Numerical investigations on phase change material-based battery thermal management system

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Abstract. Battery module is the power source of electric vehicle (EV). Temperature field of the module affects its performance and life. Battery thermal management system (BTMS) with phase change material (PCM) ensures temperature uniformity within the module. In this paper, two-dimensional model was developed to simulate the thermal and cyclic performances of different PCMs so as to select the suitable one to act as a medium for controlling the temperature of battery in the BTMS. Octadecane, Eicosane, Docosane, Tetracosane and RT25 are the five different considered and they were exposed different thermal conditions through four case studies. Simulation of the five PCMs were carried out in four different cases with COMSOL Multiphysics software. Docosane takes 4500 s to reach the threshold temperature of 60°C and 8790 s to cool to ambient temperature which is performing fairly good in all the PCMs and it was selected as the PCM in BTMS. Three-dimensional model was developed to simulate the BTMS and simulation was carried out with COMSOL Multiphysics software. The battery module is within the acceptable temperature range while heating with a maximum temperature of 52.1°C. The desired temperature uniformity of the battery was observed from the results. PCM was effectively used in the BTMS with a maximum value of maximum liquid fraction of 0.9 achieved in 9210 s.

1. Introduction

Environmental pollution, global warming and depletion of fossil fuels have made the world to look for renewable energy resource alternatives. Transportation sector being one of the key energy consumption sectors also seek to undergo paradigm shift towards cleaner fuels. The emission norms for conventional vehicles are becoming stringent every year in order to reduce its impact on environment. As Earth is running low on fossil fuel reserves and extraction of it has hit hard on economics stand thereby increasing the fuel cost. Due to the above stated, the rise of electric vehicles (EVs) has been observed in recent years. The challenges which hinder the popularisation of EVs are long charging time, lesser range at single charge, availability of charging stations, high initial cost, battery life, weight and size of battery and degradation of battery performance with time. Charging the battery of EVs during the off-peak duration especially at late night enables stabilization of grid as fluctuation will reduce significantly.

The various other challenges in designing of BTMS include energy utilised by BTMS, limited available space for BTMS, uneven temperature distribution within the battery which affects the performance and lifetime and increase in temperature of the battery which results in thermal runaway of the battery. Thermal runaway occurs in situation where an increase in temperature changes the condition in a way that causes a further increase in temperature. BTMS should function and maintain within optimal temperature range of battery module and minimize temperature gradient across the module so that the cycle life and calendar life is increased which can thereby be justifying the capital cost of battery.
Thermal design of battery pack must remove the heat generated from pack immediately. A good thermal design improves pack efficiency, increases life for battery module.

Rami et al. [1] has compared air-cooled and PCM based BTMS systems with 18650 battery cells. 3-D model was considered for air-cooled BTMS and 2-D model was considered for PCM based BTMS. In air cooled system, air is passed through intersection gap axially. The study concluded that at high discharge rates and high ambient temperature condition, active cooling is not preferred since turbulent air flow is required which is not practical and temperature variation among cell is above 5°C. On the contrary, PCM based systems can control maximum temperature below 55°C for the same conditions and keep the temperature variation within cells is around 0.4°C. Zhiwei et al. [2] conducted experimental and numerical study of PCM based BTMS around a cylindrical battery. Case studies with different number of fins were also conducted. The melting process when visualized can be classified into 3 regions namely ramp up, plateau and complete melting. Effective control point is at end of plateau regime and it is affected by structure of the system for heat transfer and ambient temperature. Addition of fins accelerates ramp up process alone. The suggested temperature ranges to maintain the battery is between -20°C to 60°C, it is found that best life of battery can be extrapolated when it is maintained between 15°C to 45°C. As well as the temperature difference between battery within battery module should be less than 5°C.

