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

Fatih SELİMEFENDİGİL[1,2], Fethi A. ÇAKMAK[2], Hakan F. ÖZTOP[3*]

[1]Department of Mechanical Engineering, College of Engineering, King Faisal University, Al Ahsa 31982, Saudi Arabia

[2]Department of Mechanical Engineering, Manisa Celal Bayar University, Manisa, Turkey

[3]Department of Mechanical and Nuclear Engineering, College of Engineering, University of Sharjah, 27272 Sharjah, United Arab Emirates

[4]*Department of Mechanical Engineering, Techology Faculty, Fırat University, Elazığ, Turkey

*Corresponding author, E-mail: hfoztop1@gmail.com

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, phase change material, which is a passive cooling system, was used. It has been observed that by placing phase change material around the battery, it effectively reduces the peak temperature during the end of discharge in the battery cell. RT-27 and nano-doped RT-27 with suitable melting range were used as phase change materials. 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*

1. Introduction

Today, global warming resulting from greenhouse gas emissions has led to the use of low-emission 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[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 ℃ to 60 ℃ [8, 9]. The optimal operating range for these batteries is 15℃ to 35℃ [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 systems are needed to cool batteries in electric vehicles for safety [14-16]. Thermal management plays an important role in safe operation, high efficiency and long service life in batteries[17]. Passive or active thermal management (TM) systems are available. While an active cooling is designed using air or liquid, a passive system is possible with the use of phase change materials (PCMs) [18, 19].

PCMs used for battery TM system are passive systems. It does not impose an additional burden on system operation like other active methods. PCMs 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 PCMs 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 PCMs 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 phase-changing material 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 $LiFePO_4$ 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^{o}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 PCMs 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 ^{o}C, 30 ^{o}C and 40 ^{o}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 ^{o}C under normal conditions, was reduced to 42.77 ^{o}C by using Al_2O_3/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 PCMs, 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 PCMs 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 PCMs can be used as a passive system for TM of the battery. They suggested adding nanoparticles due to the PCM's low thermal conductivity.

Literature studies have shown that PCMs 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. RT-27 was used as PCM because of its suitable melting ranges. 0.01 and 0.03 Cu 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-PCMs while the outcomes will be beneficial for the thermal design and optimization studies related to the cooling system design of battery packs.

2. 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 0.3 C and 0.5 C discharge rates for different models.

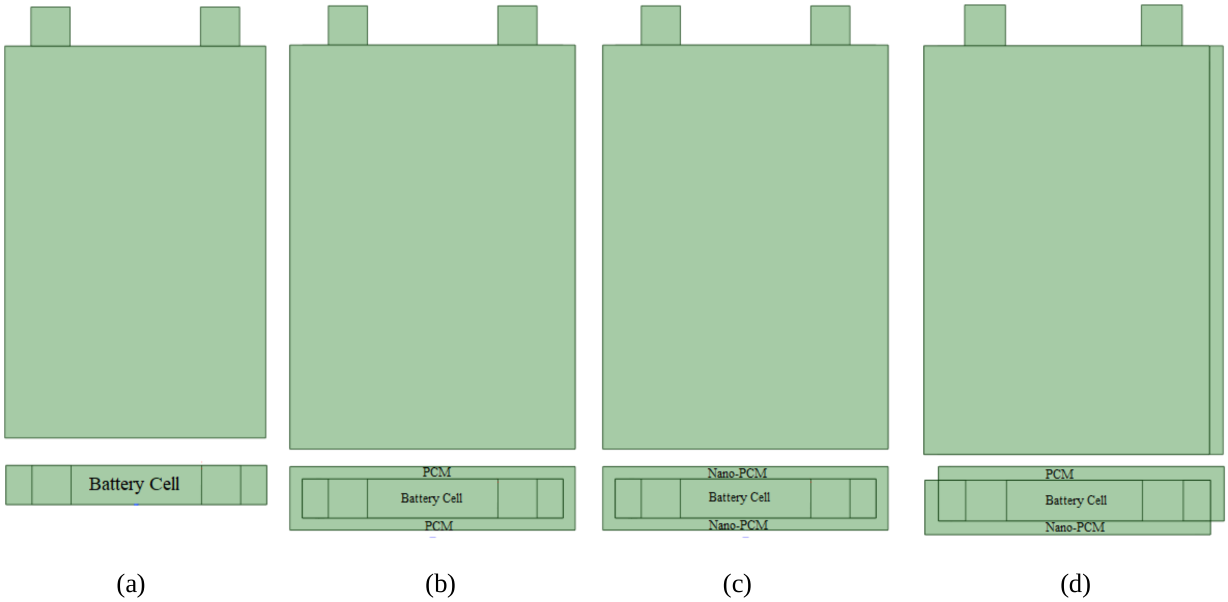


Figure 1. Battery models a) Battery only b) Coated with PCM c) Coated with Nano-PCM d) Coated on two sides (PCM and Nano-PCM)

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

Table 1. Thermophysical properties of RT-27 [33]

Melting range	28 - 30 ^{o}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^3
Constant density in liquid state	760 kg/m^3
Liquid dynamic viscosity	3.42x10^{-3} kg/ms

Thermophysical properties of nano-PCM used in the numerical study were presented in Eqns. (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 Table 2.

