# NUMERICAL ANALYSIS FOR THE IMPACTS OF USING NANO-ENHANCED PCM ON THE THERMAL MANAGEMENT OF BATTERY MODULE

by

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The temperature and temperature differences in the battery module rise as a result of the high heat output produced by lithium-ion batteries during operation. This can reduce the operating safety of the battery and reduce the battery life. As a result, the temperature of the batteries must be controlled well by thermal management. Thermal control of batteries employs both active and passive techniques. In this study, PCM, which is a passive cooling system, was used. It has been observed that by placing PCM around the battery, it effectively reduces the peak temperature during the end of discharge in the battery cell. The RT-27 and nano-doped RT-27 with suitable melting range were used as PCM. Four different situations were investigated at 0.3C and 0.5C discharge conditions. These are battery models coated with only the battery, RT-27, coated with nano-RT-27, and coated with RT-27 and nano-RT-27, respectively. The peak temperature was found to be higher when the battery module without PCM was compared to the others. The battery module coated on both surfaces with RT-27 and nano-RT-27 performed better than the other modules. At 0.3 C-Rate, the peak temperature reduces by 1.8 K while it is 4.4 K at 0.5C-Rate.

Key words: PCM, thermal management, battery, nano-PCM, CFD

### Introduction

Today, global warming resulting from GHG emissions has led to the use of lowemission energy sources in many areas. The necessity of reducing dependence on fossil fuels has created a need for an alternative energy source, especially in the automotive sector. Electric vehicle production in the automotive industry is increasing [1]. Electric vehicles have become increasingly used due to their high energy conversion efficiency and zero emissions

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[2]. Batteries are the most common way to store energy in electric vehicles [3]. As the main power source for electric cars, alkaline, sodium, lead, and lithium batteries are employed [4]. Lithium-ion batteries are a widely used power source for electric vehicles [5-7]. The operating ranges of lithium-ion batteries are from -20 °C to 60 °C [8, 9]. The optimal operating range for these batteries is 15 °C to 35 °C [10-12]. However, lithium-ion batteries face the problem of overheating, which limits the rapid development of electric vehicles. Especially in recent years, undesirable situations such as spontaneous combustion or electric vehicles explosion have been encountered [13]. It is therefore critical to ensure that lithium-ion batteries can operate safely and efficiently. Although increasing vehicle performance seems to be the main purpose, battery thermal management (TM) systems are needed to cool batteries in electric vehicles for safety [14-16]. The TM plays an important role in safe operation, high efficiency and long service life in batteries [17]. Passive or active TM systems are available. While an active cooling is designed using air or liquid, a passive system is possible with the use of PCM [18, 19].

The PCM used for battery TM system are passive systems. It does not impose an additional burden on system operation like other active methods. The PCM are materials in which thermal energy is stored in the form of latent heat [20]. When the temperature of the environment increases, PCM undergoes phase changes such as melting and solidification. The phase change process is endothermic. The PCM absorbs heat at this time. When the substance reaches the phase change temperature, it begins to melt and the temperature remains constant until this process is over [21]. It is considered as a disadvantage that PCM have low thermal conductivity. This situation can be improved by adding nano-sized particles to these materials [22]. Generally, metal oxides and metals are used an nanoparticles. Metal oxides are more preferred due to their properties such as better stability, low cost and reliable performance [23].

Research on the use of PCM for TM of batteries is increasing nowadays. Wang *et al.* [24] noted that lithium-ion batteries generate a lot of heat during operation, negatively affecting battery capacity, lifespan and operating safety. In their study, they designed a passive and low-cost TM system using a PCM with a battery. The thermal conductivity, viscosity, latent heat and thickness, which are the design parameters of the PCM layer, were numerically investigated. It has been observed that the temperature drops effectively at the end of the discharge in the battery. As a result, at the end of 5C discharge, the temperature was reduced from 320.10 K to 316.84 K. It has been emphasized that PCM thickness greater than 6 mm will impair TM performance. Fan *et al.* [14] suggested the use of metal-finned PCM for battery TM. The study was carried out numerically with the ANSYS FLUENT program. The use of metal-finned PCM has been shown to further improve uptime compared to PCM alone.

