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Numerical Study on Enhancing the Cooling Efficiency of Lithium-Ion Batteries Using Nano-fluids

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ABSTRACT:
Electric vehicles have become a leading solution to address environmental issues caused by emissions from traditional vehicles. The primary energy source for electric vehicles is lithium-ion batteries. However, these batteries generate significant heat during operation, which poses a heightened risk of explosion. The optimal operating temperature for lithium-ion batteries, to ensure performance, longevity, and safety, ranges from 20 to 40°C. Therefore, a stable and efficient cooling system for the battery is critical during operation. This paper presents a study on the simulation of lithium-ion battery cooling using a nano-coolant. The battery cell is positioned next to a wave-shaped cooling channel, with coolant (water and nanofluids) introduced into the channel at a Reynolds number of 106. Heat generated by the battery is simulated using the NTGK model in ANSYS Fluent, while the cooling process is modeled with the same software. The results indicate that the maximum temperatures in the battery pack when using water, 2% nanofluid, and 3% nanofluid were 320.350°K, 318.606°K, and 317.280°K, respectively.

KEYWORDS: *Lithium-ion battery; nanofluid cooling system; electric vehicle; ANSYS Fluent.*

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I. INTRODUCTION

Developing environmentally friendly vehicles, such as hybrid and fully electric cars, represents a significant trend in automotive research and development to address environmental pollution. Electric vehicles primarily rely on lithium-ion batteries due to their longevity, safety, and durability. However, these batteries generate substantial heat during operation, which not only impacts their performance and lifespan but also poses a risk of fire and explosion in electric vehicles. Numerous studies indicate that the optimal operating temperature for batteries should be maintained between 20°C and 40°C [1]. To maintain this temperature range, an effective cooling system is essential.

Various cooling systems have been investigated to cool the battery, including air cooling, liquid cooling, and phase change material (PCM) cooling. Among these methods, air cooling [2-4] is simple. Nevertheless, achieving a uniform temperature distribution among battery cells poses significant challenges with this approach. Liquid cooling addresses the limitations of air cooling and offers higher cooling efficiency, as the heat transfer coefficient of liquids exceeds that of air[5-7]. Liquid cooling can be categorized and indirect cooling. However, direct cooling is less commonly employed due to its inherent complexity[6,7].PCM cooling has garnered substantial attention in recent research [8]. PCMs exhibit advantageous specific heat properties owing to the latent heat-reing phase transitions. Several case studies [9, 10] demonstrate that this cooling method can effectively maintain the temperature of the battery ever, uniform temperature distribution among the cells remains a challenge.

In recent years, researchers worldwide have increasingly focused on cooling methods using nanofluids. These fluids consist of traditional coolants, such as water, mixed with nanoparticles (e.g., Al_2O_3, Cu, CuO, SiC, ZnO, TiO_2, and SiO_2). Numerous studies have demonstrated that nanofluids enhance heat transfer properties, offering potentially better cooling performance than conventional methods.

This paper aims to investigate the improvement in cooling performance of battery packs using nanofluids. The battery cell is placed adjacent to a wave-shaped cooling channel, with the coolant (water or nanofluids) injected into the channel at a Reynolds number of 106. The heat generated by the battery is simulated using the NTGK model in ANSYS Fluent, while the cooling model is simulated using ANSYS FLUENT software. The results indicate that the maximum temperatures in the battery pack when using water, 2% nanofluid, and 3% nanofluid were 320.350ºK, 318.606ºK, and 317.280ºK, respectively.

II. COMPUTATIONAL DOMAIN AND GOVERNING EQUATIONS

The three-dimensional model of the cooling channel and lithium battery cell, developed using the ANSYS Workbench platform, is presented in Figure 1 (a). The detailed specifications of the 18650-type lithium-ion battery are provided in Table 1. Liquid coolant is introduced at the inlet, flows through the lithium battery pack, and exits through the outlet, enabling effective cooling and heat dissipation. The nanoparticles used in this study were Al_2O_3, and the properties of the nanofluid solution were calculated based on the literature [11]. The thermal and physical properties of the materials used in the study, including water, nanofluids, the cooling channel, and the lithium-ion battery cells are shown in Table 2.