Table 2. Thermophysical properties of 0.01 and 0.03 Nano-PCM

Property	Solid volume fraction- 0.01	Solid volume fraction- 0.03
Density	841.94 kg/m^3	1005.82 kg/m^3
Thermal conductivity	0.247 W/mK	0.26 W/mK
Heat storage capacity	2185 J/kgK	1872 J/kgK

2.1. 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 x 20 mm x 3 mm prismatic battery is designed for operation. 1mm thick PCM and nano-PCM were used as coatings. The numerical study was carried out at 300K ambient temperature. The battery models shown in Figure 1 were considered. The behavior of phase-changing materials 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 the following equation [34]:

$$j_{ECh} = aY[U - (\varphi_+ - \varphi_-)] \qquad (1)$$

where j_{ECh} denotes the volumetric flow, α is the specific area of the electrode plate. Here, φ_+ ve φ_- 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:

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

$$U = \left(\sum_{3}^{n=0} b_n (DOD)^n\right) - C_2(T - T_{ref}) \qquad (3)$$

where, C1 and C2 reprsent the NTGK model’s specific parameters.

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

Continuity Equation:

$$\frac{d(\rho_{pcm})}{dt} + \frac{d(\rho_{pcm}u)}{dx} + \frac{d(\rho_{pcm}v)}{dy} = 0 \tag{1}$$

Momentum Equation:

$$\frac{d(\rho_{pcm}u)}{dt} + \frac{d(\rho_{pcm}u^2)}{dx} + \frac{d(\rho_{pcm}uv)}{dy} = -\frac{dp}{dx} + \frac{d}{dx}\left(\mu\frac{du}{dx}\right) + \frac{d}{dy}\left(\mu\frac{du}{dy}\right) + \rho g + S \tag{2}$$

Energy Equation:

$$\frac{d(\rho_{pcm}h_e)}{dt} + \frac{d(\rho_{pcm}uh_e)}{dx} + \frac{d(\rho_{pcm}vh_e)}{dy} = \frac{d}{dx}\left(k_{pcm}\frac{dT}{dx}\right) + \frac{d}{dy}(k_{pcm}\frac{dT}{dy}) \tag{3}$$

Energy equations for PCM according to enthalpy porosity approach:

$$H = h_e + \Delta H \tag{4}$$

$$h_e = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{5}$$

Here h_e is the sensible heat and h_{ref} is the reference enthalpy at the Tref temperature.
When the PCM reaches its melting temperature, its latent heat is expressed as:

$$\Delta H = \beta L \tag{6}$$

where β stands for liquid fraction.

$$\beta = \begin{cases} 0, & T < T_s \\ \dfrac{T - T_s}{T_l - T_s}, & T_s < T < T_l \\ 1, & T > T_l \end{cases} \tag{7}$$

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 (Cu) was used as nanoparticle. Density, specific heat, latent heat and thermal conductivity of nano-PCM were calculated with the following relations [22, 36]:

$$\rho_r = (1 - \varphi) + \frac{\rho_P}{\rho_{PCM}} \varphi \tag{8}$$

$$(\rho C_p)_r = (1 - \varphi) + \frac{(\rho C_p)_p}{(\rho C_p)_{PCM}} \varphi \tag{9}$$

$$L_{fPCM} = \frac{(1 - \varphi)(\rho L)_{PCM}}{\rho_{fPCM}} \tag{11}$$

$$k_r = \frac{k_p + 2k_{PCM} - 2\varphi(k_{PCM} - k_p)}{k_p + 2k_{PCM} - \varphi(k_{PCM} - k_p)} \tag{12}$$

