral elements with local refinement near the battery surface and coolant region is generated to accurately capture sharp temperature and velocity gradients. To address the thermal and hydrodynamic boundary layers required by the standard k–ε wall function approach, inflation layers were applied along solid–fluid interfaces. A total of 626182 nodes is used. Fig. 2 illustrates the grid size of the present model.

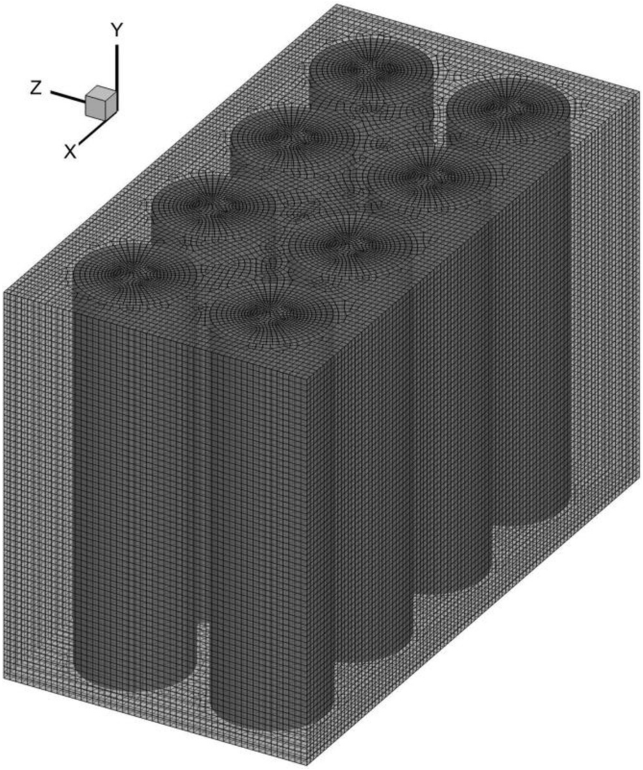


Fig. 3. Grid size of the model.

The specifications of the Li-ion battery pack are provided in Table 1.

Table 1. Specifications of Li-ion battery pack [12, 13].

Sr. No.	Parameters	Value
1	Mass of an individual cell	0.045 kg
2	Nominal voltage of the individual cell	3.6 V
3	Nominal capacity of the individual cell	2.2 A
4	Diameter of an individual cell	18 mm

5	Height of individual cell	65 mm
6	Density of individual cell	2722 kg/m^3
7	Specific heat capacity of individual cell	1200 J/kgK
8	Thermal conductivity of individual cell	k_r=0.2 W/mK, k_z = 37.6 W/mK
9	Density of PVC casing	100 kg/m^3
10	Specific heat capacity of PVC casing	500 J/kgK
11	Thermal conductivity of PVC casing	0.1 W/mK

Finite volume-based ANSYS Fluent is used to determine the thermal behavior of a Li-ion battery pack by developing a 3-D transient conjugate heat transfer model. The temperature and velocity fields of the liquid coolant region, such as water and ionanofluid, are determined using the k-epsilon (k-ε) turbulence model. While the melting and solidification of the PCM battery domain are captured by employing the enthalpy-porosity method. The coolants are assumed to be incompressible fluids, and density variation is assumed using the Boussinesq approximation. The general governing equation for coolant using the standard k-ε turbulence model based on Reynolds-Averaged Navier-Stokes (RANS) equation [14, 15] is provided below:

Continuity equation:
$$\nabla.\vec{V} = 0 \tag{1}$$

Momentum equation:
$$\rho_f\left(\frac{\partial\vec{V}}{\partial t} + \vec{V}.\nabla\vec{V}\right) = -\nabla p + \nabla.\left[(\mu_f + \mu_t)(\nabla\vec{V} + \nabla\vec{V}^T)\right] + g\rho_f\beta_f(T - T_{ref}) \tag{2}$$

Energy equation:
$$\rho_f C_{p,f}\left(\frac{\partial T}{\partial t} + \vec{V}.\nabla T\right) = \nabla.\left(\left(k_f + \frac{\mu_t C_{p,f}}{Pr_t}\right)\nabla T\right) \tag{3}$$

Turbulent kinetic energy equation (k-equation):
$$\frac{\partial(\rho_f k)}{\partial t} + \nabla.\left(\rho_f\vec{V}k\right) = \nabla.\left(\left(\mu_f + \frac{\mu_t}{\sigma_k}\right)\nabla k\right) + P_k - \rho_f \tag{4}$$