Ping *et al.* [25] proposed PCM and fin system for the TM of the LiFePO<sub>4</sub> battery module. The effects of PCM type, PCM thickness, fin spacing, fin thickness on cooling performance were numerically investigated. As a result, it has been observed that the surface temperature of the battery is below 51 °C at 3C discharge rate in the optimum design. Jilte *et al.* [26] emphasized that an efficient battery cooling system is necessary for the safe use of electric cars. For this purpose, they presented a new design by connecting liquid channels to the PCM layer around the cylindrical battery. In this way, heat distribution can be achieved from the PCM layer to both the environment and the convection air. As a result, they were able to keep the battery temperature below 41.2 °C even in high ambient temperatures such as 40 °C. Safdari *et al.* [27] used a hybrid system consisting of passive PCM and active air cooling for TM of the battery. The system is designed in three ways: circular, rectangular, and hexagonal in equal

volumes surrounding the battery cell. Latent heat has been found to be advantageous in the TM of the battery and the circular PCM configuration works best. Verma et al. [28] aimed to passively cool the battery by using PCM of different thicknesses. For this purpose, 3 mm, 7 mm, 9 mm, and 12 mm thick capric acid were used. In the study carried out in environments with 294 K and 323 K temperatures, it was observed that the maximum temperature in the battery was reduced to 305 K with the 3 mm thick design. Sun et al. [4] suggested that the low heat conduction disadvantage of PCM can be solved by adding fins. The fin model has been shown to improve battery runtime. When the model with fins is compared with the model without it, the operating time is improved by 157%, 189%, and 238% at ambient temperatures of 20 °C, 30 °C, and 40 °C, respectively. The study was carried out numerically and experimentally. Bais et al. [29] examined the reduction of the maximum temperature value by using the RT-42 PCM for the safe operation of lithium-ion batteries at a discharge rate of 3C, which is three times the normal value. However, due to the low thermal conductivity of RT-27, it was noted that the peak temperature was reduced by using it together with  $Al_2O_3$  nanoparticles. The temperature of the battery, which is at risk of burning above 50 °C under normal conditions, was reduced to 42.77 °C by using Al<sub>2</sub>O<sub>3</sub>/RT-42. Sazvar et al. [30] performed a numerical study on the cooling of the battery using PCM, which is a passive battery cooling system. Due to the low heat conduction of PCM, nanoparticles in various proportions have been used. The results showed that the heat transfer was 48% better with the use of nanoparticles. Mitra et al. [31] noted that PCM cannot keep battery temperatures within safe ranges due to their low thermal conductivity. In their studies, metal and carbon-based thermal conductivity enhancers were examined. As a result of the study, it was seen that using carbon nanofiber gave better results than others. Yang et al. [32] emphasized that lithium-ion batteries are sensitive to high temperatures and their TM should be done. The study was made as a compilation to examine the studies on this subject. It has been emphasized that PCM can be used as a passive system for TM of the battery. They suggested adding nanoparticles due to the PCM low thermal conductivity.

Literature studies have shown that PCM can be used for TM of batteries. In this study, it is aimed to control the peak temperature at the end of the discharge by coating PCM and nano-PCM on the lithium-ion battery in various arrangements. To the best of authors' knowledge such a comparison has never been performed. If the peak temperature is reduced and temperature uniformity is maintained, the operating time and safety of the battery can be improved. The RT-27 was used as PCM because of its suitable melting ranges. The 0.01 and 0.03 cooper nanoparticles were used as nanoparticles. Four different models are presented for analysis. These are only models coated with battery, PCM, coated with nano-PCM and coated with two different surfaces (PCM and nano-PCM). Analyzes were performed numerically at 0.3C and 0.5C discharge rates. Performance improvement of the battery module with nano-enhanced PCM was analyzed for different arrangement of PCM and nano-PCM while the outcomes will be beneficial for the thermal design and optimization studies related to the cooling system design of battery packs.

### Numerical model

Four different models are designed for TM of the battery. These are only models coated with battery, PCM, coated with nano-PCM, and coated with two different surfaces (PCM and nano-PCM). The battery has geometry of 20 mm wide, 30 mm high, and 3 mm thick. The coating thickness was chosen as 1 mm. Figure 1 shows the geometries of all models. Analyses were made for 0.3C and 0.5C discharge rates for different models.

A lithium-ion battery module was used as a battery. The RT-27 was used as PCM because it has suitable melting ranges. Thermophysical properties of the PCM used in the models are given in tab. 1.