2.2. Solution Method

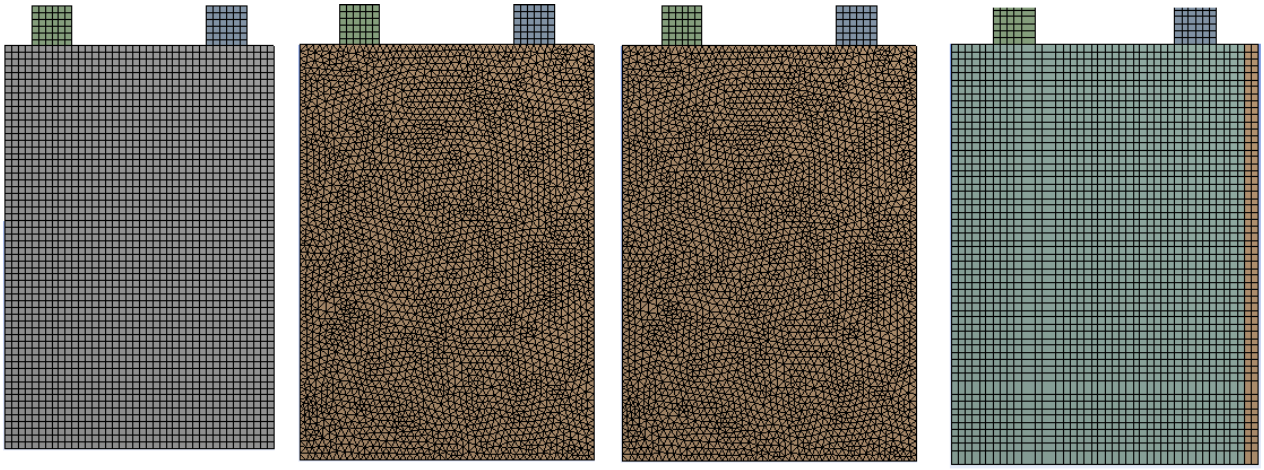
To solve the governing equations with mentioned boundary and intial conditions, the finite volume method (FVM) is applied. The governing equation is solved with ANSYS Fluent solver. SIMPLE algorithm was used for pressure-velocity coupling while convective terms in the momentum and energy equations were 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}.

2.3. 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 Figure 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)



(a) (b) (c) (d)

Figure 2. Mesh of models a) Only the battery b) Coated with PCM c) Coated with Nano-PCM d) Coated on two surfaces (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.

Table 3. Grid independence test results. Maximum temperature variation for different grid sizes by using PCM and Nano-PCM (0.03 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

2.4. Code Validation

Validation of the code is made by using the numerical results of Siruvuri and Budarapu [35]. 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 Figure 3. At the lowest flow rate, the variaition amount is 9.04% while for the other flow rates deviations between the results were found below 2%.

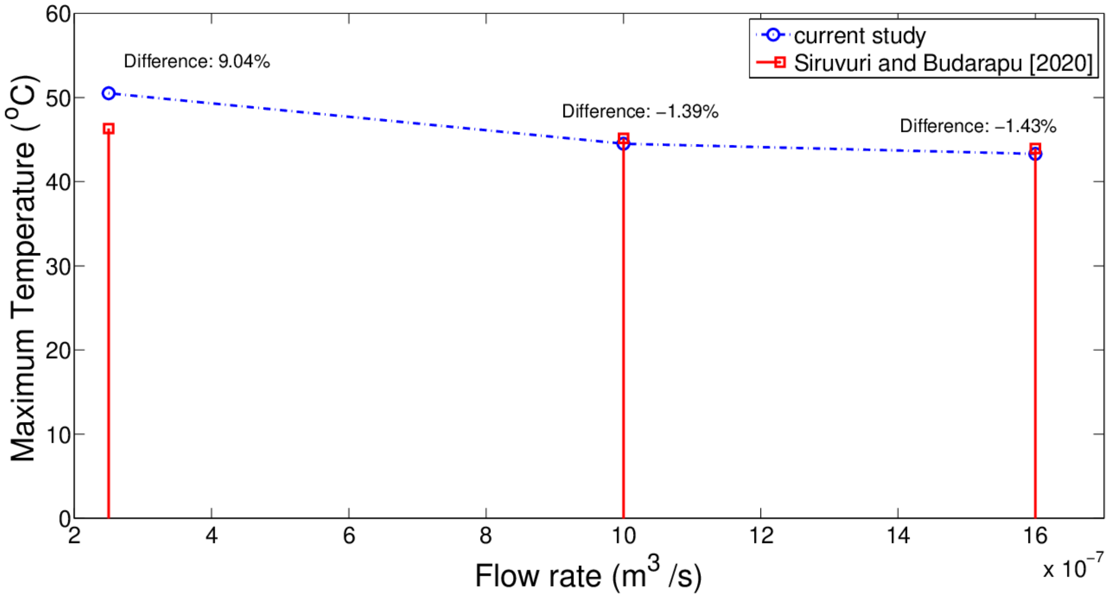


Figure 3. Comparison of peak temperature of the battery module by using the cooling system in Ref. [37] at various flow rates

3. 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.

3.1. Results for C-Rate of 0.3

All models have been analyzed for the battery with a discharge rate of 0.3 C-Rate, and the temperature contours are given in Figure 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 Figure 5 for all models. At the end of the discharge, PCM and nano-PCM melt with increasing temperature. The PCM's 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 Table 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.