Dissipation rate equation (ε-equation):
$$\frac{\partial(\rho_f\varepsilon)}{\partial t} + \nabla.\left(\rho_f\vec{V}\varepsilon\right) = \nabla.\left(\left(\mu_f + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right) + C_1\frac{\varepsilon}{k}P_k - C_2\frac{\varepsilon^2}{k}\rho_f \tag{5}$$

Where, $\vec{V}$ is the velocity vector, p is fluid pressure, g is the gravitational acceleration, t is the time, ρ_f is the fluid density, μ_f is the fluid viscosity, μ_t is the turbulent viscosity, β_f is the fluid thermal expansion coefficient, T is the fluid temperature, T_{ref} is the reference temperature, $C_{p,f}$ is the specific heat of he fluid, k_f is the fluid thermal conductivity, Pr_t is the turbulent Prandtl number, k is the kinetic energy, ε is the dissipation rate of turbulence, σ_k is the turbulent kinetic energy diffusion constant, σ_ε is the turbulent dissipation rate diffusion constant, and P_k is the production of turbulent kinetic energy. C_1 and C_2 are the empirical constants representing the production and dissipation rates of turbulence, respectively. The subscript 'f' in Eqs. (1)-(5) refers to thermo-physical properties of the liquid coolant used (water and ionanofluid).

In the present study, the ionanofluid (INF) comprises a base fluid as [C4mim] [NTf2] ionic liquid ($\Phi = 0$) and different volume fractions of SWCNTs (i.e. $\Phi = 0.0025$, 0.0050, 0.010, 0.015 and 0.020≤). The thermal properties of water, ionic liquid and SWCNT nanoparticles used in current simulations are provided in Table 2. In the present study, ionanofluid-based SWCNT is assumed to be a homogeneous fluid with enhanced temperature-dependent properties.

Table 2. Thermo-physical properties of Water, Ionic liquid ([C4mim] [NTf2]) and nanoparticle (SWCNT) at 300.15 K.

Property	Water [16]	[C4mim] [NTf2] [17–19]	SWCNT [20, 21]
C_{pf} (kJ.kg^{-1}.K^{-1})	4.182	1.740	0.71
ρ_f (kg.m^{-3})	998.2	1470	2100
k_f (W.m^{-1}.K^{-1})	0.6	0.126	3000
μ_f (Pa.s)	1.003×10^{-3}	0.035	-
β_f (K^{-1})	2.07×10^{-4}	5.2×10^{-4}	1.5×10^{-5}

Table 3. Thermo-physical properties of SWCNT based Ionanofluid [22].

Thermo-physical Property	Correlation
Density, ρ_f	$\rho_f = (1-\Phi)\rho_{il} + \Phi\rho_{np}$
Heat capacity, $(\rho C_p)_f$	$(\rho C_p)_f = (1-\Phi)(\rho C_p)_{il} + \Phi(\rho C_p)_{np}$
Dynamic viscosity, μ_f	$\mu_f = \frac{\mu_{il}}{(1-\Phi)^{2.5}}$
Thermal conductivity, k_f	$k_f = k_{il}\left[\frac{k_{np} + 2k_{il} - 2\Phi(k_{il} - k_{np})}{k_{np} + 2k_{il} + \Phi(k_{il} - k_{np})}\right]$
Thermal expansion coefficient, $(\rho\beta)_f$	$(\rho\beta)_f = (1-\Phi)(\rho\beta)_{il} + \Phi(\rho\beta)_{np}$

The thermo-physical properties, including density (ρ_f), specific heat capacity ($C_{p,f}$), thermal conductivity (k_f) and dynamic viscosity (μ_f) have been determined using the correlations reported in the study [22]. The effective temperature-dependent properties of INF are provided in Table 3.

The subscripts 'il' and 'np', which appeared in correlations of Table 3, represent ionic liquid and SWCNT nanoparticles, respectively. The influence of variations of SWCNTs concentrations (Φ) in ionanofluid on thermal performance of Li-ion battery pack is also investigated in the current study. In the present study, the aforementioned properties are employed in ANSYS Fluent via user-defined functions (UDF) developed in C language.

