

BATTERY THERMAL MANAGEMENT SYSTEM USING ORGANIC PHASE CHANGE MATERIAL RT-35 ENHANCED WITH METALLIC HEAT SINKS

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Abstract

The current study aims at investigating the impact of phase change material if used in battery thermal management system with an objective of preventing them from deformation, damage or thermal runaway. CFD simulations have been performed for investigating the impact of PCM RT-35 simply mounted around the lithium-ion battery vs PCM RT-35 along with the aluminum metallic inserts in the form of fins. The output results suggest that metallic inserts along with the PCM perform uniform melting as compared to the PCM alone. In this way, the thermal management system consisting of the PCM along with the metallic inserts performed efficiently and the time for the PCM melt was reduced leading to reduction in the overall temperature of the system. All the tasks of the simulations including geometry, meshing, solution setup and post processing are done in ANSYS Fluent. The mathematical model has been solved using FVM which is built-in in ANSYS Workbench.

1. INTRODUCTION

The lithium-ion batteries (LIBs) have appeared as a best alternative against the conventional fossil-fuel combustion engines to keep the environment clean and healthy. One of the major issues coming with these batteries is their increased temperature during the operational conditions which is due to passing of electric current and occurring of chemical reactions as a result. If this temperature is not removed accordingly, it will destroy or deform the batteries which will not work properly and their replacement with new batteries becomes necessary to run the vehicle on the road. This is why, an efficient cooling system is necessary for securing the batteries called thermal management system. Offering a good battery

thermal management system will remove the excessive heat from the batteries preventing overheating, increase its performance and come up with safety interest like thermal runaway. The variability of different cooling modes of the battery depends on the battery and the applications. The pertinent research on different methods of cooling will be described below.

Zhao et al. [1] considered water and copper for water-Cu nanofluid and used it in a channel introduced for the thermal management of a battery pack and observed in increased cooling of 12.35% as a result. Sudhakaran et al. [2] analyzed numerically the impact of PCM based cooling system on batteries. In their study, they simulated several cases based on PCM thickness, PCM material type, heat transfer

coefficient and metallic additives and found that the PCM material type and the PCM thickness were the most influential parameters for the battery thermal management system as compared to the PCM thickness and heat transfer coefficient. Several battery thermal management systems were reviewed by Zichen et al. [3], who reported that air-cooled battery thermal management system is not cost-effective and is costly in perspective of operation and maintenance, and claimed that other techniques such as use of PCM is better. The research investigations by Bibin et al. [4] reveal that use of PCM based thermal management systems are very much effective heat storage systems during the cold weather environment. They conducted their studies in batteries in the electronic vehicles. Their report proposed that using the hybrid technique, i.e., using the air-based along with PCM based battery thermal management systems can enhance the performance by 23.68 percent. Qin et al. [5] have done a literature review of the studies done on air-based temperature control of the battery. Their results demonstrate that the method of air-based thermal management along the with forced convection, which is more beneficial than PCM and heat pipes, is the most successful in battery thermal management out of all the techniques to enhance the air-based battery cooling systems. Wu et al. [6] conducted their literature review study on liquid-based thermal management of batteries and concluded that the usage of metallic plates along with nanofluids can increase the heat transfer coefficient because of the increased thermal conductivity and these can be used in thermal management of the batteries. Wang et al. [7] proposed a new enclosure design of a battery pack which was water-cooled. They clarified that the power-consumption based cooling system efficiency will need to be taken into consideration for the optimized flow rate. The studies were conducted by Liu et al. [8] for investigating the effects of PCM and other metallic objects on battery thermal management systems using the recent computational and experimental research. They concluded that PCM can be applied by applying external material that enhances the ability of the thermal management system by increasing the heat transfer coefficient but practically this causes extra mass which burdens the load of material, like metal fins, metallic nanoparticles, etc., on the vehicle.