Ziye et al. [3] worked on experimental and numerical study of PCM for power battery BTMS. In this research work, PCM is filled in a cylindrical container which has four heater rods which were used to simulate heat generated by battery. The quarter of the cylindrical container was taken as computational domain and ANSYS FLUENT software was used for the thermal simulation of the system. Low phase change temperature hinders the cooling process of the system. Temperature obtained from simulation is higher than that obtained from experimental studies and this could be due to heat losses to ambient medium in experimental set up. It was concluded that low paraffin composite has superior temperature control. Hassan Fathabadi [4] proposed a PCM based BTMS for prismatic battery to EV application. The BTMS contain ducts to allow air pass through via natural convection, it also has volume expansion receptacle for the expansion of PCM to take place in battery module. Low maximum temperature dispersion was obtained in each battery. Better thermal performance of BTMS for various ambient temperatures was reported and concluded that uniform voltage distribution assists in battery management.

Morteza Alipanah and Xianglin [5] performed numerical investigations of cooling system based on PCM for BTMS application for Li-ion battery. The 2-D model was considered for formulation of the field and computational analysis was carried out. The rectangular geometry was taken for PCM and specified heat flux boundary conditions were considered on two opposite sides. The performance of PCM was simulated for varying thicknesses of PCM. The battery discharge time increased under acceptable temperature range while the temperature uniformity decreased with increase in PCM thickness. Increase in temperature uniformity, discharge time and decrease in surface temperature were achieved by using metal matrix.

From the literature, it is evident that not much research has been reported on the cyclic performance of BTMS and discharging of thermal energy from BTMS. The objectives of the present work are to analyse and evaluate the performance of the passive BTMS, reduce the maximum temperature in battery module, improve temperature uniformity in battery module and analyse the cyclic performance of BTMS. To the extent possible, the objectives are to be achieved with acceptable trade-off.

2. Problem description
Initially, two-dimensional mathematical model is considered to simulate the thermal response of the phase change material (PCM). Five different PCMs with different melting points were considered as shown in Table 1 for selecting the best PCM and implement the same as working medium in Battery thermal management system (BTMS) of the EV. Four different cases were considered for every PCM to understand the complete thermal response of different PCMs. Case-1 and Case-2 are adopted to
understand the melting and solidification process of PCM. Case-3 and Case-4 are adopted to understand the cyclic performance of PCM.

A rectangular two-dimensional domain (x-y plane) of dimensions 9 mm × 65 mm was the computational domain for the two-dimensional model as shown in Figure 1. In all the cases, the ambient temperature was considered as 20°C and the horizontal sides of the domain are treated as insulated. Hence, two boundary conditions that are applicable to four cases of the two-dimensional simulation are:

\[
\frac{\partial T(x,0,t)}{\partial y} = 0 \quad \text{(1)}
\]

\[
\frac{\partial T(x,L_1,t)}{\partial y} = 0 \quad \text{(2)}
\]

Initial condition for any case of the two-dimensional domain is:

\[T(x,y,0) = T_i \quad \text{(3)}\]

The initial temperature of the PCM was considered as 20°C in case 1, case 3 and case 4 and 70°C in case 2. Heat flux is imposed on the two vertical faces of the computational domain in case 1. Natural convection cooling of the PCM due to heat transfer from both the vertical faces of the domain was considered in case 2. For case 1 and case 2 the boundary conditions will be

For case 1:

\[q = -k \frac{\partial T(0,y,t)}{\partial x} \]

\[q = k \frac{\partial T(L_2,y,t)}{\partial x} \quad \text{(4)}\]

For case 2:

\[k \frac{\partial T(0,y,t)}{\partial x} = h \left( T(0,y,t) - T_\infty \right) \]

\[-k \frac{\partial T(0,L_2,t)}{\partial x} = h \left( T(0,L_2,t) - T_\infty \right) \quad \text{(5)}\]

**Figure 1.** Two-dimensional computational domain

For case 3, PCM is exposed to constant heat flux for 2 hours duration for heating followed by natural convection cooling for 3 hours duration. Constant heat flux is applied for heating of the PCM until the
maximum temperature of any location in the PCM reached to 60°C and followed by natural convection cooling is applied in case 4. Numerical simulations for different PCMs in different cases were carried out using COMSOL Multiphysics 5.5 software.