Figure 1. Battery models; (a) battery only, (b) coated with PCM, (c) coated with nano-PCM, and (d) coated on two sides (PCM and nano-PCM)

Table 1. Thermophysical properties of RT-27 [33]		
Melting range	28-30 °C	
Latent Heat	179 kJ/kg	
Solid state heat storage capacity	1800 J/kgK	
Liquid heat storage capacity	2400 J/kgK	
Solid state thermal conductivity	0.24 W/mK	
Liquid thermal conductivity	0.15 W/mK	
Constant density in solid state	870 kg/m <sup>3</sup>	
Constant density in liquid state	760 kg/m <sup>3</sup>	
Liquid dynamic viscosity	$3.42 \times 10^{-3}$ kg/ms	

Thermophysical properties of nano-PCM used in the numerical study were presented in eqs. (9)-(13). They were obtained separately for 0.01 and 0.03 nanoparticles while the thermophysical properties for of nano-enhanced PCM are given in tab. 2.

	Table 2.	Thermo	physical	properties	of 0.01	and 0.03	Nano-PCM
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Property	Solid volume fraction $-0.01$	Solid volume fraction $-0.03$	
Density	841.94 kg/m <sup>3</sup>	1005.82 kg/m <sup>3</sup>	
Thermal conductivity	0.247 W/mK	0.26 W/mK	
Heat storage capacity	2185 J/kgK	1872 J/kgK	

# Governing equations

The study was carried out using the Newman, Tiedemann, Gu and Kim (NTGK) electrochemical model MSMD module in the ANSYS FLUENT package program. Energy, melting solidification and MSDM models were used in the study. A 30 mm  $\times$  20 mm  $\times$  3 mm prismatic battery is designed for operation. The 1 mm thick PCM and nano-PCM were used as coatings.

The numerical study was carried out at 300 K ambient temperature. The battery models shown in fig. 1 were considered. The behavior of PCM can be analyzed by methods based on temperature and enthalpy. In the temperature-based method, temperature is treated as a dependent variable and the solid-liquid interface is expressed separately [34]. In the enthalpy-based method, the solid-liquid interface is not expressed separately. It can be studied similarly to a single phase [4, 27, 35].

The NTGK model is an empirical electrochemical model which can be found in the FLUENT software. The volumetric flow transfer rate is specified by using [34]:

$$j_{ECh} = \alpha Y [U - (\varphi_+ - \varphi_-)] \tag{1}$$

where  $j_{ECh}$  denotes the volumetric flow and  $\alpha$  – the specific area of the electrode plate. Here,  $\varphi_+$  ve  $\varphi_-$  are the positive and negative electrodes while *U* and *Y* represent the parameters for the functions of the discharge depth (DoD). The voltage current response curve for a certain battery can be collected experimentally and then identified by fitting a curve to the data. The following formulation has been adopted as:

$$Y = \left[\sum_{5}^{n=0} a_n \left(DoD\right)^n\right] \exp\left[-C_1\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right]$$
(2)

$$U = \left[\sum_{3}^{n=0} b_n \left(DoD\right)^n\right] - C_2 \left(T - T_{\text{ref}}\right)$$
(3)

where  $C_1$  and  $C_2$  represent the NTGK model's specific parameters.

In the PCM-domian, conservation equations of mass, momentum, and energy are expressed as:

Continuity equation

$$\frac{\partial(\rho_{\rm PCM})}{dt} + \frac{\partial(\rho_{\rm PCM}u)}{dx} + \frac{\partial(\rho_{\rm PCM}v)}{dy} = 0$$
(4)

Momentum Equation

$$\frac{\partial(\rho_{\rm PCM}u)}{\partial t} + \frac{\partial(\rho_{\rm PCM}u^2)}{\partial x} + \frac{\partial(\rho_{\rm PCM}uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{d}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) + \rho g + S$$
(5)

**Energy Equation** 

$$\frac{\partial \left(\rho_{\text{PCM}}h_{e}\right)}{\partial t} + \frac{\partial \left(\rho_{\text{PCM}}uh_{e}\right)}{\partial x} + \frac{\partial \left(\rho_{\text{PCM}}vh_{e}\right)}{\partial y} = \frac{\partial}{\partial x}\left(k_{\text{PCM}}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{\text{PCM}}\frac{\partial T}{\partial y}\right)$$
(6)

Energy equations for PCM according to enthalpy porosity approach:

$$H = h_e + \Delta H \tag{7}$$

$$h_e = h_{\rm ref} + \int_{T_{\rm ref}}^{T} C_p dT \tag{8}$$

where  $h_e$  is the sensible heat and  $h_{ref}$  – the reference enthalpy at the  $T_{ref}$  temperature.