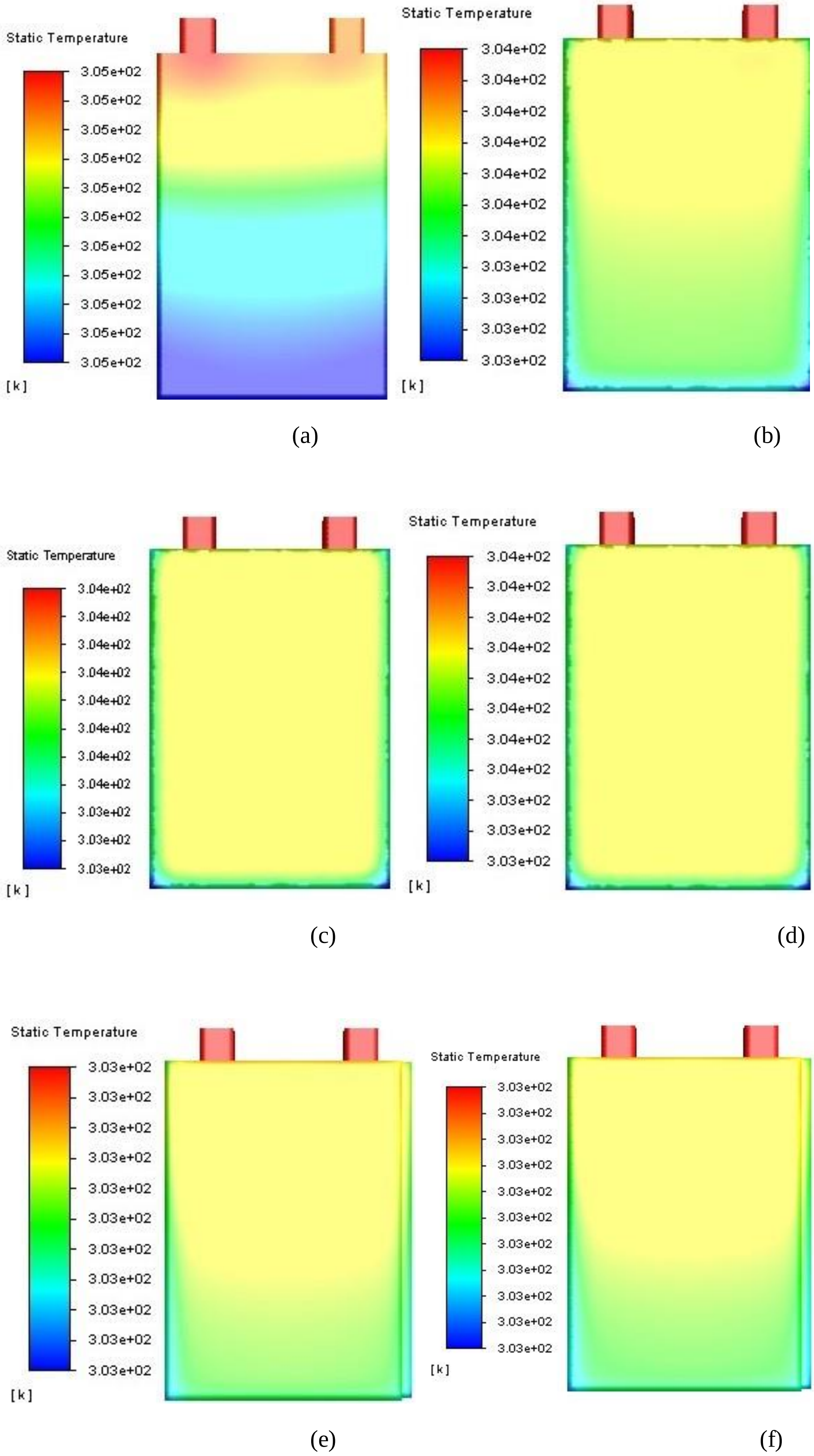


Figure 4. Temperature Contours a) Battery only b) Coated with PCM c) Coated with 0.01 percent Nano-PCM d) 0.03 percent Nano-PCM e) Two-sided coated (PCM and 0.01 Nano-PCM) PCM) f) Two-sided coated (PCM and 0.03 Nano-PCM)