Lazrak et al. [9] conducted computational/empirical investigation on a recently constructed chamber to improve the control of battery heat by using PCMs. With the assistance of a copper grid with PCM, they have been achieving promising results of a reduced thermal residence. Lyu et al. [10] investigated the impact of thermoelectric cooling of the batteries of electric vehicles for their thermal management. Comparing the effectiveness of air and water cooling, they found that the water-cooled thermal management system decreased the battery temperature by 43 °C when used the copper battery holder. Siddique et al. [11] investigated the pros and cons of both the methods, the active and passive battery thermal management systems. The outcome of their research revealed that if PCM base is rectangular, will perform better if PCM base is cylindrical. Zhang et al. [12] investigated numerically the thermal management of batteries for their thermoelectrical effect. To regulate the thermal status of each battery, they introduced a thermoelectric chip into the liquid-based cooling system for controlling the liquid mass flow rate. Pesaran et al. [13] examined the factors, which influence the heat in battery in electric and hybrid car. They discovered the key issues to be addressed which are the location of the battery packs in cars and thermoelectrical controlling. Mali et al. [14] investigated the battery thermal management by focusing on the energy efficiency. The paper revealed that the analysis of the optimality of the supercapacitors demonstrate that the supercapacitors are able to regulate the current peaks and consequently the temperature of battery packs can be regulated hence making the weight and cost incurred by them well justified if it reduces the risk of thermal run away. Kadam et al. [15], in their study, used graphene nanoparticles to enhance the thermal conductivity of PCMs that has 58 °C as its melting point. This setup was introduced for the thermal management of lithium-ion battery pack without the influence of buoyancy force and current, which remains constant in the discharge current. They found that the maximum temperature of batteries is around 43 °C, 56 °C and 60 °C at 1C, 2C and 3C respectively. Yousefi et al. [16] considered various metallic enclosures for his numerical study to analyze the performance of battery thermal management system. The outcome of their study suggested that the

copper enclosure keeps the battery pack at the lowest temperature. Heyhat et al. [17] considered a PCM and studied the cases, such as included metallic foam (porous-PCM), metallic fins and CuO nanoparticles into it for the lithium-ion battery thermal management system for constant discharge current. They found out that porous-PCM composition performance is better than the fin-PCM and nanoparticle-PCM. Mousavi et al. [18] conducted numerical study on hybrid battery thermal management system that includes the PCM plates and the mini-channel. The outcome of their study reveal that the hybrid thermal management system is more efficient than the PCM alone. With different arrangements of PCM plates, the temperature of the LIBs could be reduced for a range of 5.6 °C to 16.12 °C. Gaddale et al. [19] conducted a comparative numerical study for the battery thermal management by considering organic and inorganic phase change materials. Their analysis shows that the performance of inorganic PCM is more efficient. An experimental study by [20] revealed that the battery thermal management is more efficient is copper foam is used along with the PCM instead of PCM alone. Moreover, the outcome of a number of research papers, whether the study is numerical or experimental, show that applying PCM to the problems of battery thermal management is a promising step, and if metallics inserts like foam, fins, nanoparticles, etc., as well as liquid cooling enhances the performance of PCM to a higher level [21-29]. In the current study, we investigate the impact of phase change material if used in battery thermal

management system with the objective of preventing them from deformation, damage or thermal runaway. CFD simulations have been performed for investigating the impact of PCM RT-35 simply mounted around the lithium-ion battery vs PCM RT-35 along with the aluminum metallic inserts in the form of fins.

2. PROBLEM STATEMENT

The battery cell under consideration is a 3D cylindrical lithium-ion battery cell of 18 mm diameter and 65 mm of height. This battery cell is then enclosed with a circular heat sink of thickness of 1 mm having mounted 8 uniformly distributed plate fins on the outer face. The length, width and height of each fin are 2 mm, 1 mm and 65 mm respectively. A 3 mm thick layer of RT-35 PCM is placed in between the heat sink and another circular metallic holder of thickness of 1 mm, where fins are embedded into the PCM layer, as shown in Figure 1. For the sake of a deeper analysis and comparison, another geometric configuration is also considered in which the fins are absent when compared with the previous configuration. Both geometric configurations are given in Figure 1. The heat source is the internal heat generation rate ($\dot{Q}$ rate which generates a heat load equivalent to 200000 W/m^3) because of electrochemical reactions occurring inside the lithium-ion battery cell.