When the PCM reaches its melting temperature, its latent heat is expressed as:

$$\Delta H = \beta L \tag{9}$$

where  $\beta$  stands for liquid fraction.

$$\beta = \begin{cases} 0, & T < T_s \\ \frac{T - T_s}{T_l - T_s}, & T_s < T < T_l \\ 1, & T > T_l \end{cases}$$
(10)

The ambient temperature and heat transfer coefficient were taken as 300 K and 5 W  $/m^2$ K. It is assumed that there is no heat loss at the poles' extremes. In this study, battery models coated with PCM and nano-PCM are designed for TM of batteries. Copper was used as nanoparticle. Density, specific heat, latent heat and thermal conductivity of nano-PCM were calculated with the following relations [22, 36]:

$$\rho_r = (1 - \varphi) + \frac{\rho_P}{\rho_{\text{PCM}}}\varphi \tag{11}$$

$$\left(\rho C_{p}\right)_{r} = (1-\varphi) + \frac{\left(\rho C_{p}\right)_{p}}{\left(\rho C_{p}\right)_{PCM}}\varphi$$
(12)

$$L_{fPCM} = \frac{(1-\varphi)(\rho L)_{PCM}}{\rho_{fPCM}}$$
(13)

$$k_{r} = \frac{k_{p} + 2k_{PCM} - 2\varphi(k_{PCM} - k_{p})}{k_{p} + 2k_{PCM} - \varphi(k_{PCM} - k_{p})}$$
(14)

### Solution method

To solve the governing equations with mentioned boundary and initial conditions, the finite volume method is applied. The governing equation is solved with ANSYS FLUENT solver. The SIMPLE algorithm was used for pressure-velocity coupling while convective terms in the momentum and energy equations were discretized using the QUICK (Quadratic Upstream Interpolation for Convective Kinematics) technique. Under relaxation parameters for pressure and melting fraction were taken as 0.2 and 0.3. The assumption of solution convergence occurs when the proportional error drops to less than  $10^{-7}$ .

### Mesh independence study

Mesh structures must be assigned to battery models in order for the analysis to be performed properly. The grid structures assigned for the four different models are shown in fig. 2. Mesh statistics are as follows:

- Battery model only Nodes: 18193, Elements: 14832.
- Nodes: 40963, Elements: 110785 in models coated with PCM and nano-PCM.
- Nodes: 36127, Elements: 26352 in models with two different coatings (with PCM and nano-PCM).

In order to control the effect of grid size on the result and reduce the computation time, a grid independence study was performed only in the battery model. For the test, mesh

structures with element sizes of 1 mm, 0.75 mm, 0.5 mm, and 0.25 mm were formed for the uncoated only battery model and the maximum temperatures at the end of the discharge were compared. Table 3 shows the comparison results of the peak temperature with different grid sizes when PCM and PCM-nano are used for coating of the battery surfaces.



Figure 2. Mesh of models; (a) only the battery, (b) coated with PCM, (c) coated with Nano-PCM, and (d) coated on two surfaces (PCM and nano-PCM)

interent grid sizes by using 1 civi and i and i civi (0.05 solid volume fraction)		
Grid type	Element number	Maximum temperature
G1	2321	309.12 K
G2	4124	308.25 K
G3	8356	305.24 K
G4	16128	303.98 K
G5	26352	303.47 K
G6	85124	303.42 K

Table 3. Grid independence test results; maximum temperature variation for different grid sizes by using PCM and Nano-PCM (0.03 solid volume fraction)

### Code validation

Validation of the code is made by using the numerical results of Siruvuri and Budarapu [37]. In the study, cooling system for BTM of a battery pack of five cells was designed. For a constant 5C charge/discharge peak temperature variation at three different flow rates of the cooling system was shown in fig. 3. At the lowest flow rate, the variation amount is 9.04% while for the other flow rates deviations between the results were found below 2%.





#### **Results and discussion**

The main purpose of this study is to surround the batteries with PCM and nano-PCM so that they can operate in the safe temperature range. In this way, at the end of the discharge, the maximum temperature is reduced and safe operating temperatures can be obtained. Analyzes were performed separately for four different models.

### Results for C-Rate of 0.3

All models have been analyzed for the battery with a discharge rate of 0.3C-Rate, and the temperature contours are given in fig. 4. Peak value of the temperature drops when PCM is used, and its value is further reduced by using nano-enhanced PCM. Time-dependent temperature graphs are presented in fig. 5 for all models. At the end of the discharge, PCM and nano-PCM melt with increasing temperature. The PCM ability to absorb heat during phase change appears to heat up less than the PCM or nano-PCM uncoated model.