| Type of PCM | Melting Temperature (°C) |
|-------------|--------------------------|
| Octadecane  | 28.1                     |
| Eicosane    | 36.6                     |
| Docosane    | 44                       |
| Tetracosane | 50.6                     |
| RT 25       | 25                       |

PCM is selected through the two-dimensional numerical simulation is considered as the medium to regulate the temperature of the battery module in EV. A battery module with 444 cells is considered with 37×12 arrangement for the numerical study as shown in Figure 2. The dimensions of the battery module are 740 mm × 300 mm × 65 mm. Three-dimensional mathematical model is developed to simulate the transient temperature distribution in the battery module. Considering the symmetry of the field, a quarter of the module is considered as computational domain for simulation. The dimensions of the computational domain are 370 mm × 150 mm × 65 mm. Numerical simulation for the battery module was carried out using COMSOL Multiphysics 5.5 software. Cells with the specification of 18650 are considered to use in battery module. Grid independent tests has been done for both two dimensional and three-dimensional fields.

![Figure 2. BTMS (a) Orthogonal view and (b) Top view](image)

### 3. Mathematical model

The following are the assumptions considered for two-dimensional modelling of PCM and three-dimensional modelling of BTMS in the present work:

For two-dimensional modelling of PCM:
- Two-dimensional field (x-y plane).
- The melted PCM flow is incompressible, laminar, unsteady and Newtonian.
- PCM domain is treated as isotropic and homogeneous.
- Heat transfer by radiation mechanism is neglected.
- Viscous dissipation work is neglected related to PCM in liquid phase

For three-dimensional modelling of BTMS:
- The melted PCM flow is incompressible, laminar, unsteady and Newtonian.
• Steady and uniform volumetric heat generated in the cell.
• Contact resistances between the PCM and cells are neglected.
• Battery module and PCM domain is treated as isotropic and homogeneous.
• Heat transfer by radiation mechanism is neglected.
• Viscous dissipation work is neglected related to PCM in liquid phase

3.1. Two-dimensional mathematical modelling of PCM

Governing differential equation for temperature distribution of PCM [7] is

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} - \rho c_p v T \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} - \rho c_p v T \right)$$

Equations of motion applicable liquid phase of the PCM [7] are

\[ \text{x-component: } \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial P}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + F_b \]
\[ \text{y-component: } \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = - \frac{\partial P}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \]

where, \( F_b = -\rho \text{liquid} (1 - \beta(T - T_m)) g \) - buoyancy force which is a source term

The density and thermal conductivity of PCM can be modelled as [7]

\[ \rho_{PCM}(T) = \rho_{solid} + (\rho_{liquid} - \rho_{solid}) B(T) \]  
\[ k_{PCM}(T) = k_{solid} + (k_{liquid} - k_{solid}) B(T) \]

where, \( B(T) \) is the fluid fraction or melt fraction which is defined as [7]

\[ B(T) = \begin{cases} 0 & \text{if } T < (T_m - \Delta T) \\ (T - T_m + \Delta T)/(2\Delta T) & \text{if } (T_m - \Delta T) \leq T \leq (T_m + \Delta T) \\ 1 & \text{if } T > (T_m + \Delta T) \end{cases} \]

The specific heat of PCM can be modelled as [7]

\[ c_{PCM}(T) = c_{p\text{solid}} + (c_{p\text{liquid}} - c_{p\text{solid}}) B(T) + L_h D(T) \]

where, \( D(T) \) is dirac delta function and is given by [7]

\[ D(T) = e^{-\frac{(T-T_m)^2}{2\Delta T^2}} \sqrt{\pi(\Delta T)^2} \]