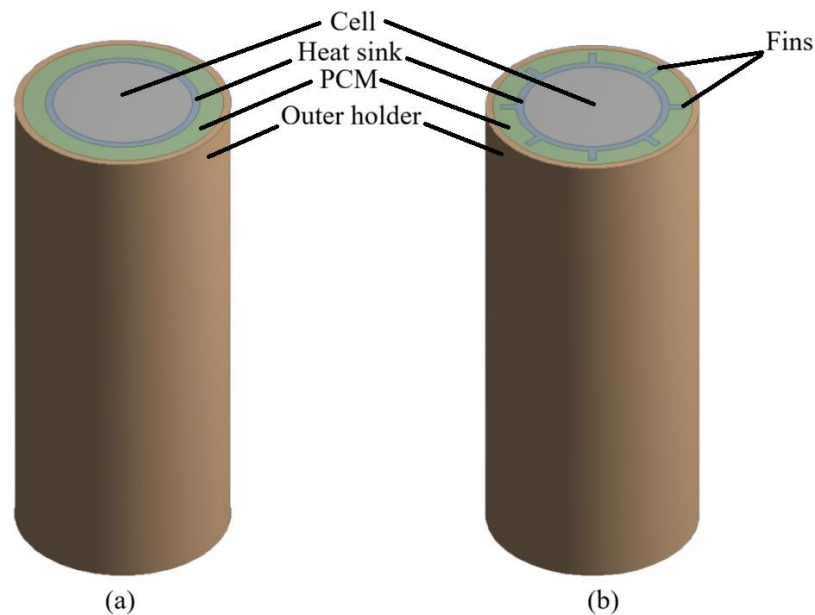


Figure 1. Computational domain with (a) heat sink without fins and (b) heat sink with fins.

The material properties of the cell, PCM, heat sinks and the outer holder are given in the following tables.

Table 1. The material properties of the lithium-ion battery cell.

Property	Value	Unit
Density	2092	Kg/m ³
Thermal conductivity	18.2	W/(m-k)
Specific heat	678	J/(Kg-K)

Table 2. The material properties of the PCM RT-35.

Property	Value	Unit
Density	820	Kg/m ³
Thermal conductivity	0.2	W/(m-k)
Specific heat	2000	J/(Kg-K)
Latent heat	160	KJ/Kg
Viscosity	0.02	Kg/(m-s)
Solidus temperature	307	K
Liquidus temperature	309	K

Table 3. The material properties of heat sinks and the outer holder (aluminum).

Property	Value	Unit
Density	2719	Kg/m ³
Thermal conductivity	202.4	W/(m-k)
Specific heat	871	J/(Kg-K)

3. MATHEMATICAL FORMULATION

In this section, we give some flow and thermal assumptions and the governing equations of the problem.

3.1 Flow and Thermal Assumptions

- The problem under consideration is a 3D, laminar, incompressible and transient problem.
- The density of the PCM is assumed to be constant and radiations are ignored.
- The material properties of the materials are constant in order to observe the pure melting process to compare the two heat sink designs.
- The enthalpy-porosity method is used for the melting of PCM because this method does not

require the liquid-solid interface during the melting process [23-26]. This method considers the computational domain to be porous. The porosity of all the cells is determined by liquid fraction γ , which takes 0 for the solid phase and 1 for the liquid phase.

A source term $\vec{S}_u$, where $\vec{S}_u = A_{mush} \frac{(1-\gamma)^2}{\gamma^3 + \varepsilon} \vec{u}$ is included in the momentum equations to identify the solid zone, the mushy zone, and the liquid zone, where A_{mush} is the mushy zone constant, ε is small number whose value is taken to be 1×10^{-3} to avoid 0 in the numerator in $\vec{S}_u$. The γ is calculated as

$$\gamma = \begin{cases} 0, & \text{if } T < T_s \\ \frac{T - T_s}{T_l - T_s}, & \text{if } T_s < T < T_l \\ 1, & \text{if } T > T_l \end{cases} \quad (1)$$

3.2 Mathematical Model

The mathematical model that governs the flow is

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0, \quad (2)$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = \mu \nabla^2 \vec{u} - \nabla p - \rho \vec{g} + \vec{S}_u, \quad (3)$$

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot (\lambda \nabla T), \quad (4)$$

where t , $\vec{u}$, p and $\vec{g}$ are the time, velocity vector, pressure and gravitational acceleration respectively. H is the enthalpy, which is the sum of the latent enthalpy ΔH and sensible enthalpy h_s , i.e.,

$$H = \Delta H + h_s, \quad (5)$$

$$\Delta H = \gamma L_h, \quad (6)$$

$$h_s = h_{ref} + \int_{T_{ref}}^T c_p dt, \quad (7)$$

where γ is the liquid fraction, L_h is the latent heat of fusion, h_{ref} is the reference enthalpy at T_{ref} . For fins, only heat conduction is considered governed by the equation

$$\frac{\partial}{\partial t} (\rho_{fin} c_{p,fin} T) = \nabla \cdot (\lambda_{fin} \nabla T). \quad (8)$$

The boundary conditions at the external boundaries and interfaces of the lithium-ion cell, PCM, heat sinks and metallic outer holder are as follows.

Table 4. Thermal and flow boundary conditions.