The PCM and cells of the Li-ion battery are modelled as a stationary solid-liquid domain in which no fluid movement occurs (i.e. $\vec{V} = 0$). In such a case, the heat transfer is only due to conduction and the latent heat of absorption during the melting process. The radiation effect is neglected due to the low temperature difference. The heat transfer in the PCM region within the Li-ion battery pack is described by the energy equation in the following form:

Energy equation including conduction and phase change process [23]:

$$\frac{\partial(\rho H)}{\partial t} = \nabla.(k\nabla T) + q_{gen} \tag{6}$$

Where, H is the volumetric enthalpy of PCM, ρ is the density of PCM, k is the thermal conductivity of PCM, ∇T is the temperature difference. The volumetric heat generation by the battery (q_{gen}) in terms of internal resistance (R), current (I), and battery volume cells (V), is given as,

$$q_{gen} = \frac{RI^2}{V} \tag{7}$$

The volumetric enthalpy (H) is given as,

$$H = h + \Delta H \tag{8}$$

Where, h is the sensible enthalpy and is given as,

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{9}$$

Where, h_{ref} is the reference enthalpy, T_{ref} is the reference temperature and C_p is the specific heat capacity of PCM.

The latent heat of enthalpy is given as,

$$\Delta H = \lambda L \tag{10}$$

Where, L is the latent heat of PCM, and λ is the liquid fraction of PCM. In the solid phase, $\lambda = 0$ If the PCM temperature is less than the solidus temperature $(T < T_s)$. On the contrary, in the liquid phase, $\lambda = 1$ If the PCM temperature is more than the liquidus temperature $(T > T_l)$. In a mushy region $(T_s < T < T_l)$, the liquid fraction of PCM during absorption of latent heat can be determined by using the following equation,

$$\lambda = \frac{T - T_s}{T_l - T_s} \tag{11}$$

The thermal properties of n-octadecane PCM material, being considered in recent numerical work, have been provided in Table 3.

Table 4. Thermal and physical properties of n-octadecane PCM material [15].

Property	Solid-phase $(T \leq T_s)$	Mushy region $(T_s \leq T \leq T_l)$	Liquid-phase $(T \geq T_l)$
Specific heat, C_p ($kJ.kg^{-1}.K^{-1}$)	2150	$C_p(T)$	2180
Density, ρ ($kg.m^{-3}$)	814	$\rho(T)$	724
Thermal conductivity, k ($Wm^{-1}.K^{-1}$)	0.358	$k(T)$	0.152
Latent heat of fusion, H ($J.kg^{-1}$)	-	225,000	-

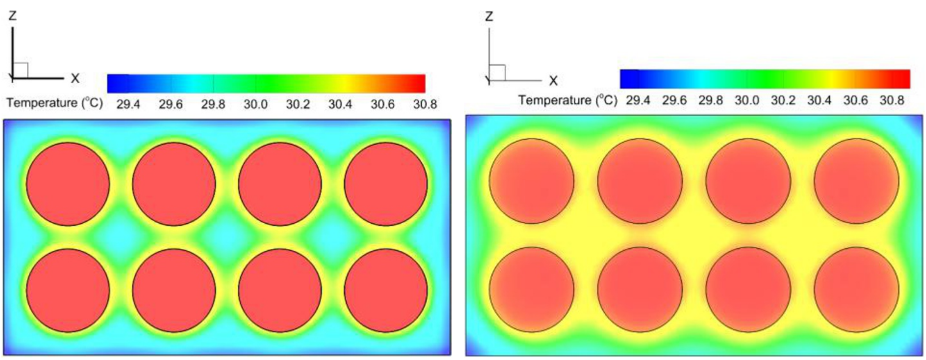
In the present study, normal octadecane (n-octadecane) is employed as the PCM material. Its melting point temperature is approximately 27.7 °C (300.85 K) [24]. $T_l = 303.15\ K$ and $T_s = 301.15\ K$ are the values that are taken into consideration for n-octadecane.

At the coolant inlet, a uniform velocity inlet boundary condition was applied, with an inlet temperature equal to the ambient coolant temperature. The turbulence quantities for the k–ε model have been initialized by specifying the hydraulic diameter and turbulence intensity. At the outlet, a pressure outlet condition with zero-gauge pressure is utilized to allow fully developed flow to exit the domain. The outer walls of the battery are assumed to be adiabatic, neglecting heat loss to the external environment. The PCM domain is initially considered to be solid at constant ambient temperature below its melting point. The liquid fraction of PCM was set to zero. No-slip boundary conditions were imposed on all solid surfaces. Buoyancy effects in the coolant were modeled using Boussinesq approximation, with the reference temperature set at the inlet coolant temperature.