As the time evolves until t = 720, significant temperature drops are obtained when PCM or nano enhanced PCM are imposed. By using PCM and inclusion of nanoparticles significantly alters the temperture dynamics. Comparison of maximum temperature for different cases is presented in tab. 4. There is 1 K temperature drop is found when PCM is imposed. An additional 0.4 K temperature drop is found by using nanoparticles. The loading amount has very slight impact on the overall performance. The best case is obtained when using PCM and nano enhanced PCM together while 1.8 K temperate drop is found as compared to reference case.

Battery model without PCM	305.212 K
Battery model with PCM	304.227 K
Battery model with nano-PCM at 0.01 ratio	303.877 K
Battery model with nano-PCM at 0.03 ratio	303.859 K
Two-surface coated battery model with PCM and 0.01 nano-PCM	303.473 K
Two-surface coated battery model with PCM and 0.03 nano-PCM	303.466 K

Table 4. Maximum temp	erature values for	or 0.3 C-Rate	discharge value
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#### Results for C-Rate Value of 0.5

The configuration with 0.5C-Rate is examined and temperature contours are given in fig. 6. Peak value of the temperature is higher for all cases as compared to case of 0.3C-Rate. When using PCM and nano enhanced PCM, significant reduction of the peak temperature is obtained while temperature variation becomes more uniform as compared to reference case.

Time dependent variation of maximum temperature is shown in fig. 7 for different configurations. A saturation type curve is seen for all cases while the discrepancies between cases of without PCM and others are higher in the interval t=600-1000. As it is seen in tab. 5, max temperature drop of 2.5 K is obtained by using PCM. A further 1 K temperature drop is seen by using nano enhanced PCM at the loading of 0.03. However, the best configuration is seen when combined utilization of PCM and non-enhanced PCM are used. In this case, peak temperature drop of 4.4 K is obtained as compared to reference case. As compared to lower C-rate case, impact of using PCM and nano-enhanced PCM on the TM is more effective. It is observed that at two different C-rates, coating battery surfaces with nano-enhanced PCM has higher peak temperature as compared to case using PCM and nano-enhanced PCM together. As

nano-PCM are not cost-effective solution, using this hybrid arrangement has benefits not only for reducing the peak temperature more and providing temperature uniformity, it also provides cost-effective solution for battery TM.



Figure 4. Temperature Contours; (a) battery only, (b) coated with PCM, (c) coated with 0.01% nano-PCM, (d) 0.03% nano-PCM, (e) two-sided coated (PCM and 0.01 nano-PCM), and (f) two-sided coated (PCM and 0.03 nano-PCM)

Table 5. Maximum tem	perature values for 0.5	C-Rate discharge value
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Battery model without PCM	317.04 K
Battery model with PCM	314.45 K
Battery model with nano-PCM at 0.01 ratio	313.53 K
Battery model with nano-PCM at 0.03 ratio	313.50 K
Two-surface coated battery model with PCM and 0.01 nano-PCM	312.39 K
Two-surface coated battery model with PCM and 0.03 nano-PCM	312.37 K



Figure 5. Time-dependent temperature graph at 0.3 C-Rate discharge rate



Figure 6. Temperature contours; (a) battery only, (b) coated with PCM, (c) coated with 0.01% nano-PCM, (d) 0.03% nano-PCM, (e) two-sided coated (PCM and 0.01 Nano-PCM), and (f) two-sided coated (PCM and 0.03 nano-PCM)



Figure 7. Time-dependent temperature graph at 0.5 C-Rate discharge rate

#### Conclusion

In this study, different arrangements of using PCM and nano-enhanced PMC are considered for battery TM system. Maximum temperature was increased and inhomogeneous thermal distribution were observed when the loading rate was increased. Therefore, suitable cooling systems should be designed to eliminate uneven thermal distribution and reduce the peak value of the temperature. Best model was achieved when covering the battery with PCM and nano-enhanced PCM. As compared to reference case, at the C-Rate of 0.3, the peak temperature drops by about 1.8 K while it is reduced by about 4.4 K at 0.5 C-Rate. Temperature uniformity is also provided by using PCM and nano-enhanced PCM. A cost-effective solution if proposed by using PCM and nano-enhanced PCM together for battery TM. The study can be extended to include different arrangement of modules, thickness of the coating material, the type of nano-particle and phase-change material, and different discharge speeds. A liquid cooling system may also be incorporated with nano-enhanced PCM for better TM and effective cooling for battery modules.

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