Sr. No.	Location	Thermal condition	Flow condition
1.	Top boundaries	$\frac{\partial T_{cell_top}}{\partial n} = \frac{\partial T_{heat\ sink_top}}{\partial n}$ $= \frac{\partial T_{PCM_top}}{\partial n} = \frac{\partial T_{outer\ cover_top}}{\partial n} = 0$	$u = v = w = 0$
2.	Bottom boundaries	$\frac{\partial T_{cell_bottom}}{\partial n} = \frac{\partial T_{heat\ sink_bottom}}{\partial n}$ $= \frac{\partial T_{PCM_bottom}}{\partial n} = \frac{\partial T_{outer\ cover_bottom}}{\partial n} = 0$	$u = v = w = 0$
3.	Outer cover wall	$\frac{\partial T}{\partial n} = 0$	$u = v = w = 0$
4.	PCM-heat sink interface	$T_{PCM} = T_{heat\ sink} ,$ $k_{heat\ sink} \frac{\partial T_{heat\ sink}}{\partial n} = k_{PCM} \frac{\partial T_{PCM}}{\partial n}$	$u = v = w = 0$
5.	PCM-cell interface	$T_{PCM} = T_{cell} ,$ $k_{PCM} \frac{\partial T_{PCM}}{\partial n} = k_{cell} \frac{\partial T_{cell}}{\partial n}$	$u = v = w = 0$
6.	Solid PCM-liquid interface	$T_{S,PCM} = T_{L,PCM}$ $k_{S,PCM} \frac{\partial T_{S,PCM}}{\partial n} = k_{L,PCM} \frac{\partial T_{L,PCM}}{\partial n}$	$u = v = w = 0$

The load applied to the battery cell is a C5 rate, which is equivalent to 200000 W/m^3 of heat generation rate within the battery cell, i.e.,

$$\dot{q} = 200000 \text{ W/m}^3 \quad (9)$$

The remaining external boundaries in the computational domain are thermally insulated while the internal boundaries define interfaces between the cell, PCM and the metallic heat sinks with fins and without fins.

The initial conditions are as below.

$$t = 0, T_0 = 303 \text{ K}, u = v = w = 0. \quad (10)$$

4. SOLUTION PROCEDURE

We solve the flow problem numerically using Finite Volume Method which is built-in in ANSYS Fluent

16.2. All the tasks of simulations, i.e., geometry creation, meshing, choice of models, solution and postprocessing have been performed using ANSYS Workbench. For calculations, SIMPLE scheme is used for the pressure-velocity coupling. For spatial discretization, the Green-Gauss Cell-Based method is used for the gradient calculations, second order interpolation is used for the pressure for enhanced accuracy in the pressure-velocity coupling, and second order upwind scheme is used for the momentum and energy equations. The threshold for the residuals is set to below 10^{-3} for continuity, momentum equations while it is 10^{-6} for the energy

equation. The calculations are performed unless the PCM melts completely.

5. MESH DETAILS

For using the finite volume method, the computational domain must be divided into small volumes (elements). The most of the mesh elements are hexahedral. A very few elements are other than hexahedral for the shape adoption of the battery cell. The conformal mesh is used on all the interfaces for better accuracy. The computational domain division into small elements is set to size of 1 mm. The total

number of small elements in the computational mesh is 45936 and number of nodes 48240. The maximum skewness of mesh elements is 0.3824 which is very much enough for the accuracy of the results. The maximum orthogonal quality of the mesh is 0.99975 while the minimum orthogonal quality is 0.87301, and average orthogonal quality is 0.99163 which another indicator of a good quality mesh. These metrics are of the mesh for the case of heat sink without fins. The mesh metrics for the finned heat sink slightly different, but they also give comparable accuracy.

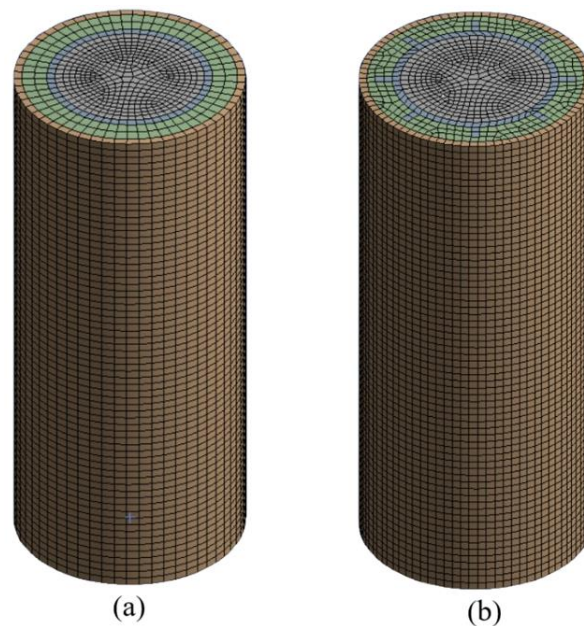


Figure 2. Computational mesh with (a) heat sink without fins and (b) heat sink with fins.