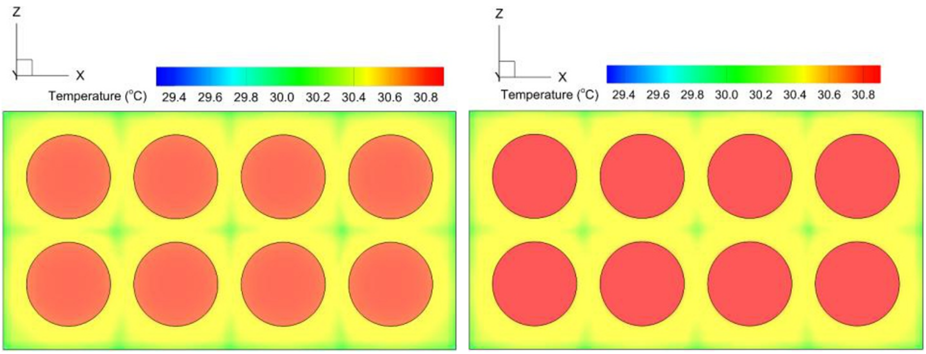
The 3-D transient conjugate heat transport problem is solved using ANSYS Fluent based on the finite volume approach. The governing equations for mass, momentum, energy, and turbulence have been discretized over unstructured control volumes. The pressure–velocity coupling is handled using the SIMPLE algorithm, while 2nd order upwind scheme is applied for momentum, energy, turbulent kinetic energy, and dissipation rate to improve solution accuracy. k–ε turbulence model with standard wall functions has been utilized to characterize the turbulent flow behavior in the coolant region. The PCM material was modeled using the enthalpy-porosity approach, where latent heat was integrated into the energy equation, and a mushy-zone source term reduced velocity during solidification. A transient scheme with a constant time step was employed, and convergence at each time step was achieved when residuals of continuity and momentum fell below 10^{-4} and the energy equation below 10^{-6}. The results from the simulations of PCM, ionanofluid and water are compared and discussed in detail. The transient simulations were run for 1000 seconds with a fixed time step size.

3 Results and Discussions

In this section, the thermal performance of the present 18650 Li-ion battery pack using water, ionanofluid and PCM material as coolant is presented. The effect of the variation of volume fraction of SWCNTs in INF is also discussed.



(a) (b)



(c) (d)

Fig. 4. Estimated temperature distribution at the top surface of Li-ion 18650 battery pack filled with: (a) n-octadecane PCM, (b) pure water, (c) ionic liquid (Φ = 0), and ionanofluid (Φ = 0.020).

Figure 4 illustrates the predicted temperature contours at the top surface of the 18650 lithium-ion battery pack for four cooling configurations using n-octadecane PCM, pure water cooling, ionic liquid (φ = 0), and ionanofluid (φ = 0.020). In the PCM case (Fig. 4a), the battery surface reaches a maximum temperature with significant localized hot spots around the cell periphery. The cooling rate is relatively low since heat is mainly dissipated by conduction and latent heat absorption. The PCM decreases temperature rise but insufficiently dissipates the heat, resulting in non-uniform temperature distribution and higher thermal gradients within cells. Pure water cooling (Fig. 4b) lowers overall temperature relative to the PCM case due to convective heat removal. However, considerable temperature differences persist near the downstream region, indicating low thermal conductivity and weaker heat diffusion throughout the coolant domain.

Compared to water, the ionic liquid coolant (Fig. 4c) improves temperature uniformity due to its better thermal transport properties and higher heat capacity. Though there are still some modest gradients around the battery limits, the temperature contours become smoother, and there are fewer hot areas. The ionanofluid case (Fig. 4d) has the most uniform temperature distribution and the lowest peak temperature. The inclusion of nanoparticles improves effective thermal conductivity and turbulent energy transport, hence increasing the convective heat transfer coefficient. As a result, heat is dissipated more efficiently, and the temperature field is practically uniform across all cells, considerably reducing hot spot development. The results indicate that combining enhanced thermal conductivity of ionanofluid with convective cooling improves thermal management over conventional water cooling and PCM-only systems.

