Numerical Study of a Lithium-Ion Battery Cooling Using Nanofluids

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Abstract: The cooling performance of a thermal battery plays a critical role in its efficiency, lifespan, and safety. This importance stems from the heat generated during charging and discharging processes. As temperatures rise, key battery characteristics are significantly affected. The present paper presents a numerical investigation of the cooling of a Lithium-ion battery composed of 90 cells. It was found that the coolant inlet velocity significantly impacts the module's temperature distribution and the maximum temperature difference. The effect of using nanofluids was studied with three different types of nanoparticles (alumina, copper, and fullerene) dispersed in water as the base fluid. The results show that the temperature difference in the module varies depending on the nature and volume fraction of the nanoparticles.

Keywords: CFD, Lithium-Ion battery, cooling, nanofluids, battery thermal management.

1. INTRODUCTION

Lithium-ion batteries play an essential role in many modern applications, including electric vehicles, portable electronic devices, and renewable energy storage. The rapid development of lithium-ion battery technology has led to a growing demand for efficient cooling systems to maintain their optimum operating temperature. Inadequate battery cooling can lead to reduced efficiency, shorter lifespan, and even safety risks, such as overheating and fire. In response to these challenges, extensive research has focused on the use of nanofluids to improve the battery cooling process.

Currently, the majority of researchers have investigated the impact of improved heat transfer on battery performance through experimental, theoretical, and numerical studies. Experimental studies are frequently used to validate numerical results in practical cases, but they are generally more costly than other types of investigations.

The The impact of using a thermoelectric cooler (TEC) to cool a lithium-ion plate battery was numerically simulated using COMSOL software (H. Alhumade et al. 2022). The heated part of the TEC was cooled by a heat sink, while the cold part was mounted on the battery. Three main types of heat sinks were used. A non-Newtonian hybrid nanofluid served as the working fluid. For nanofluids with volume fractions of 0.05%, 0.25%, and 0.5%, values for heat sink temperature, battery temperature, and TEC hot end temperature were calculated by varying the inlet Reynolds number (Re) between 200 and 800. The results show that the application of model C resulted in higher TEC temperatures. Models A and B kept battery and heat sink temperatures lower during periods of both low and high Re. As Re increases, battery, TEC, and heat sink temperatures decrease while the amount of ΔP increases. The highest and lowest ΔP values were found in models C and A, respectively. The addition of nanoparticles increased the ΔP by 267% and around 95% at Re = 200 and Re = 800, respectively.

Yue Yang et al. (2022) created electrochemical-thermal combination models for the Li-ion cell module arranged in series, investigating a unique mixed thermal management system comprising phase change material (PCM) and liquid cooling via a thermally conductive structure. The hybrid cooling system was initially tuned using this method, studying the impact of cell separation and incoming liquid velocity on electrical, chemical, and thermal efficiencies. As spacing increases, the highest temperature and the selection temperature difference decrease, but once the gap reaches around 4 mm, the rate of decrease almost disappears. The main reason for discharge imbalance between cells in the battery module is diffusion polarization in the electrolyte, which can be corrected by the suggested hybrid cooling system according to a theoretical calculation used to assess and quantify unequal discharge.

Gaoliang Liao et al. (2022) carried out an investigation of a liquid cooling battery thermal management system (BTMS) for 18650 lithium-ion batteries. Nanofluids with high thermal conductivity were used as coolants to improve thermal performance. Various nanofluids were compared with water to evaluate their cooling effectiveness. The best-performing solution was a Cu water-based nanofluid, which reduced the maximum temperature difference between battery and water by 1.066 K and 12.6%, respectively. The results show that although the volume percentage and displacement velocity of the nanofluids increase simultaneously with the pressure drop, the maximum temperature difference and the maximum battery temperature decrease.

Md Faizan, Sukumar Pati (2022) investigated a dual cooling method combining forced convection cooling and convergent channels with composite phase change material (CPCM). The results showed that when hybrid cooling is used, the unit temperature is lowered below the safety limit. In addition, higher temperature uniformity and improved thermal performance are achieved when the CPCM surrounds the battery cell rather than being sandwiched between the cold plates and the battery cell.