The viscosity of PCM can be modelled as [7]

\[ \mu(T) = \mu_l (1 + A(T)) \]

where, \( A(T) \) is a porosity operator and is given by [7]

\[ A(T) = \frac{C_m (1 - B(T))^2}{B(T)^3 + \varepsilon} \]

3.2. Three dimensional mathematical modelling of BTMS

Governing differential equation for temperature distribution of the cell is [1]:

$$\rho c_p \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q_g$$

Governing differential equation for temperature distribution of PCM [7]:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} - \rho c_p v T \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} - \rho c_p v T \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} - \rho c_p v T \right)$$
Equations of motion related to liquid phase of PCM [7]:

\[ x\text{-component: } \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \]

\[ y\text{-component: } \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + F_b \]

\[ z\text{-component: } \rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = - \frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \] (17)

where, \( F_b = -\rho_{\text{liquid}}(1 - \beta(T - T_m))g \) which is a source term related to buoyancy force.

Thermophysical properties of the PCM and corresponding constants like \( A(T) \), \( B(T) \) and \( C(T) \) are modelled using Equations (8) to (14). The thermal energy storage of PCM can be modelled as [8]

\[ Q_s(T) = \begin{cases} 
\rho_{\text{solid}} c_{\text{solid}} (T - T_0) & \text{if } T < T_m \\
\rho_{\text{solid}} c_{\text{solid}} (T_m - T_0) + \frac{\rho_{\text{solid}} + \rho_{\text{liquid}}}{2} L_h & \text{if } T = T_m \\
\rho_{\text{solid}} c_{\text{solid}} (T_m - T_0) + \frac{\rho_{\text{solid}} + \rho_{\text{liquid}}}{2} L_h + \rho_{\text{liquid}} c_{\text{liquid}} (T - T_m) & \text{if } T > T_m 
\end{cases} \] (18)

Initial condition:

\[ T(x, y, z, 0) = T_l \] (19)

Boundary conditions:

\[ \frac{\partial T(x, y, 0, t)}{\partial z} = 0 \]
\[ \frac{\partial T(x, y, L_z, t)}{\partial z} = 0 \]

\[ k \frac{\partial T(0, y, z, t)}{\partial x} = h \left( T(0, y, z, t) - T_\infty \right) \]
\[ k \frac{\partial T(L_x, y, z, t)}{\partial x} = 0 \]

\[ k \frac{\partial T(x, 0, z, t)}{\partial y} = h \left( T(x, 0, z, t) - T_\infty \right) \]
\[ k \frac{\partial T(x, L_y, z, t)}{\partial y} = 0 \] (20)

4. Results and discussion

4.1. Simulation of PCMs for case 1 (Heat flux imposed on PCM)

Transient variation of maximum, average and minimum temperatures of different PCMs when exposed to same heat flux in case 1 are shown in Figure 3. The solid-liquid interface moves from the sides to the centre of the PCM during heating process while the PCM is executing the phase change. It is observed that the solid PCM moving downwards and the liquid PCM moves upwards during the phase change process, which can be attributed to the principle of buoyancy. Complete phase change occurred in PCMs like Eicosane, Docosane and RT 25 during the stipulated duration of the heating process which is evidenced with the trend of minimum temperature. PCMs like Octadecane and Tertracosane are still with solid phase by the end of the duration of heating. The durations to attain the maximum temperature of 60°C for Octadecane, Eicosane, Docosane, Tertracosane and RT 25 are 6010s, 4170s, 4500s, 21550s, 3200s, respectively for the thermal conditions. One of the necessary requirements for the PCM to act as a working medium in BTMS is to absorb large quantity thermal energy while the phase change in progress which means the PCM should take more time duration for the execution of melting process.
Figure 3. Variation of temperature with time for case-1: (a) Octadecane (b) Eicosane (c) Docosane (d) Tetracosane and (e) RT25