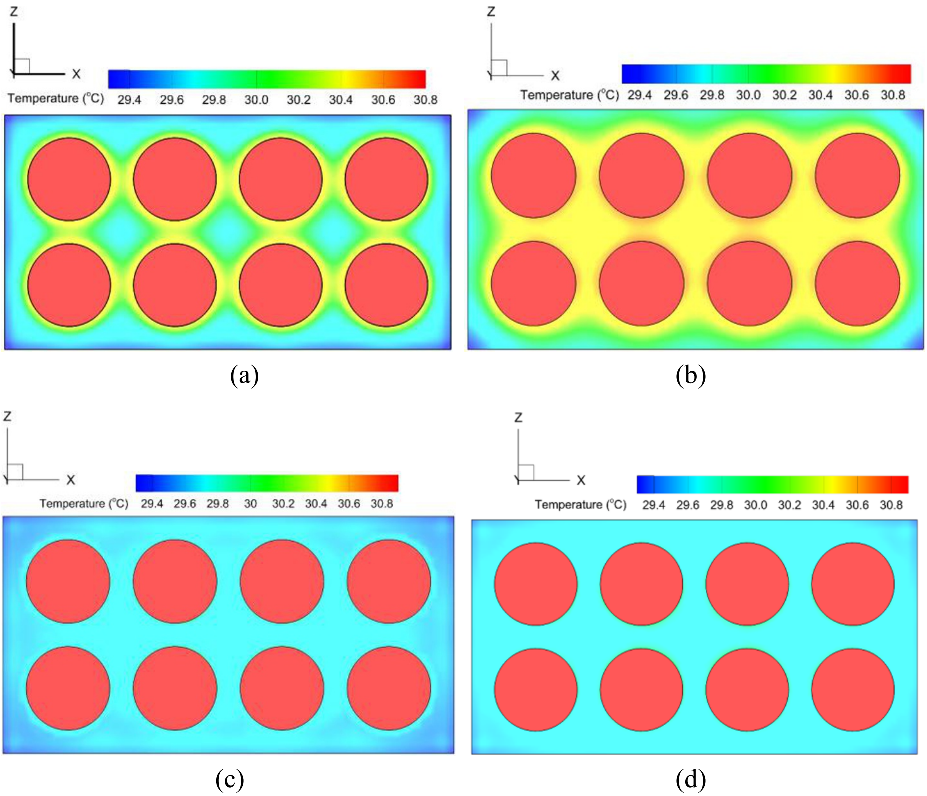


Fig. 5. Estimated temperature field at the bottom surface of 18650 Li-ion battery pack filled with: (a) n-octadecane PCM, (b) pure water, (c) ionic liquid (Φ = 0), and ionanofluid (Φ = 0.020).

Figure 5 represents the estimated temperature fields at the bottom surface of the 18650 lithium-ion battery pack for four cooling configurations using n-octadecane PCM, pure water cooling, ionic liquid (φ = 0), and ionanofluid (φ = 0.020). In the PCM-only configuration (Fig. 5a), higher temperatures and a non-uniform distribution are observed in the battery contact regions. The PCM absorbs heat through latent heat storage; however, due to its low thermal conductivity, heat spreads slowly across the bottom surface. The result is localized heat accumulation beneath the cells, and it also causes noticeable temperature variations between nearby batteries.

Pure water cooling (Fig. 5b) decreases the temperature compared to the PCM case because convective heat transfer removes heat continuously. However, the cooling effect is uneven all over the flow path, with warmer zones appearing downstream, indicating that the coolant gradually heats as it absorbs energy from successive cells.

The ionic liquid case (Fig. 5c) exhibits enhanced temperature uniformity. The enhanced heat transfer capacity and thermal transport capability improve heat diffusion throughout the base surface, minimizing local hot spots and smoothing temperature gradients around the battery base. The ionanofluid cooling system (Fig. 5d) results in the most uniform temperature distribution and the lowest temperature variation across the entire bottom surface.