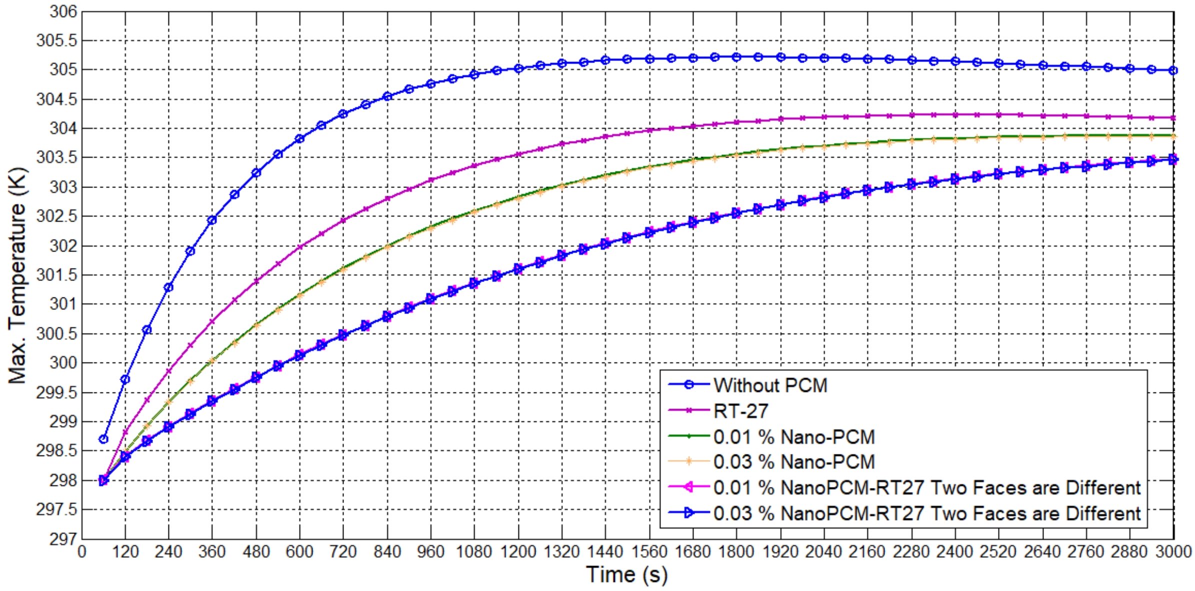


Figure 5. Time-dependent temperature graph at 0.3 C-Rate discharge rate

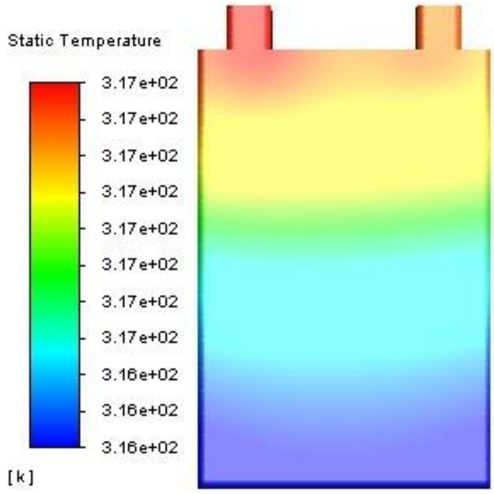
Table 4. Maximum temperature values for 0.3 C-Rate discharge value

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

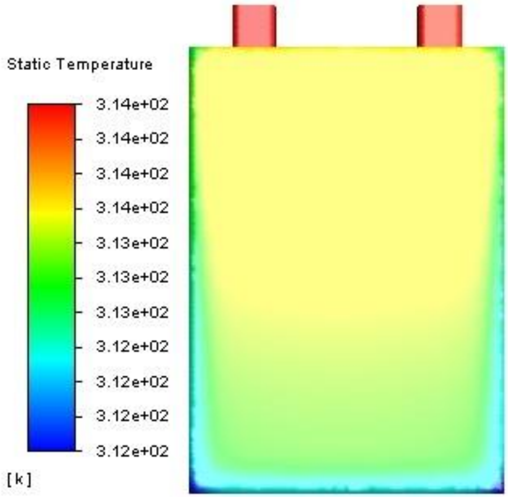
3.2. Results for C-Rate Value of 0.5

The configuration with 0.5 C-Rate is examined and temperature contours are given in Figure 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.

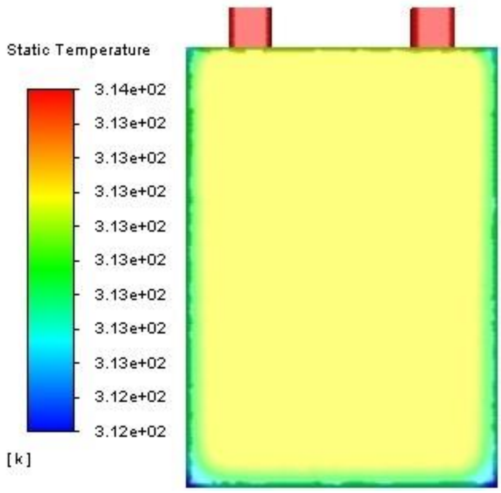
Time dependent variation of maximum temperature is shown in Figure 7 for different configurations. A saturation type curve is seen for all cases while the discrepancies between cases of without PCM and others are higher in the interval t=600-1000. As it is seen in Table 5, max temperature drop of 2.5 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-PCMs 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.



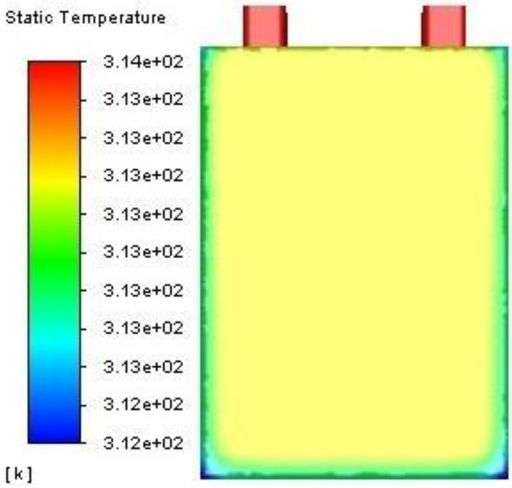
(a)