4.2. **Simulation of PCMs for case 2 (Natural convection cooling of PCM)**

Transient variation of maximum, average and minimum temperatures of different PCMs when undergoing natural convection cooling under the same thermal conditions in case 2 are shown in Figure 4. The solid-liquid interface moves from the sides to the centre of the PCM during cooling process while
the PCM is executing the liquid-solid phase change. Movement of the liquid PCM upwards can be observed, while the solidification due to natural convection cooling is in progress. Complete phase change occurred in PCMs like Eicosane, Docosane and RT 25 with in the reasonable duration compared to the other two PCMs such as Octadecane and Tertracosane. Completion of phase during natural convection cooling is witnessed with the trend of maximum temperature. The time taken for the attainment of the lowest temperature of PCM which is very nearer to ambient conditions by Octadecane, Eicosane, Docosane, Tertracosane and RT 25 are 25900s, 10080s, 8490s, 25040s and 13390s, respectively. The required characteristic to be possessed by the PCM in BTMS is quick dissipation of thermal energy and consequent completion of liquid-solid phase change process.

![Graphs showing temperature variation with time for Octadecane, Eicosane, Docosane, Tertracosane, and RT 25.](image)

**Figure 4.** Variation of temperature with time for case-2: (a) Octadecane (b) Eicosane (c) Docosane (d) Tetracosane and (e) RT25
4.3. Simulation of PCMs for case 3

Transient variation of maximum, average and minimum temperatures of different PCMs when exposed to cyclic conditions under the same thermal environment in case 3 are shown in Figure 5. PCMs are exposed to simultaneous heating and cooling processes in defined durations in case 3. Among the different PCMs, both solid-liquid phase change during heating process and liquid-solid phase change during cooling process were incomplete in the defined durations for Tetracosane and Octadecane. It can be observed that there is no deviation between maximum, average and minimum temperatures for Tetracosane while undergoing phase change processes. Before the commencement of liquid-solid phase change process due to cooling, solid-liquid phase change process was successfully completed for PCMs like Eicosane, Docosane and RT25. Liquid-solid phase change process was successfully completed in the defined duration for Eicosane and Docosane, among this early phase change was observed for Docosane. The maximum temperatures reached by Octadecane, Eicosane, Docosane, Tetracosane and RT25 in case 3 are 88.44 °C, 140.68 °C, 128.59 °C, 49.70 °C, 187.1 °C respectively.
Figure 5. Variation of temperature with time for case-3: (a) Octadecane (b) Eicosane (c) Docosane (d) Tetracosane and (e) RT25

4.4. Simulation of PCMs for case 4

Transient variation of maximum, average and minimum temperatures of different PCMs when exposed to cyclic conditions under the same thermal environment in case 4 are shown in Figure 6. In case 4, every PCM is exposed to heating process till the temperature attained at any location is 60°C and followed by this, they are allowed to cool for the duration which is twice that of the duration required to attain 60°C. Among the different PCMs, the time taken to attain 60°C for Tetracosane was almost four times higher than the other PCMs. In addition to this time taken to complete the phase change process upon cooling is also very high for Tetracosane. 21600 s is the duration to reach till 60°C and 26280 s is the duration to cool to ambient temperature for Tetracosane. Octadecane takes 6010 s to reach till 60°C and 26680 s to cool to ambient temperature. Though the time taken to reach threshold safety temperature is little high, cooling period is very very high for Octadecane which makes this not preferred in terms of reusability. Docosane takes 4500 s to reach till 60°C and 8790 s to cool to ambient temperature which is performing fairly good for attaining the threshold temperature and cooling to ambient temperature from threshold temperature compared with all other PCMs. According to thermodynamic energy balance it was evaluated that Docosane takes 4629.98 s to reach 60 °C which is approximately closer to the simulated results. Hence, the simulation results are validated with the help of fundamental principle ‘conservation of energy’.
Figure 6. Variation of temperature with time for case-4: (a) Octadecane (b) Eicosane (c) Docosane (d) Tetracosane and (e) RT25

4.5. Simulation of BTMS
Considering the results of two-dimensional simulations for four different cases applied to five different PCMs, Docosane was selected as the PCM in the BTMS. Operating conditions of EV were taken into consideration in which BTMS is employed and five hours duration was considered to simulate the thermal conditions of the BTMS. Among the five hours duration, in the first two hours duration the vehicle is in operation and the consequent heat generation in the battery is taking place. The vehicle will not be in the operation for the remaining three hours and there will not be any heat generation in the battery during this period.