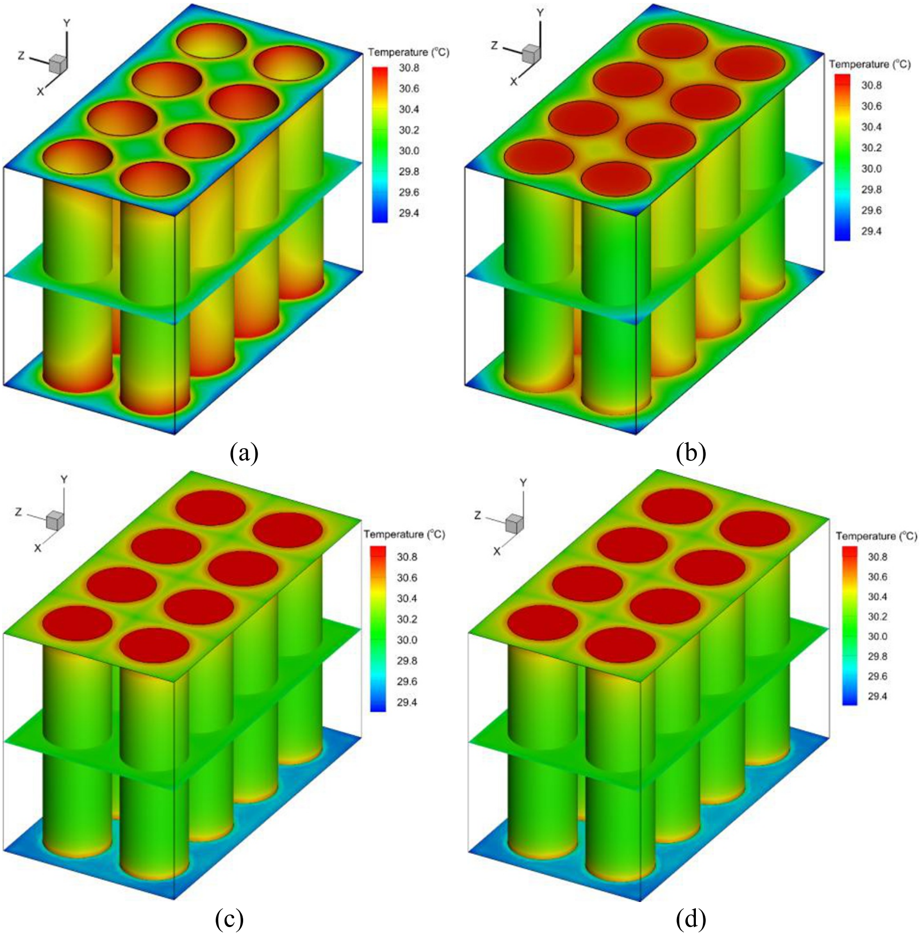


Fig. 6. Estimated 3-D temperature distribution of Li-ion 18650 battery pack filled with: (a) n-octadecane PCM, (b) pure water, (c) ionic liquid (Φ = 0), and ionanofluid (Φ = 0.020).

Nanoparticle dispersion increases effective thermal conductivity, which enhances convective heat transfer and enables enhanced transfer of heat and removal. As a result, thermal accumulation beneath individual cells is reduced, and all batteries have approximately equal temperature levels.

Figure 6 depicts the predicted three-dimensional temperature contours of the Li-ion 18650 battery module occupied with four different cooling media: (a) n-octadecane PCM, (b) pure water, (c) ionic liquid (φ = 0), and (d) ionanofluid (φ = 0.020). The color bar ranges from 29.4 °C (blue) to 30.8 °C (red), with red zones showing hot regions in the cell cores and blue regions indicating effective heat removal at the outer enclosure. For all cases, the highest temperature happens at the top circular regions of the cells, corresponding to maximum internal heat generation with limited radial heat dissipation. The best performance is observed in the ionanofluid (d), where nanoparticles increase effective thermal conductivity and heat diffusion, leading to the most uniform green contour and the lowest maximum temperature of all cases.

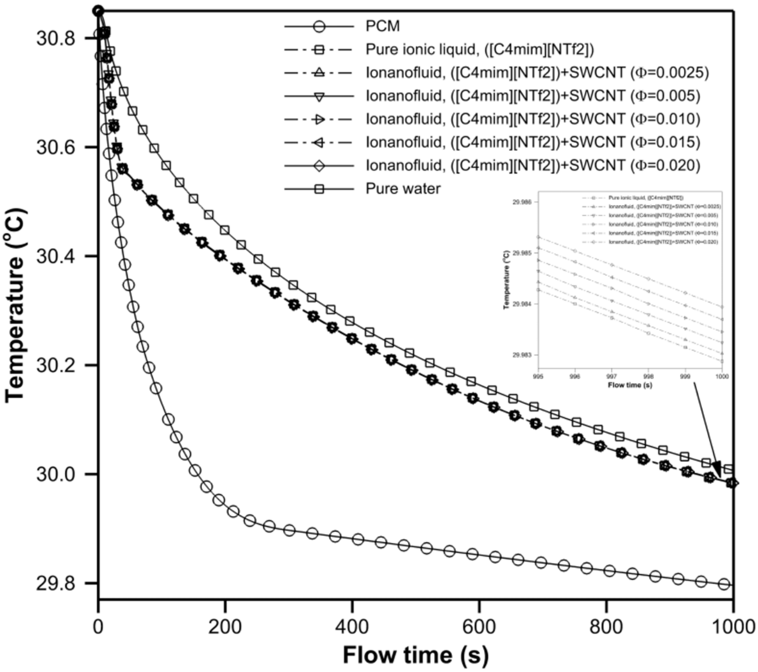


Fig. 7. Variation of average battery pack temperature with flow time for different cooling media.