A unique liquid cooling system with stepped and zigzag channels consisting of alumina nanofluid and copper coating was numerically investigated by K. Joshi et al. (2023) to improve the cooling capacity and temperature distribution of the battery thermal control system during discharge and charge processes. The results indicate that the maximum temperature and temperature non-uniformity of the battery module are significantly reduced when a cooling alumina nanofluid with a volume fraction of 2% is added. Various studies using numerical, experimental, and mathematical methods have been conducted in the past to show the impact of different cooling systems using various coolants on the electrical and thermal performance of many engineering systems. (K. Anand et al. (2023) ; S. Panchal et al. (2023) ; H. Abdulrassul et al. (2022) ; A. Kayser et al. (2022) ;R. Braga et al. (2023) ; S. Nurul et al. (2021)).

2. PHYSICAL MODEL

A 2D numerical simulation was conducted to study the cooling of a Lithium-ion battery in the presence of nanofluids, using ANSYS Fluent computational fluid dynamics (CFD) software. The battery module consisted of 90 cylindrical lithium-ion cells with nominal specifications of 54 V/13.2 Ah. The cooling plates, made from aluminum, were sandwiched between two rows of cells. The gaps between two adjacent cells in the x-axis and y-axis directions were 2 mm and 4 mm, respectively, with air filling the space between adjacent cells in the x-axis direction. A detailed schematic diagram is shown in Figure 1.

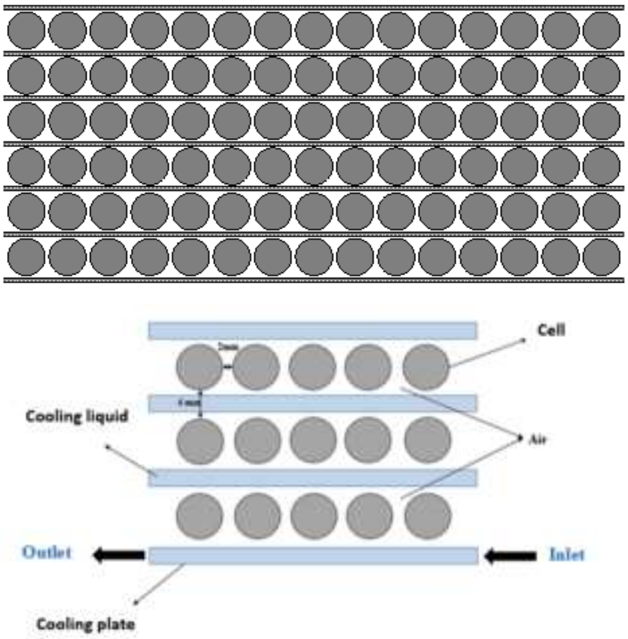


Figure 1. Schematic diagram of the battery module

3. BOUNDARY CONDITIONS

The boundary conditions for the inlet and outlet of the liquid cooling system were defined as velocity inlet and pressure outlet, respectively. All surfaces inside the battery module were set as adiabatic boundary conditions. The initial liquid inlet and cell temperatures were set at 25°C and 31°C, respectively. The flow was considered laminar.

4. GOVERNING EQUATIONS

The energy conservation equations for the cell (battery) and liquid coolant (water) are as follows (Z. Rao et al. 2017):

$$\rho_b \, C_b \frac{\partial T}{\partial t} = \nabla.(\lambda_b \, \nabla T) + \dot{Q} \tag{1}$$

$$\rho_w \, C_w \frac{\partial T_w}{\partial t} = \nabla.(\lambda_b \nabla T_w) - \nabla.(\rho_w C_w \vec{v} T_w) \tag{2}$$

The equations for conservation of mass and momentum of liquid cooling are expressed as follows (Y. Huo et al. 2015):

$$\frac{d\rho_w}{dt} + \nabla.(\rho_w \vec{v}) = 0 \tag{3}$$

$$\frac{d}{dt}(\rho_w \vec{v}) + \nabla.(\rho_w \vec{v}\vec{v}) = -\nabla p \tag{4}$$