Three-dimensional simulation of the BTMS was carried out for five hours and the simulation results are presented in Figure 7. The temperature of the battery is varying with time and the it is maintained within the desired limits with a maximum value of 52.1°C. Highest spatial temperature difference at an instant observed is 8.9°C in the battery and the same is observed as 12.2 °C in the PCM. The liquid fraction of the PCM and energy stored in the PCM were continuously increased with time in the duration of heating process. The increasing trends of liquid fraction and energy stored in the PCM were continued even after the heating period. These are due to the prevailing temperature difference between battery and the PCM and dominant rate of heat transfer from the battery to PCM compared to rate of heat transfer from the PCM to ambient air. The PCM was effectively used which was reassured by the value of maximum liquid fraction of 0.9 achieved in 9210 s. The instant at which the spatial temperature difference goes beyond 5 °C is 10920 s. The maximum energy stored by the PCM was observed as 427000 J in 8100 s duration. At
the end of 5 hours, the thermal energy stored in PCM was observed as 378000 J, which is significantly high and still needs to be dissipated.

![Figure 7](image-url)

**Figure 7.** Variation of (a) temperature of the battery (b) temperature of PCM (c) thermal energy stored in the PCM and (d) liquid fraction of PCM with time in BTMS

### 5. Conclusion

Two-dimensional model was developed to simulate the thermal and cyclic performances of different PCMs so as to select the suitable one to act as a medium for controlling the temperature of battery in the BTMS. Octadecane, Eicosane, Docosane, Tetracosane and RT25 are the five different considered and they were exposed different thermal conditions through four case studies. Simulation of the five PCMs were carried out in four different cases.

- The durations to attain the maximum temperature of 60°C for Octadecane, Eicosane, Docosane, Tetracosane and RT25 are 6010s, 4170s, 4500s, 21550s, 3200s, respectively when all the PCMs were exposed to same heat flux during heating of process in case 1.
- The time taken for the attainment of the lowest temperature of PCM which is nearer to ambient conditions by Octadecane, Eicosane, Docosane, Tetracosane and RT25 are 25900s, 10080s, 8490s, 25040s and 13390s, respectively when all the PCMs were allowed to natural convection cooling in case 2.
- Solid-liquid and liquid-solid phase change processes was successfully completed in the defined durations for Eicosane and Docosane while all the PCMs were exposed to simultaneous heating...
and cooling processes in the defined durations in case 3. Among the two PCMs, an early liquid-solid phase change was observed for Docosane.

- Every PCM is exposed to heating process till the temperature attained at any location is 60°C and followed by this, they are allowed to cool for the duration which is twice that of the duration required to attain 60°C in case 4. Docosane takes 4500 s to reach till 60°C and 8790 s to cool to ambient temperature which is performing fairly good for attaining the threshold temperature and cooling to ambient temperature from threshold temperature compared with all other PCMs.

Considering the results of two-dimensional simulation results for four different cases applied to five different PCMs, Docosane was selected as the PCM in the BTMS. Three-dimensional simulation of the BTMS was carried out for five hours and the simulation results are presented.

- The temperature of the battery is varying with time and it is maintained within the desired limits with a maximum value of 52.1°C.
- Highest spatial temperature difference at an instant observed is 8.9°C in the battery and the same is observed as 12.2 °C in the PCM.
- The PCM was effectively used which was reassured by the value of maximum liquid fraction of 0.9 achieved in 9210 s.
- The instant at which the spatial temperature difference goes beyond 5 °C is 10920 s.
- The maximum energy stored by the PCM was observed as 427000 J in 8100 s duration.

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