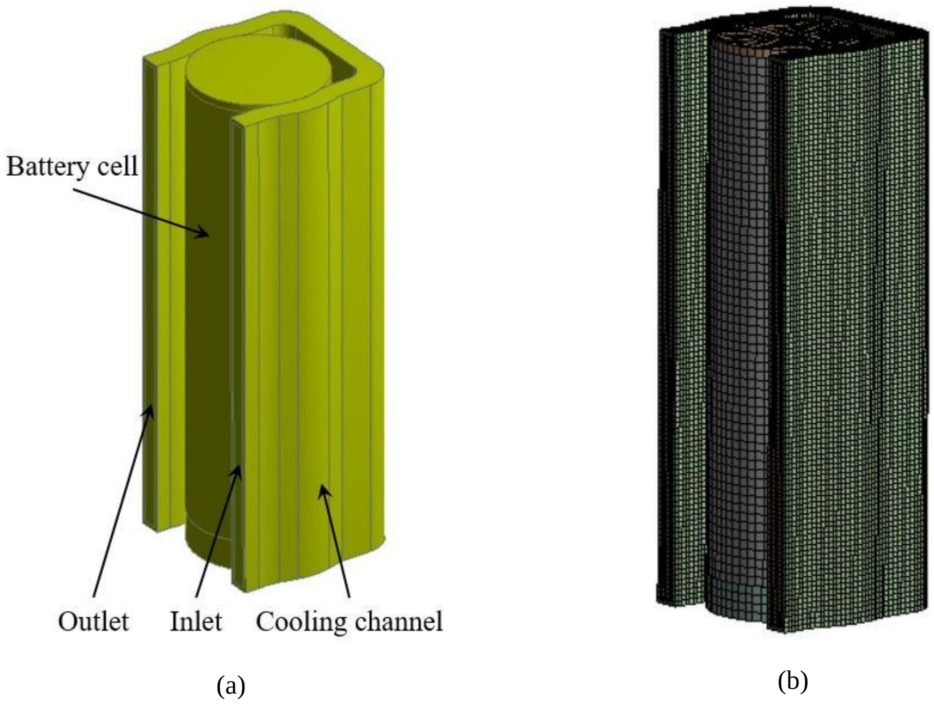


Figure 1: (a) 3D model of cooling channel and Lithium battery celland (b) 3D meshing of cooling channel and Lithium battery cell

Table 1. The properties of 18650 cylindrical Lithium-ion cell

No.	Parameters	Value
1.	Cathode material	$LiFePO_4$
2.	Anode material	Graphite
3.	Electrolyte	Carbonate base
4.	Nominal capacity	1500 mAh
5.	Nominal voltage	3.2V
6.	Dimensions	18mm diameter x 65 mm height

Table 2. Thermal physical properties of materials of the coolant, cooling channel and lithium battery cell.

No.	Parameters	Materials				
		Water	2% Nano-fluid	3% Nano-fluid	Aluminum	Battery
1.	Density (kg/m^3), ρ	998.2	1055.836	1084.654	2719	2018
2.	Heat capacity (J/kgK), c	4128	3931.451241	3816.162046	891	1282
3.	Thermal conductivity (W/mK), k	0.6	0.634	0.652	202.4	2.7
4.	Dynamic viscosity (kg/ms), μ	1.003×10^{-3}	0.001198	0.001332	-	-

The computational domain is discretized using a structured hexahedral mesh, as shown in Fig. 1 (b). Three-dimensional physical models of the battery cell are used for all computational models in this study. To ensure mesh independence, three mesh sizes were tested: 140,783, 265,566, and 500,132 elements, with the mesh density nearly doubling with each refinement. Figure 3 presents the results of the grid independence study, showing the maximum temperature over time for different element counts. The second mesh size (265,566 elements) is used for this study.

The energy conservation equation of the battery is given as follows:

$$\rho_b c_b \left(\frac{\partial T_b}{\partial t}\right) = k_b \left\{\frac{\partial}{\partial x}\left(\frac{\partial T_b}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial T_b}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\partial T_b}{\partial z}\right)\right\} + Q_{gen} \tag{1}$$

where ρ_b, c_b, T_b are the density, heat capacity and temperature of the lithium bat-tery, respectively; k_b is the thermal conductivity of the battery which is assumed to be isotropic; Q_{gen} is the heat generation rate in the battery.In this study, the heat generation of the cylindrical battery at discharge rates of 3Cused the NTGK model in ANSYS Fluent [12].

The energy conservation equation of the coolant is:

$$\rho_l c_l \left(\frac{\partial T_l}{\partial t}\right) + \nabla(\rho_l c_l v T_l) = \nabla(k_l \nabla T_l) \tag{2}$$

where ρ_l, c_l, T_l, k_l, and v are the density, heat capacity, temperature, thermal conductivity and velocity of the liquid coolant, respectively.