For nanofluid flow simulation, we opted for the Mixture two-phase model, the equations governing the flow are (A. Benabderrahmane et al. 2017):

$$\nabla.(\,\rho_m \overrightarrow{V_m}) = 0 \tag{5}$$

$$\nabla.\sum_{k=1}^{n}(\rho_k \, C_{pk} \, \varnothing_k \, V_k T) = \nabla.(k_m \, \nabla \, T) \tag{6}$$

$$\begin{aligned} \rho_m \, \overrightarrow{V_m} \, \nabla \, \overrightarrow{V_m} = -\nabla P_m + (\mu_m \, \nabla \, \overrightarrow{V_m}) + \rho_m \, g \\ + \, \nabla.\sum_{k=1}^{n}(\varnothing_k \, \rho_k \, \vec{V}_{dr,k} \, \vec{V}_{dr,k}) \end{aligned} \tag{7}$$

The mixture properties are defined as:

Velocity	$\overrightarrow{V_m} = \frac{\sum_{k=1}^{n} \rho_k \, \varnothing_k \, V_k}{\rho_m}$
Density	$\rho_m = \sum_{k=1}^{n} \rho_k \, \varnothing_k$
Viscosity	$\mu_m = \sum_{k=1}^{n} \varnothing_k \, \mu_k$

5. MESH INDEPENDENCE STUDY

To assess the influence of grid size on the calculation results, a grid sensitivity study was conducted by varying the total number of grid distributions in the radial and axial directions. Various combinations of grids were analyzed to ensure that the numerical results are independent of the mesh size used.

Table 1 shows the evolution of the average Nusselt number as a function of the number of cells for a range of Reynolds numbers. It has been found that increasing the number of meshes does not change the solution but does require more computing time.

Table 1. Effect of mesh on Nusselt number results.

	Nombres des nœuds			
	390210	**447095**	**580043**	
Re	**Nu** moyen			$\left\|\varepsilon_{max}\right\|$
710	37.04	38.20	37.17	**0.057**
1065	47.19	48.95	49.62	**0.049**
1420	53.33	55.82	58.11	**0.082**
1775	77.12	79.45	79.08	**0.025**

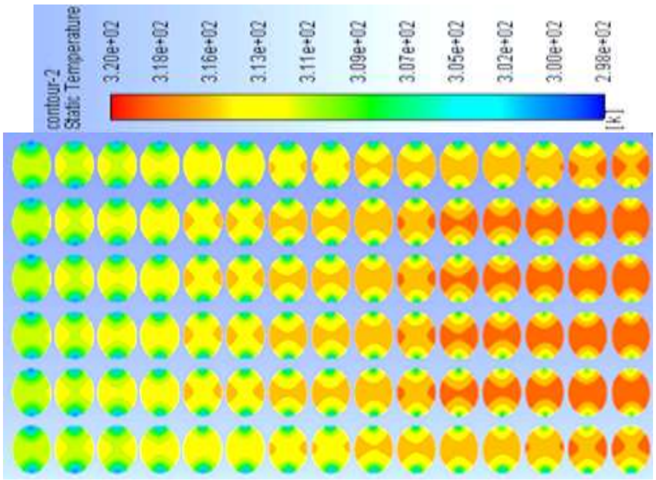
6. RESULTS AND INTERPRETATIONS

6.1 Effect of velocity inlet on the cells temperature distribution

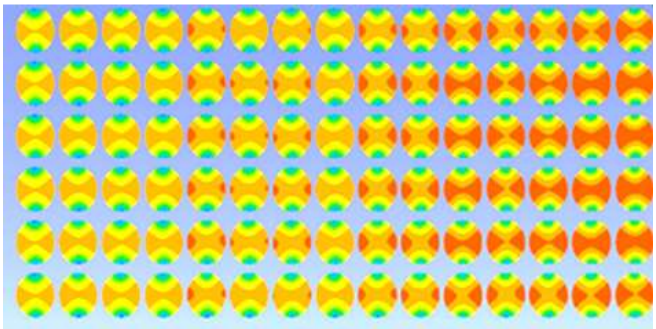
The study focused on exploring how fluid inlet velocity influences the cooling efficiency of the battery module. Four distinct inlet velocities (0.1, 0.2, 0.3, and 0.4 m/s) were examined under controlled inlet temperature and module conditions. Figure 2 illustrates temperature contours across the module after a rapid charging cycle at varying inlet velocities. Notably, when the inlet velocity is below 0.2 m/s, the temperature distribution within the module exhibits significant non-uniformity.