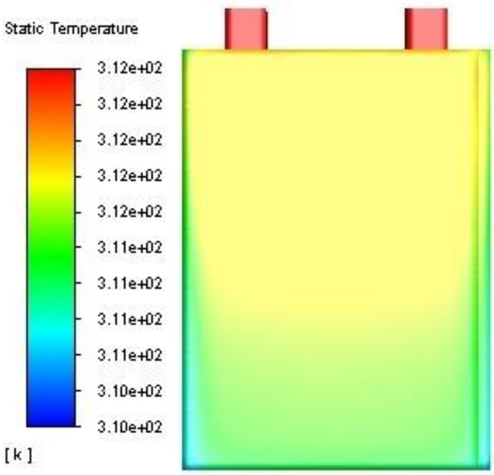
(b)



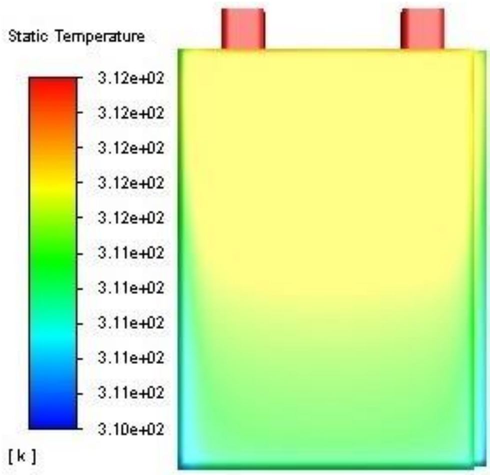
(c)



(d)



(e)



(f)

Figure 6. Temperature Contours a) Battery only b) Coated with PCM c) Coated with 0.01 percent Nano-PCM d) 0.03 percent Nano-PCM e) Two-sided coated (PCM and 0.01 Nano-PCM) PCM) f) Two-sided coated (PCM and 0.03 Nano-PCM)

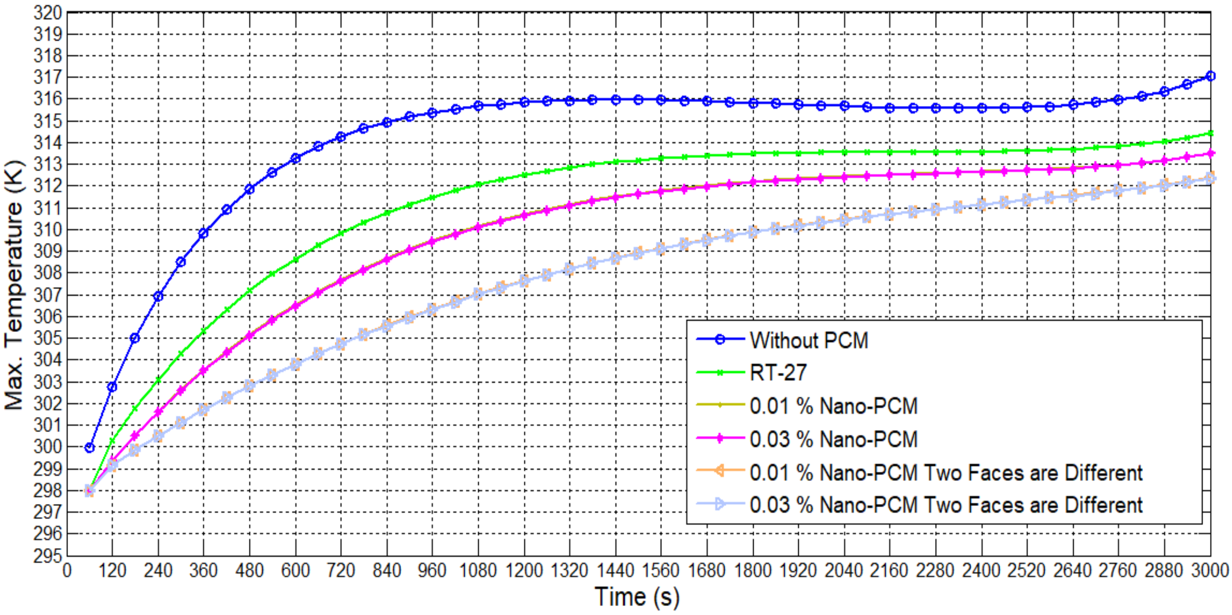


Figure 7. Time-dependent temperature graph at 0.5 C-Rate discharge rate

Table 5. Maximum temperature values for 0.5 C-Rate discharge value

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

4. 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 extend 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.