The continuous equation and momentum conservation equation of the coolant are given as follows:

$$\nabla v = 0 \tag{3}$$

$$\rho_l \frac{dv}{dt} = -\nabla p + \mu \nabla^2 v \tag{4}$$

The mechanism of heat transfer from the battery to the coolant is as follows: heat generated by the battery is conducted to the cooling channel, and then the heat is carried away by the coolant within the channel through convective heat transfer.

In this context, the rate of convective heat transfer can be expressed by the following equation:

$$Q = Ah(T_c - T_l) \tag{9}$$

where Q represents the rate of heat transfer out of the cooling channel (W), h is heat transfer coefficient (W.m^{-2}K^{-1}), A is the surface area (m^2), T_c is the surface temperature of the cooling channel (^{0}C), and T_l is the temperature of the liquid coolant (^{0}C). In this work, heat convection transfer mode was considered with a coefficient of convection value equal to 10 W/m²K.

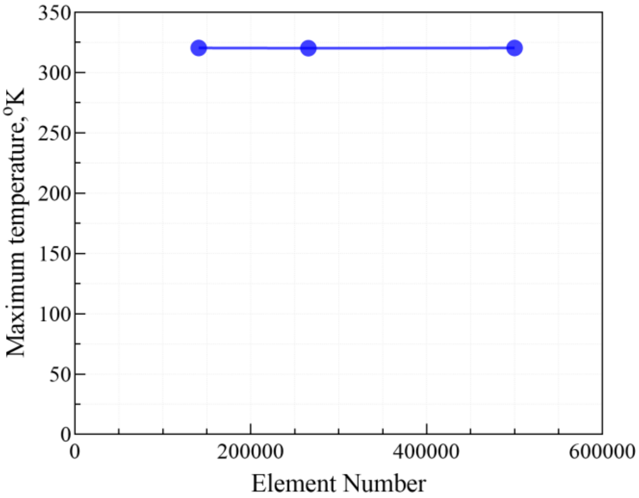
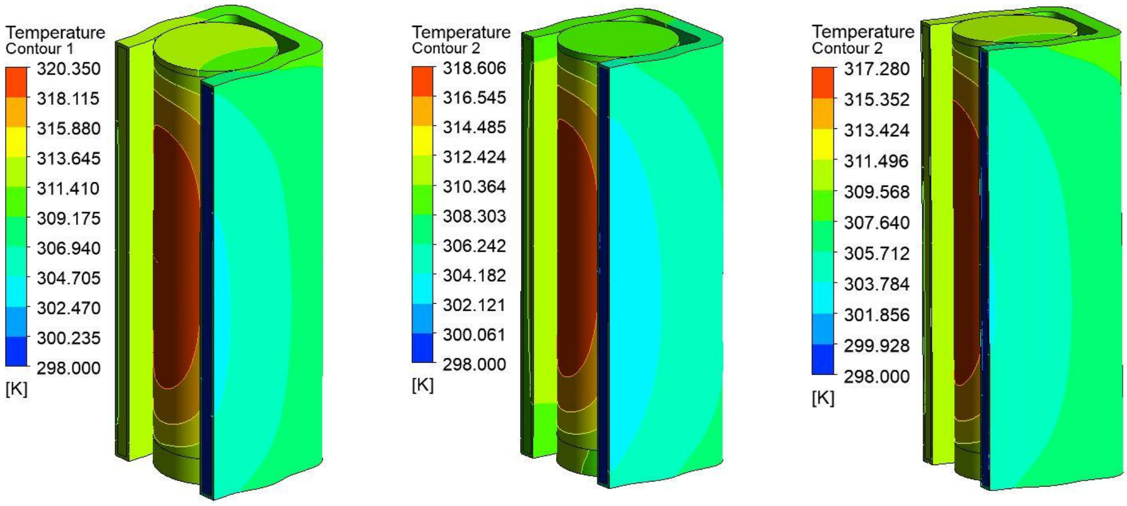
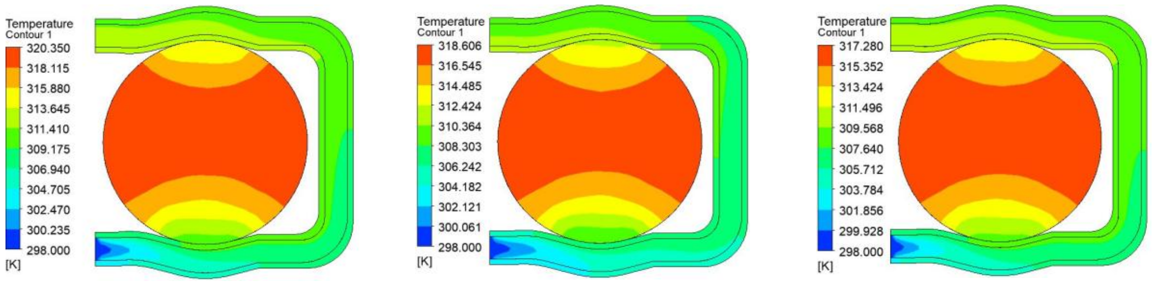