Figure 7 illustrates the variation of average battery pack temperature with flow time for different cooling media, namely PCM, pure water, pure ionic liquid (i.e. $\Phi = 0$) and ionanofluid containing SWCNT nanoparticles at various volume fractions (i.e. Φ = 0.0025, 0.0050, 0.010, 0.015 and 0.020≤). All cases begin close to the same temperature (~30.8 °C), but the rate of cooling varies significantly. Due to latent heat absorption during melting, PCM exhibits the fastest decrease in temperature in the beginning of the process, resulting in a lower temperature for the entire process. Pure water shows the highest temperature among liquid coolants, indicating a low capacity to remove heat. Because of its higher thermal conductivity and stability, the ionic liquid is superior to water. The ionanofluid cooling performance is further enhanced by the addition of SWCNT nanoparticles, and the temperature gradually decreases as the concentration of the nanoparticles increases, demonstrating enhanced effective thermal conductivity and heat transfer. Longer flow times make the difference prominent (see Fig.7), where the lowest temperature among liquid coolants is achieved for maximum volume fraction of nanoparticles ($\varphi = 0.020$) for ionanofluid.

5. Conclusion

A three-dimensional transient numerical simulation was carried out to examine the thermal management of an 18650 Li-ion battery pack utilizing PCM, pure water, pure ionic liquid [C4mim] [NTf2], and SWCNT-based ionanofluid with various nanoparticle volumes (Φ = 0.0025, 0.0050, 0.010, 0.015 and 0.020≤). The three-dimensional transient conjugate heat transport problem is solved with ANSYS Fluent® using the finite volume method. A k-ε turbulence model with standard wall functions was used to analyze the turbulent flow behavior in the coolant region. The enthalpy-porosity approach was utilized for simulating the PCM material, which included latent heat in the energy equation and reduced velocity during solidification with a mushy-zone source term. The temperature-dependent properties for ionanofluid are employed for all simulations. The following noticeable points can be drawn from the present study:

- It is observed that PCM suppressed thermal spikes most effectively and provided the lowest peak battery temperature due to high latent heat absorption,
- The ionanofluid performed better than water and pure ionic liquid due to the addition of nanoparticles, which enhanced effective thermal conductivity and heat transfer.
- Increasing the SWCNT volume fraction (Φ) improved temperature uniformity and consistently reduced the average and maximum cell temperature.
- The lowest cooling performance is observed for the water case. On the other hand, PCM provided superior short-term thermal control, while ionanofluid provided superior stability for long-term heat removal.

Disclosure of Interest. The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Al-Zareer, M., Dincer, I., Rosen, M.A.: A review of novel thermal management systems for batteries. International Journal of Energy Research **42**(10), 3182-3205 (2018).
2. Hu, X., Li, S., Peng, H.: A comparative study of equivalent circuit models for Li-ion batteries. Journal of Power Sources **198**, 359-367 (2012).
3. Hwang, F.S., Confrey, T., Reidy, C., Picovici, D., Callaghan, D., Culliton, D., Nolan, C.: Review of battery thermal management systems in electric vehicles. Renewable and Sustainable Energy Reviews **192**, 114171 (2024).
4. Hu, X., Wang, Y., Feng, X., Wang, L., Ouyang, M., Zhang, Q.: Thermal stability of ionic liquids for lithium-ion batteries: A review. Renewable and Sustainable Energy Reviews **207**, 114949 (2025).
5. Shahjalal, M., Shams, T., Islam, M.E., Alam, W., Modak, M., Hossain, S. Bin, Ramadesigan, V., Ahmed, M.R., Ahmed, H., Iqbal, A.: A review of thermal management for Li-ion batteries: Prospects, challenges, and issues. Journal of energy storage **39**, 102518 (2021).
6. Rao, Z., Wang, S.: A review of power battery thermal energy management. Renewable and Sustainable Energy Reviews **15**(9), 4554-4571 (2011).
7. Murali, G., Sravya, G.S.N., Jaya, J., Naga Vamsi, V.: A review on hybrid thermal management of battery packs and it's cooling performance by enhanced PCM. Renewable and Sustainable Energy Reviews **150**, 111513 (2021).