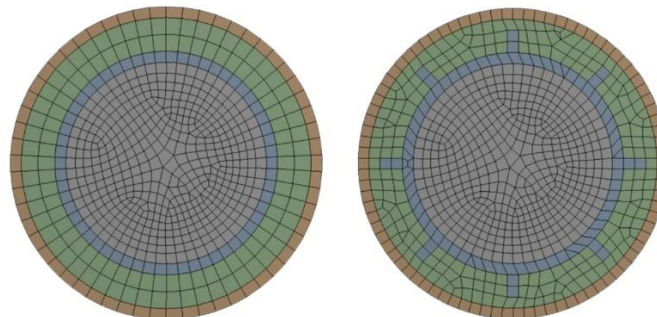


Figure 3. Top face view of the computational mesh with (a) heat sink without fins and (b) heat sink with fins.

6. RESULTS AND DISCUSSION

In this section, we give detailed discussion of the influence of the heat sink design on lithium-ion battery cell's temperature and melting of the PCM.

6.1 Transient Thermal and Phase Change Response

In Figure 4, we can see that the initial temperature of the lithium-ion battery cell is 303 K. Its temperature rises quickly from 303 K to 307 K for both designs of heat sink, i.e., the heat sink without fins and the heat sink with fins. After 307 K, the rise of the cell temperature slows down for both the designs, but it is clear that the battery cell temperature is lower in case of the heat sink with fins. This is because the heat is dissipated by the heat sink with fins more quickly into the PCM and the PCM starts melting more rapidly as the interface area between the heat sink and

the PCM is more in case of finned heat sink than the case of heat sink without fins which is evident from the liquid fraction curves in Figure 5 and also from subsequent contours graphs.

The temperature curves rise during the melting of the PCM. The rate of increase of the battery cell's temperature is very much lower than the time duration when there is no melting, clearly indicating the impact and role of the PCM. After melting of the PCM, the slope of the temperature curves again rises for both the cases, as combinedly observed from Figures 4 and 5. From Figure 5, it is clear that the PCM melts completely before 850 seconds, which indicates that the PCM has completed its role. For the time after 850 seconds, either system requires active cooling, or increase the PCM thickness.

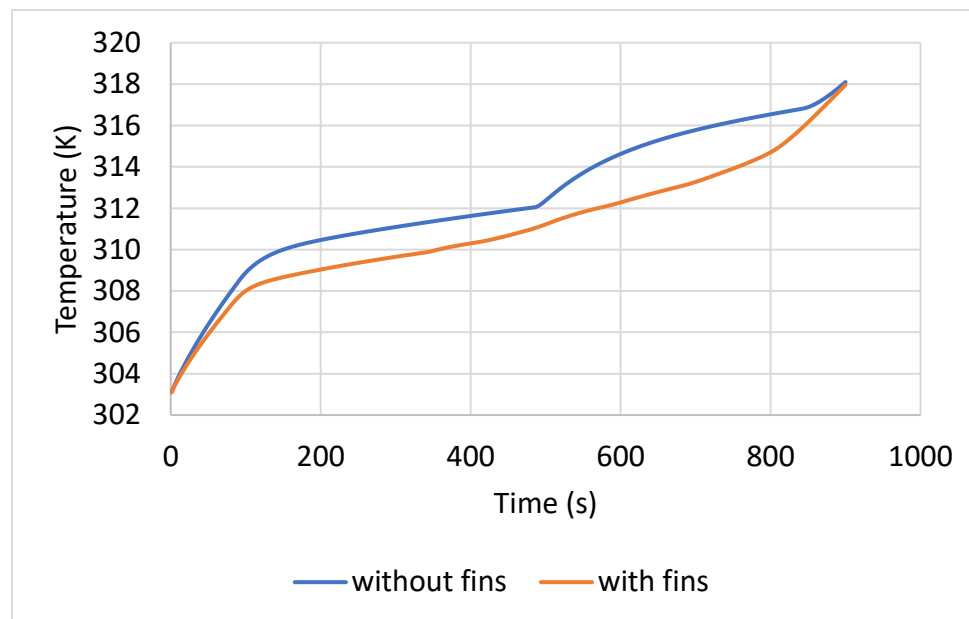


Figure 4. Cell temperature curves for heat sink without fins and heat sink with fins.