Figures 3 and 4 present the module's peak temperature and maximum temperature differential (ΔT max) as a function of different inlet velocities. Initially, both metrics decrease sharply and stabilize around velocities exceeding 0.3 m/s. This implies that an inlet velocity of 0.3 m/s can adequately facilitate efficient cooling within this water cooling system.

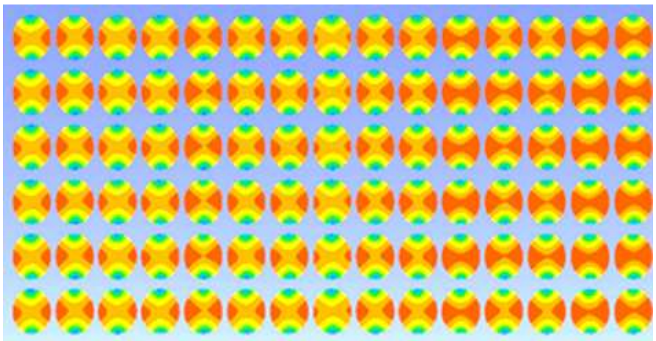
These results underscore the fundamental principles of fluid dynamics and heat transfer in battery thermal management. Maintaining optimal fluid velocities is crucial for achieving uniform temperature distribution and enhancing overall cooling performance. This physical understanding highlights the necessity of balancing flow dynamics with thermal requirements to optimize battery operation and longevity.