References

[1] Joshy, N., et al., Experimental Investigation Of The Effect Of Vibration On Phase Change Material (PCM) Based Battery Thermal Management System, *J. Power Sources*, *450* (2020), pp. 227717. 227717. https://doi.org/10.1016/j.jpowsour.2020.227717

[2] Zhao, X., Thermal Performance Analysis And Optimal Control Of Power Lithium Cell Thermal Management System For New Energy Vehicles, *Therm. Sci.*, *24* (2020), 5 Part B, pp. 3375-3383. https://doi.org/10.1016/j.ijthermalsci.2021.106945

[3] Ding, Y., et al., Parameters Of Liquid Cooling Thermal Management System Effect On The Li-Ion Battery Temperature Distribution, *Therm. Sci.*, *26* (2022), 1 Part B, pp. 567-577. https://doi.org/10.2298/TSCI201019223D

[4] Sun, Z., et al., Thermal Management Of A Simulated Battery With The Compound Use Of Phase Change Material And Fins: Experimental And Numerical Investigations, *Int. J. Therm. Sci.*, *165* (2021), pp. 106945. https://doi.org/10.1016/j.ijthermalsci.2021.106945

[5] Fan, Y., et al., Novel Concept Design Of Low Energy Hybrid Battery Thermal Management System Using PCM And Multistage Tesla Valve Liquid Cooling, *Appl. Therm. Eng.*, *220* (2023), pp. 119680. https://doi.org/10.1016/j.applthermaleng.2022.119680

[6] John, S., et al., Numerical Investigation On The Effect Of PCM Thickness And Nano-Additive On The Cooling Performance Of Stearic Acid Based Battery Thermal Management System, *Mater. Today Proc.*, (2023), pp. S2214785323003632. https://doi.org/10.1016/j.matpr.2023.01.267

[7] Liu, H., et al., Thermal Issues About Li-Ion Batteries And Recent Progress In Battery Thermal Management Systems: A Review, *Energy Convers. Manag.*, *150* (2017), pp. 304-330. http://dx.doi.org/10.1016/j.enconman.2017.08.016.

[8] Du, W., Chen, S., Effect Of Mechanical Vibration On Phase Change Material Based Thermal Management Module Of A Lithium-Ion Battery At High Ambient Temperature, *J. Energy Storage*, *59* (2023), pp. 106465. https://doi.org/10.1016/j.est.2022.106465

[9] Li, Y., et al., A Novel Petal-Type Battery Thermal Management System With Dual Phase Change Materials, *Int. J. Heat Mass Transf.*, *207* (2023), pp. 123989. https://doi.org/10.1016/j.ijheatmasstransfer.2023.123989

[10] Cheng, J., et al., Thermal Performance Of A Lithium-Ion Battery Thermal Management System With Vapor Chamber And Minichannel Cold Plate, *Appl. Therm. Eng.*, *222* (2023), pp. 119694. https://doi.org/10.1016/j.applthermaleng.2022.119694

[11] Khaboshan, H.N., et al., Improving The Cooling Performance Of Cylindrical Lithium-Ion Battery Using Three Passive Methods In A Battery Thermal Management System. https://doi.org/10.1016/j.applthermaleng.2023.120320

[12] Rana, S., et al., Lithium- Ion Battery Thermal Management Techniques And Their Current Readiness Level, *Energy Technol.*, *11* (2023), 1, pp. 2200873. https://doi.org/10.1002/ente.202200873

[13] Rana, S., et al., Current Trends, Challenges, And Prospects In Material Advances For Improving The Overall Safety Of Lithium-Ion Battery Pack, *Chem. Eng. J.*, *463* (2023), pp. 142336. https://doi.org/10.1016/j.cej.2023.142336

[14] Fan, R., et al., Evaluation Of Fin Intensified Phase Change Material Systems For Thermal Management Of Li-Ion Battery Modules, *Int. J. Heat Mass Transf.*, *166* (2021), pp. 120753. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120753

[15] Mousavi, S., et al., An Improved Hybrid Thermal Management System For Prismatic Li-Ion Batteries Integrated With Mini-Channel And Phase Change Materials, *Appl. Energy*, *334* (2023), pp. 120643. https://doi.org/10.1016/j.apenergy.2023.120643

[16] Mokashi, I., et al., Maximum Temperature Analysis In A Li-Ion Battery Pack Cooled By Different Fluids, *J. Therm. Anal. Calorim.*, *141* (2020), 6, pp. 2555-2571. https://doi.org/10.1007/s10973-020-10063-9

[17] Afzal, A., et al., Effect Of Parameters On Thermal And Fluid-Flow Behavior Of Battery Thermal Management System, *Therm. Sci.*, *25* (2021), 5 Part B, pp. 3775-3787. https://doi.org/10.2298/TSCI191206290A

[18] V R, S., Chanda, S., Thermal Performance Evaluation Of PCM-MF Composite Heat Sinks Under Varying Ambient Conditions, *Int. J. Heat Mass Transf.*, *206* (2023), pp. 123927. https://doi.org/10.1016/j.ijheatmasstransfer.2023.123927

[19] Yue, Q.L., et al., Advances In Thermal Management Systems For Next-Generation Power Batteries, *Int. J. Heat Mass Transf.*, *181* (2021), pp. 121853. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121853

[20] Özel, M., et al., Faz Değiştiren Malzemeli Duvarlarda Sıcaklık Dağılımının Nümerik Analizi, *DÜMF Mühendis. Derg.*, (2021), pp. 803-810. https://doi.org/10.24012/dumf.1051456