In Figure 5, the liquid fraction remains zero until achieving the melting temperature of the PCM. After 90 seconds, the PCM starts melting and liquid fraction curves rise linearly while the slope of the

curve for heat sink with fins is higher due to rapid distribution of the heat into the PCM. This is why the melting of PCM is completed earlier for heat sink with fins.

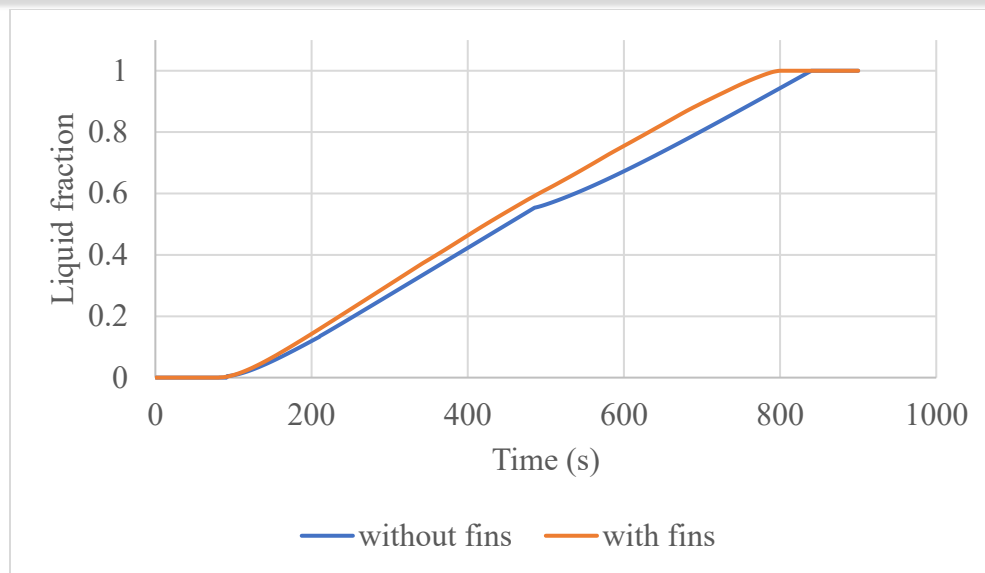


Figure 5. Liquid fraction curves for heat sink without fins and heat sink with fins.

6.2 Spatial Thermal and PCM Liquid Fraction (Contour Analysis)

In this subsection, we discuss the local response of the lithium-ion battery cell temperature and the PCM with the help of contours graphs. After each 300 seconds, the contours graphs are captured for temperature and liquid fraction for both the heat sinks at a cross-sectional circular plane and are placed side-by-side in the text in Figure 6 to Figure 9.

In Figures 6(a) and 6(b), we see that the lithium-ion cell is the most heated body in the domain because of the heat generation source of 200000 Watt/m^3 . The heat spreads outward normal along the radial direction. The heat is dissipated into the PCM mounted around the battery cell. We observe that the heat dissipation is more rapid in case of heat sink with fins because of more surface area at the interface between the heat sink and the PCM, Figure 6(b). The

impact of this heat dissipation is also seen in Figures 6(c) and 6(d) where we see that the liquid fraction is covering more space in case of heat sink with fins than the heat sink without fins. As the time passes, the heat spreads into all the bodies in the radial direction. The pattern of the contours is similar during the whole process.

In Figure 8, after 900 seconds, the contours pattern reveals that the PCM is fully melt in both the cases of heat sink without fins and heat sink with fins.

From Figures 6 to 8, we observe also that after each 300 seconds, the rise in battery cell's maximum temperature is around 3.5°C . In Figure 9, the rise in battery cell's maximum temperature is around 11°C . The discussion makes the picture clearer because the rise in temperature is slower until the PCM is fully melt while it is much faster after the fully melt of the PCM,