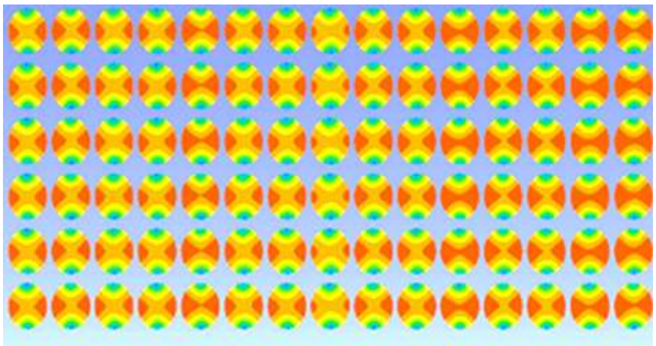
V = 0.1 m/s



V = 0.2 m/s



V = 0.3 m/s



V = 0.4 m/s

Figure 2. Module temperature contours for different velocity inlet

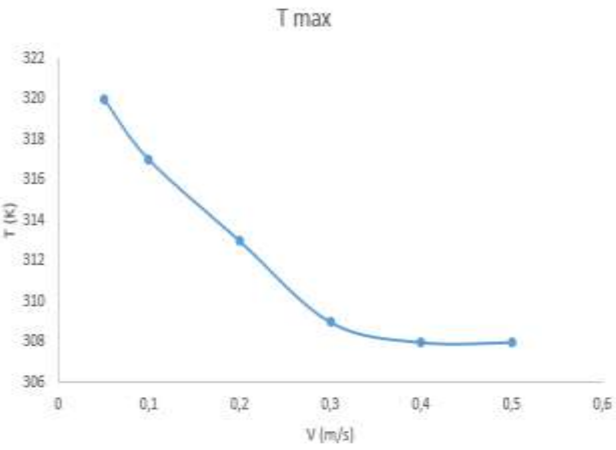


Figure 3. T_{max} of the module as a function of inlet velocity

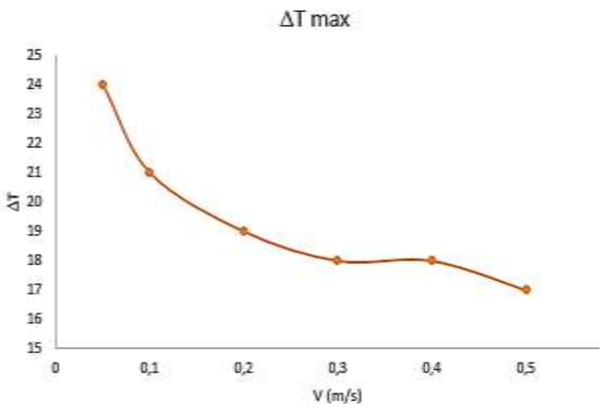


Figure 4. ΔT_{max} of the module as a function of inlet velocity

6.2 Effect of nanofluids on temperature distribution

The study investigated the impact of using nanofluids as coolants, employing three types of nanoparticles (copper, alumina, and fullerene). A Mixture model was employed to simulate the two-phase flow of nanofluids, with water as the primary phase and nanoparticles dispersed in the base liquid as the secondary phase.

Figure 5 illustrates the evolution of temperature difference within the module when nanoparticles are dispersed in water. It demonstrates that nanofluids effectively reduce module temperatures due to significantly enhanced heat transfer facilitated by the high thermal conductivity of nanoparticles. Thermal conductivity, a measure of a material's ability to conduct heat, plays a crucial role in enhancing heat dissipation capacity. Notably, the fullerene/water coolant exhibits superior performance, attributed to fullerene's exceptional thermophysical properties including high thermal conductivity and heat capacity.

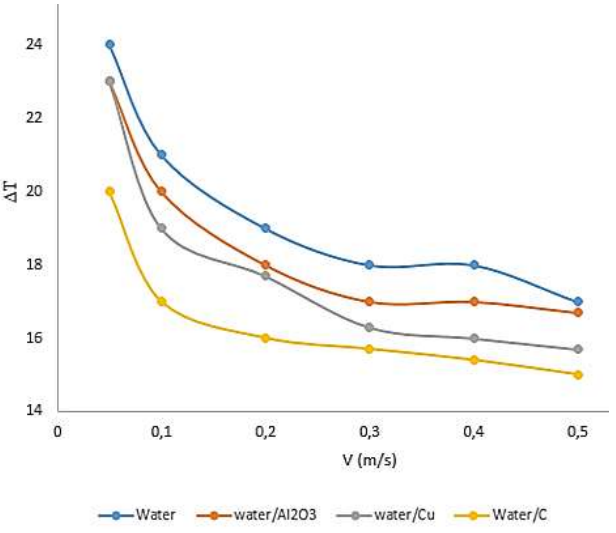


Figure 5. Effect of nanofluids on ΔT_{max} of the module as a function of inlet velocity

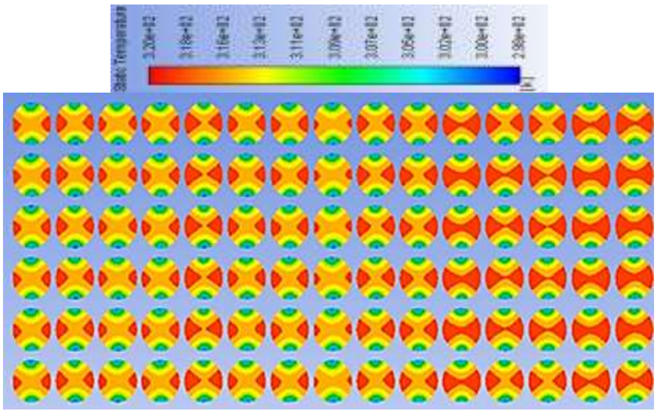


Figure 6. Module temperature contours (cooling fluid: water)

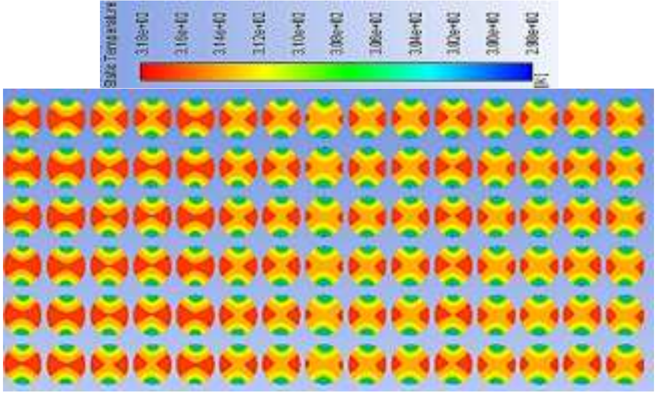


Figure 7. Module temperature contours (cooling fluid: water / Alumina)