8. Ling, Z., Zhang, Z., Shi, G., Fang, X., Wang, L., Gao, X., Fang, Y., Xu, T., Wang, S., Liu, X.: Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules. Renewable and Sustainable Energy Reviews **31**, 427-438 (2014).
9. Sabbah, R., Kizilel, R., Selman, J.R., Al-Hallaj, S.: Active (air-cooled) vs. passive (phase change material) thermal management of high power lithium-ion packs: Limitation of temperature rise and uniformity of temperature distribution. Journal of power sources **182**(2), 630-638 (2008).
10. Kummitha, O.R.: Thermal cooling of li-ion cylindrical cells battery module with baffles arrangement for airflow cooling numerical analysis. Journal of Energy Storage **59**, 106474 (2023).
11. Choudhari, V.G., Dhoble, A.S., Panchal, S.: Numerical analysis of different fin structures in phase change material module for battery thermal management system and its optimization. International Journal of Heat and Mass Transfer **163**, 120434 (2020).
12. Behi, H., Karimi, D., Behi, M., Ghanbarpour, M., Jaguemont, J., Sokkeh, M.A., Gandoman, F.H., Berecibar, M., Van Mierlo, J.: A new concept of thermal management system in Li-ion battery using air cooling and heat pipe for electric vehicles. Applied Thermal Engineering **174**, 115280 (2020).
13. Maleki, H., Hallaj, S. Al, Selman, J.R., Dinwiddie, R.B., Wang, H.: Thermal Properties of Lithium-Ion Battery and Components. Journal of The Electrochemical Society **146**(3), 947-954 (1999).
14. Panchal, S., Gudlanarva, K., Tran, M.K., Herdem, M.S., Panchal, K., Fraser, R., Fowler, M.: Numerical Simulation of Cooling Plate Using K-Epsilon Turbulence Model to Cool Down Large-Sized Graphite/LiFePO4 Battery at High C-Rates. World Electric Vehicle Journal **13**(8), 138 (2022).
15. Javani, N., Dincer, I., Naterer, G.F., Yilbas, B.S.: Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles. International Journal of Heat and Mass Transfer **72**, 690-703 (2014).
16. Dhanasekaran, A., Dhanasekaran, R., Subramanian, Y., Gubendiren, R.K., Ali, M., Raj, V., Yassin, H., Azad, A.K.: Silver Nanofluid-Based Thermal Management for Effective Cooling of Batteries in Electric Vehicle Systems. Arabian Journal for Science and Engineering, **49**(11), 14711-14728 (2024).
17. Maniwa, Y., Fujiwara, R., Kira, H., Tou, H., Kataura, H., Suzuki, S., Achiba, Y., Nishibori, E., Takata, M., Sakata, M., Fujiwara, A., Suematsu, H.: Thermal expansion of single-walled carbon nanotube (SWNT) bundles: X-ray diffraction studies. Physical Review **64**(24), 241402 (2001).
18. Franç, J.M.P., Nieto De Castro, C.A., Lopes, M.M., Nunes, V.M.B.: Influence of thermophysical properties of ionic liquids in chemical process design. Journal of Chemical & Engineering Data **54**(9), 2569-2575 (2009).
19. Paul, T.C., Mahamud, R., Khan, J.A.: Multiphase modeling approach for ionic liquids (ILs) based nanofluids: Improving the performance of heat transfer fluids (HTFs). Applied Thermal Engineering **149**, 165-172 (2019).
20. Dervishi, E., Li, Z., Xu, Y., Saini, V., Biris, A.R., Lupu, D., Biris, A.S.: Carbon nanotubes: Synthesis, properties, and applications. Particulate Science and Technology **27**(2), 107-125 (2009).
21. Hone, J., Llaguno, M.C., Biercuk, M.J., Johnson, A.T., Batlogg, B., Benes, Z., Fischer, J.E.: Thermal properties of carbon nanotubes and nanotube-based materials. Applied physics A, **74**(3), 339-343 (2002).
22. Zahan, I., Nasrin, R., Hasan, S.: Numerical Simulation of Heat Transfer Performance of Ionanofluid Flow inside Two Connected Oblique Triangular Enclosure. In Proceedings of the 13th International Conference on Marine Technology (MARTEC 2022) (2023).

23. Rohit Kumar, K., Sharan, V., Harish, R., Shyam Kumar, M.B.: Numerical study of thermal cooling for Lithium-ion battery pack using phase change material. In: IOP Conference Series: Earth and Environmental Science, **573**(1), 012018 (2020).
24. Zhao, Y., Zhang, X., Yang, B., Cai, S.: A review of battery thermal management systems using liquid cooling and PCM. Journal of Energy Storage **76**, 109836 (2024).