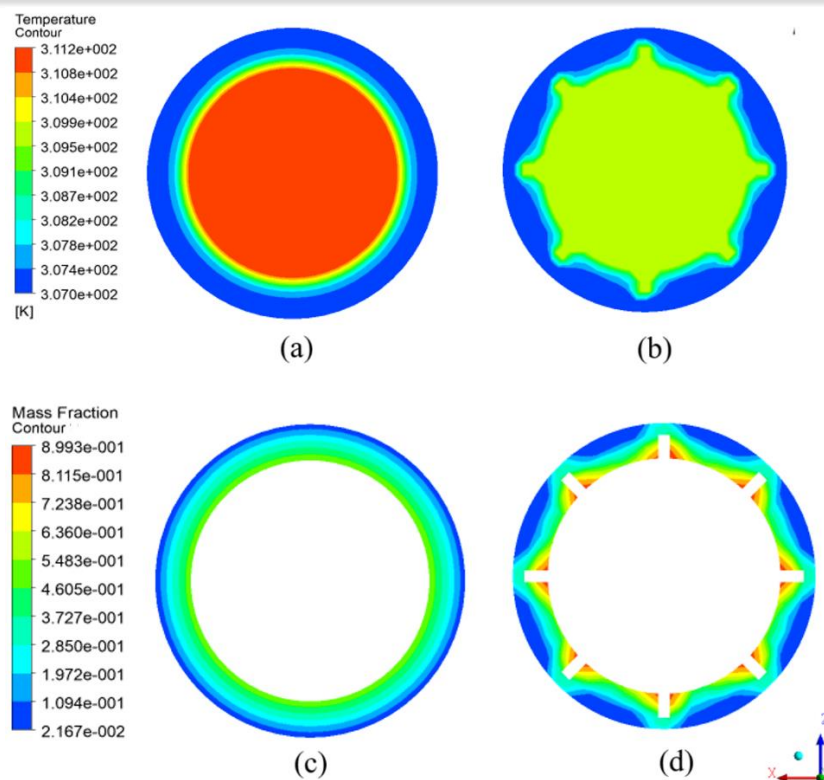


Figure 6. Temperature contours (a) heat sink without fins, (b) heat sink with fins; and Liquid fraction contours (c) heat sink without fins, (d) heat sink with fins after 300 seconds.

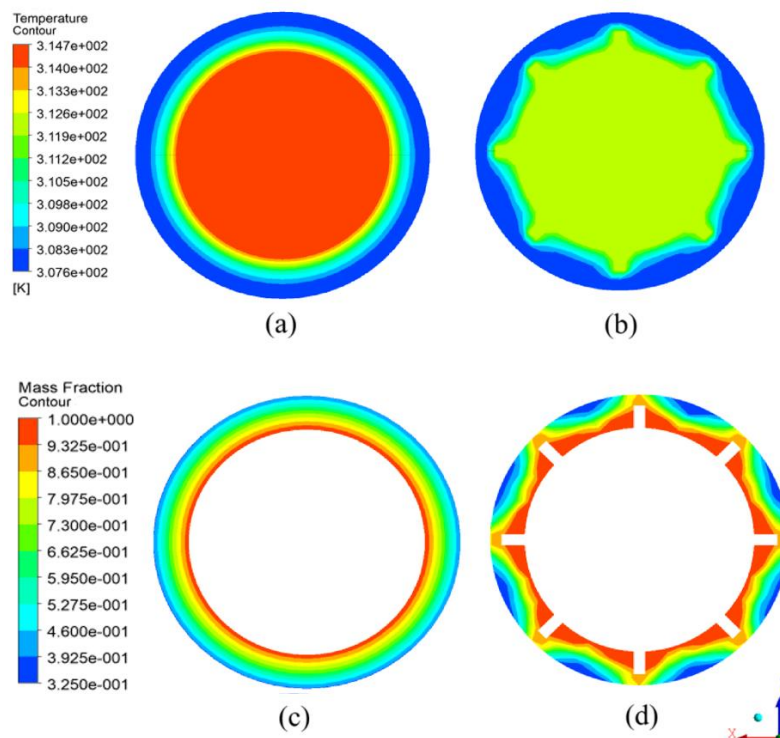


Figure 7. Temperature contours (a) heat sink without fins, (b) heat sink with fins; and Liquid fraction contours (c) heat sink without fins, (d) heat sink with fins after 600 seconds.