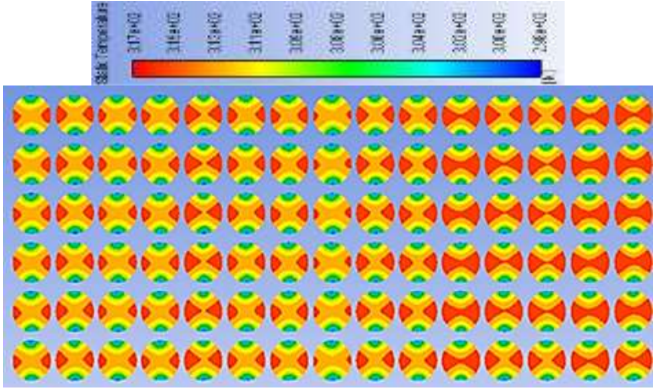


Figure 8. Module temperature contours (cooling fluid: water / copper)

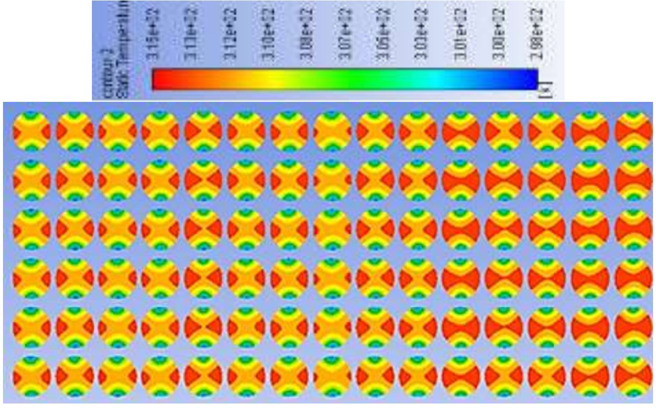


Figure 9. Module temperature contours (cooling fluid: water / Fullerene)

Figures 6-9 depict temperature contours across the module for four different coolants under identical conditions (inlet temperature of 298 K, inlet velocity of 0.3 m/s, and nanoparticle volume fraction of 0.01).

These findings underscore the physical mechanisms underlying nanofluid cooling, emphasizing the importance of nanoparticle selection and concentration in optimizing thermal management strategies for battery systems.fraction 0.01).

6.3 Effect of nanofluids on heat transfer

Figure 10 demonstrates that the Nusselt number increases proportionally with the Reynolds number and is significantly influenced by the physical properties of the fluid utilized. Notably, the use of nanofluids shows a marked enhancement in the Nusselt number.

Figure 11 highlights that the highest Nusselt number was achieved with water/fullerene as the cooling fluid. This notable improvement can be attributed to the exceptional thermal conductivity of fullerene nanoparticles. Thermal conductivity plays a pivotal role in heat transfer efficiency by enabling faster dissipation of heat from the battery module. Fullerene's high thermal conductivity enhances convective heat transfer within the cooling system, leading to more effective cooling performance.

These observations underscore the importance of nanoparticle selection and their impact on enhancing thermal transport properties in nanofluid-based cooling systems. By optimizing fluid composition and flow dynamics, engineers can effectively improve heat dissipation and enhance the overall thermal management of battery systems.

6.4 Effect of nanoparticle volume fraction on temperature distribution

To investigate the impact of fullerene nanoparticle volume fraction on module temperature distribution, the volume concentration was varied from 0.01 to 0.04. The results are depicted in Figure 12, where it is evident that the temperature difference decreases with increasing volume fraction. This reduction indicates that nanofluids effectively contribute to battery cooling.