[21] Çakmak, F.A., Faz Değiştiren Malzemelerin Bina Dış Duvarlarında Kullanımının Isı Kazanç Ve Kaybına Etkisinin Araştırılması, *Firat Univ. Inst. Sci.*, (2019)

[22] Izadi, M., et al., Charging Process Of A Partially Heated Trapezoidal Thermal Energy Storage Filled By Nano-Enhanced PCM Using Controlable Uniform Magnetic Field, *Int. Commun. Heat Mass Transf.*, *138* (2022), pp. 106349. https://doi.org/10.1016/j.icheatmasstransfer.2022.106349

[23] Jilte, R., et al., A Novel Battery Thermal Management System Using Nano-Enhanced Phase Change Materials, *Energy*, *219* (2021), pp. 119564. https://doi.org/10.1016/j.energy.2020.119564

[24] Wang, Y., et al., Performance Investigation Of A Passive Battery Thermal Management System Applied With Phase Change Material, *J. Energy Storage*, *35* (2021), pp. 102279. https://doi.org/10.1016/j.est.2021.102279

[25] Ping, P., et al., Investigation On Thermal Management Performance Of PCM-Fin Structure For Li-Ion Battery Module In High-Temperature Environment, *Energy Convers. Manag.*, *176* (2018), pp. 131-146. https://doi.org/10.1016/j.enconman.2018.09.025

[26] Jilte, R., et al., Hybrid Cooling Of Cylindrical Battery With Liquid Channels In Phase Change Material, *Int. J. Energy Res.*, *45* (2021), 7, pp. 11065-11083. https://doi.org/10.1002/er.6590

[27] Safdari, M., et al., Numerical Investigation On PCM Encapsulation Shape Used In The Passive-Active Battery Thermal Management, *Energy*, *193* (2020), pp. 116840. https://doi.org/10.1016/j.energy.2019.116840

[28] Verma, A., et al., A Comparative Study On Battery Thermal Management Using Phase Change Material (PCM), *Therm. Sci. Eng. Prog.*, *11* (2019), pp. 74-83. https://doi.org/10.1016/j.tsep.2019.03.003

[29] Bais, A.R., et al., Critical Thickness Of Nano-Enhanced RT-42 Paraffin Based Battery Thermal Management System For Electric Vehicles: A Numerical Study, *J. Energy Storage*, *52* (2022), pp. 104757. https://doi.org/10.1016/j.mtcomm.2022.104757

[30] Sazvar, B., Moqtaderi, H., A Numerical Study On The Capacity Improvement Of Cylindrical Battery Cooling Systems Using Nano-Enhanced Phase Change Material And Axisymmetric Stepped Fins, *J. Energy Storage*, *62* (2023), pp. 106833. https://doi.org/10.1016/j.est.2023.106833

[31] Mitra, A., et al., Advances In The Improvement Of Thermal-Conductivity Of Phase Change Material-Based Lithium-Ion Battery Thermal Management Systems: An Updated Review, *J. Energy Storage*, *53* (2022), pp. 105195. https://doi.org/10.1016/j.est.2022.105195

[32] Yang, L., et al., Thermal Management Of Lithium-Ion Batteries With Nanofluids And Nano-Phase Change Materials: A Review, *J. Power Sources*, *539* (2022), pp. 231605. https://doi.org/10.1016/j.jpowsour.2022.231605

[33] Mekaddem, N., et al., Paraffin/ Expanded Perlite/Plaster As Thermal Energy Storage Composite, *Energy Procedia*, *157* (2019), pp. 1118-1129. https://doi.org/10.1016/j.egypro.2018.11.279

[34] Choudhari, V.G., et al., Numerical Analysis Of Different Fin Structures In Phase Change Material Module For Battery Thermal Management System And Its Optimization, *Int. J. Heat Mass Transf.*, *163* (2020), pp. 120434. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120434

[35] Huang, R., et al., Experimental And Numerical Study Of PCM Thermophysical Parameters On Lithium-Ion Battery Thermal Management, *Energy Rep.*, *6* (2020), pp. 8-19. https://doi.org/10.1016/j.egyr.2019.09.060

[36] Bechiri, M., Mansouri, K., Analytical Study Of Heat Generation Effects On Melting And Solidification Of Nano-Enhanced PCM Inside A Horizontal Cylindrical Enclosure, *Appl. Therm. Eng.*, *104* (2016), pp. 779-790. https://doi.org/10.1016/j.applthermaleng.2016.05.105

[37] Siruvuri, S. V., & Budarapu, P. R., Studies on thermal management of Lithium-ion battery pack using water as the cooling fluid, *Journal of Energy Storage*, 29 (2020), 101377. https://doi.org/10.1016/j.est.2020.101377

RECEIVED DATE: 6.7.2023
DATE OF CORRECTED PAPER: 10.8.2023
DATE OF ACCEPTED PAPER: 25.9.2023.