Figure 2. Grid independency test

III.RESULTS AND DISCUSSION

The temperature distribution in the battery pack as a function of the nanoparticle concentration in the coolant is presented in Figure 3. From the figure, the differences in the cooling performance of the coolant are clearly evident. Specifically, when pure water is used, the temperature distribution on the battery pack reaches a maximum of 320.35°K, indicating that the heat dissipation capacity of water in this case is insufficient to effectively lower the temperature. In contrast, when nanofluids with concentrations of 2% and 3% are used, the temperature decreases to 318.606°K and 317.280°K, respectively. This reduction demonstrates that the addition of nanoparticles to the coolant enhances its heat transfer capacity, thereby improving heat dissipation efficiency and more effectively cooling the battery pack. These findings not only confirm the significant role of nanofluid solutions in temperature regulation but also suggest that adjusting the concentration of nanofluids may be a critical factor in optimizing thermal performance in lithium-ion battery cooling systems.





(a) Water (b) 2% Nanofluid (c) 3% Nanofluid

Figure 3. Temperature distribution in lithium battery pack

Figure 4 depicts the impact of nanoparticle concentration on the peak temperature of the battery pack over time. The graph indicates that as the percentage of nanofluid in the cooling system increases from 0% to 3%, the peak temperature of the lithium-ion battery pack significantly decreases. At 0% nanofluid (i.e., in a cooling system without nanofluid), the peak temperature of the battery pack reaches its maximum value. Upon increasing the concentration to 2%, this temperature begins to decline notably. Furthermore, at 3% nanofluid, the peak temperature decreases even more markedly. This reduction in peak temperature with increasing nanofluid concentration can be attributed to the enhanced thermal conductivity of the cooling system, which facilitates faster heat dissipation and reduces the risk of overheating in the battery pack. At higher concentrations, the improved heat dissipation leads to further decreases in peak temperature. Therefore, it can be concluded that increasing the percentage of nanofluid contributes to lowering the peak temperature of lithium-ion battery packs, thereby enhancing the safety and performance of battery systems in practical applications.

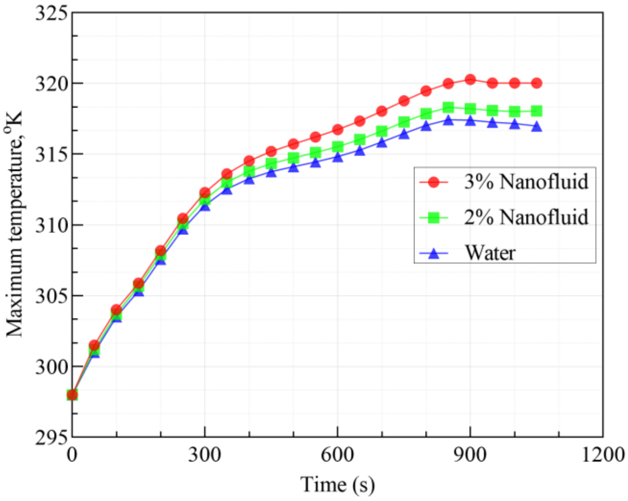


Figure 4. Maximum temperature of battery pack with different percentage of Nano-fluid

V. CONCLUSION

This paper presents a study using ANSYS Fluent software to evaluate the cooling efficiency of the battery pack when utilizing a nanocoolant. A wave-shaped cooling channel is designed to encase the battery, facilitating effective heat dissipation. The study examined the maximum temperature, temperature distribution, and temperature variation over time within the battery pack. The results indicate that increasing the nanoparticle concentration in the coolant to 2% and 3% resulted in a temperature reduction of 3.7% and 6.5%, respectively.

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