It is widely recognized in industry that the optimal operating temperature range for Lithium-Ion Batteries (LIBs) is between 20 and 40 °C, with the temperature difference (ΔT) ideally controlled below 6 °C. Effective thermal management, facilitated by nanofluid cooling systems, plays a critical role in maintaining these temperature parameters within safe and efficient limits.

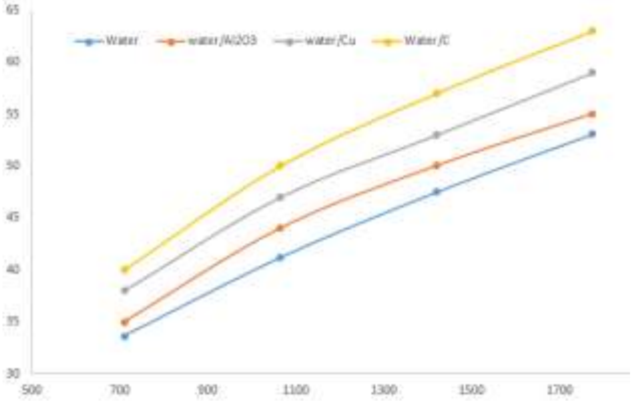


Figure 10. Effect on nanofluids on Nusselt number

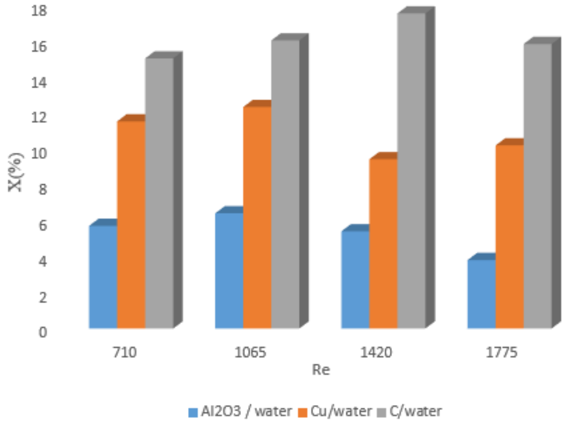


Figure 11. Rate of heat transfer improvement in the presence of nanofluids (ϕ=0.01)

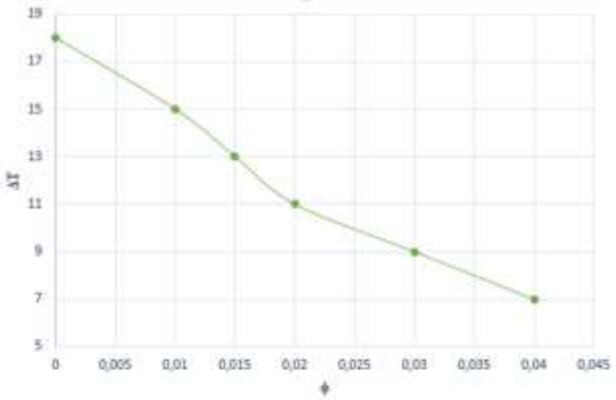


Figure 12. Variation in temperature difference as a function of fullerene nanoparticle volume fraction (Te=298k, V= 0.3 m/s)

7. CONCLUSION

A two-dimensional numerical study was conducted to investigate the cooling of a lithium-ion battery using nanofluids. The study employed a stationary laminar regime and utilized the Mixture multiphase model to simulate two-phase flow. The key findings from the investigation are summarized as follows:

- The temperature distribution within the battery module exhibits non-uniformity at inlet velocities below 0.2 m/s.
- Temperature differences stabilize noticeably for inlet velocities exceeding 0.3 m/s.
- The incorporation of nanofluids leads to a significant reduction in module temperatures.
- Fullerene nanoparticles demonstrate superior cooling performance compared to other nanoparticle types.
- Achieving a nanoparticle volume fraction exceeding 2% results in nearly uniform temperature distribution within the module and reduced cell temperatures.

These results underscore the effectiveness of nanofluids in enhancing battery cooling efficiency, with fullerene nanoparticles proving particularly advantageous. Optimizing nanoparticle concentration and flow dynamics can effectively improve thermal management strategies for lithium-ion battery systems.

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