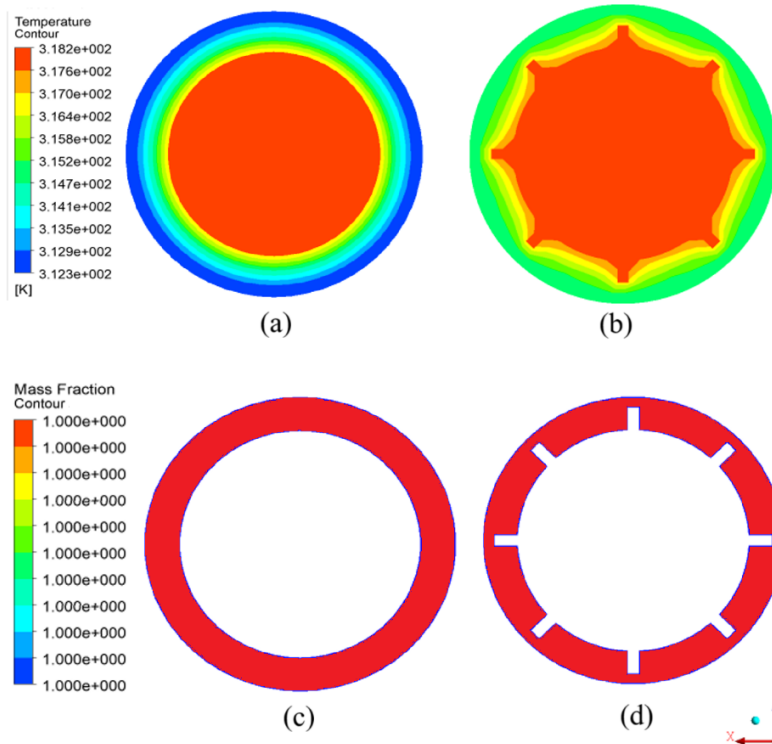


Figure 8. Temperature contours (a) heat sink without fins, (b) heat sink with fins; and Liquid fraction contours (c) heat sink without fins, (d) heat sink with fins after 900 seconds.

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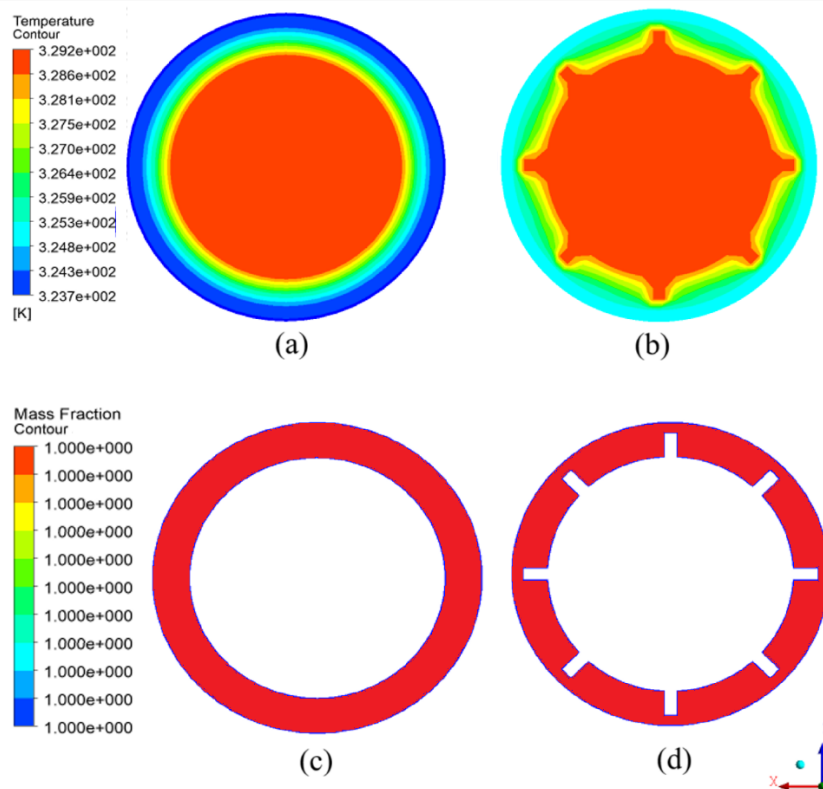


Figure 9. Temperature contours (a) heat sink without fins, (b) heat sink with fins; and Liquid fraction contours (c) heat sink without fins, (d) heat sink with fins after 1200 seconds.

7. CONCLUSIONS

The current study focusses on investigating the impact of heat sink design on the melting of phase change material for the purpose of thermal management of lithium-ion battery cell. For this, two designs are considered namely, the heat sink without fins and the heat sink with fins. The PCM considered for the study is RT-35. Findings of the present work are:

1. The temperature and the liquid fraction curves show that the temperature can be regulated significantly using PCM during the operational conditions.
2. The heat sink with fins dissipates the heat into the PCM more rapidly as compared to the heat sink without fins.
3. The gap in temperature curves for both the designs reaches up to 3 units which shows the importance of the heat sink design.
4. The complete melting of the PCM occurs earlier in case of the heat sink with fins.
5. The rise in battery cell's maximum

temperature is around 3.5 °C after every 300 seconds until the PCM is fully melt while the its rise reaches to 11 °C in next 300 seconds after the PCM is fully melt.

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