

Numerical Analysis of Battery Thermal Management Using Phase Change Material Concerning Melting Fraction and Temperature

P. Sai Kiran^{1*}, T. Kanthimathi², Murali G³, P.S.N. Masthan Vali⁴

Abstract

This work, analysis and simulates a phase change material melting for battery thermal management (BTM). Phase change materials (PCM) are the substances that, undergo through a phase transition, such as melting from solid to liquid by absorbing or releasing a significant amount of energy as heat. PCM is advantageous for the thermal control of batteries because of this characteristic. As the battery produces heat, the PCM surrounding it absorbs the heat and changes phase from solid to liquid. The heat that is absorbed during the transition process contributes in keeping the battery's temperature within safe ranges. Using a 2D rectangular domain, we analyze phase-change materials. All walls are interpreted as natural convection and the inner circle is used to fit the 18650 batteries. In this domain, we assume constant heat from the wall as the battery heats up. This can be simulated using ANSYS (fluent) 2022 R2 software. The phase change materials used in the present analysis are paraffin wax and lauric acid. For a total melting duration of 60 minutes, the counters of the liquid fraction and temperature of different PCM particles are obtained at regular intervals of 15 minutes. The contours aided in figuring out how the formation of a melting contact varies as melting progresses with time. Following a simulation lasting for 60 minutes, it was observed that the melting percentage of lauric acid was 0.61%, whereas that of paraffin wax was 0.94%. These findings suggest that the utilization of lauric acid results in a greater reduction in battery temperature as compared to the use of paraffin wax.

Keywords: battery thermal management, phase change material, lauric acid, paraffin wax, Lauric Acid

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INTRODUCTION

In recent years, due to increased energy needs and the declining availability of fossil fuels, the use of electric vehicles powered by lithium-ion batteries has become increasingly popular. However, these batteries are plagued by thermal management issues, which have led to significant research on the topic. Abas et al. [1] examined the relationship between fossil fuel production and consumption rates, Due to the problems with global warming, there has been a huge rise in energy consumption in recent years due to significant industrial expansion and population growth worldwide. Renewable energy sources might present an alluring alternative in this case; however, their energy output is not uniform, further exacerbating the problem. Classified various battery thermal management systems and

discussed the thermal model of battery packs. The BTMS's lightweight design and cost-effective energy usage remain difficult issues. Lithium-ion batteries have serious thermal problems and heat-generating phenomena. The research on various battery thermal management systems is then thoroughly analyzed and arranged into groups based on thermal cycle possibilities. Direct refrigerant two-phase cooling, second-loop liquid cooling, and cabin air cooling are all components of the battery thermal management system with a vapour compression cycle [2–4]. Akinlabi et al. [5] investigated air-cooled BTM's in detail in terms of the methods and optimization strategies employed to enhance cooling performance. Chen et al. [6] optimized the design of parallel air-cooled systems for better cooling performance. To determine the velocities in the system's cooling channels, the flow resistance network model is presented. The original BTMS and the optimised BTMS are both subjected to three-dimensional CFD computations. The results suggest that following optimisation, the BTMS's cooling performance may be greatly enhanced. The battery pack's maximum temperature differential has been lowered by 45% they are still lowered by 35% and 32%, respectively, for 4C and 5C discharge procedures following optimisation. In a separate study, kai chen et al. [7] developed a symmetrical air-cooled system to improve temperature uniformity and reduce energy consumption. According to the results, the system with a smaller number of battery cells exhibits a more consistent temperature distribution and also consumes less energy per cell. The experimental result shows at least a 43% reduction in the extreme cell-temperature variation and a minimum 33% reduction in energy consumption, while Wu et al. [8] discussed the temperature impact on battery performance and proposed a thermal management system using heat pipes. A liquid-based system is explored in terms of both primary and secondary contact modes. They employ a liquid-gas phase change technology, and warmth pipe-based BTM is possible and effective due to its high heat transfer efficiency. Huo et al. [9] designed a mini-channel cold plate-based system to cool Li-ion batteries and studied the effects of flow rate and ambient temperature, and Lai et al. [10] demonstrated a small and lighter liquid-cooled BTM system for controlling the optimal heat and temperature differential of a lithium-ion power battery set. They create a single thermally conductive structure that has three curved contact surfaces. The flow distribution over serial tests is improved by designing the inlet and outlet sites, allowing the T max and DT of a battery pack to be comparable to those of a single battery. Wang et al. [11] proposed a modular liquid-cooled system and studied the effects of coolant fluid flow rate and manner of cooling on battery module thermal behavior.

Several research has looked into the usage of phase-change material (PCM) for cooling in the scope of heat management for lithium-ion batteries. Numerically simulated the melting of PCM for thermal energy storage using ANSYS software. The contours of the liquid percentage, density, temperature, and velocity of PCM particles are shown at regular intervals over a total melting duration of 240 minutes, and the change in melting fraction with time is explained [12, 13]. Chen et al. [14] compared the performance of active air cooling and passive PCM cooling for battery thermal management systems. Mazhar et al. [15] proposed a novel approach for harnessing waste thermal energy from greywater using PCM and copper fins. Buonomo et al. [16] explore the effectiveness of PCM combined with metal foam for cooling lithium-ion batteries. Heyhat et al. [17] compared the effects of using nanoparticles, fins, and porous metal foam in a passive thermal management system for lithium-ion batteries. Weng et al. [18] explored different fin configurations for PCM cooling technology and found that an optimized PCM module with various fins can result in a lower maximum battery temperature and smaller temperature range. Murali et al. [19] reviewed studies on PCM cooling for Battery Thermal Management Systems in electric vehicles. Verma et al. [20] studied the effectiveness of using Capric acid as a passive cooling method through different thicknesses of PCM layers in reducing the maximum temperature in a battery pack. Safdari et al. [21] explored the thermal management of a conglomerate battery system using a hybrid of both passive and active modes. Cooling methods, investigating the effectiveness of different PCM vessel shapes.

Several research have been conducted to study the usage of composite phase transition materials (cpcms) for BTM. Zhiguo et al. [22] bloom a CPCM and liquid cooling system for lithium-ion batteries that effectively reduced the optimum battery compartment temperature during charge-

discharge cycles. Wu et al. [23] exhibited good cooling capacity in various battery modules using a flexible CPCM composed of a polyester thermoplastic elastomer. Jiang et al. [24] investigated the thermal control performance of a CPCM with varied mass fractions of expanded graphite and discovered that a CPCM with 16–20 wt.% EG loading performed very well. Finally, Huang et al. [25] demonstrated a unique flexible CPCM made up of SBS@PA/EG that efficiently regulated the peak temperature and temperature differential in BTM systems throughout the discharge process. Examine the impact of liquid inlet velocity and material module on thermal management performance, with a significant improvement observed in lowering cell temperature. Overall, these studies demonstrate the potential of cpcms for improving battery thermal management and offer various approaches for optimizing their performance. In this paper, passive and active air-cooled BTMS approaches are examined, along with design parameter optimization methodologies [26, 27].

MATERIALS

Mahdi et al. [28] have established the predefined properties of paraffin wax as shown on "Table 1" and [29–30] have established the predefined properties of lauric acid as shown on "Table 2". Based on his work, the current study aims to utilize these properties for further investigation.

Table 1. Properties of Paraffin Wax.

Property	Value
Solidus temperature(K)	317.5
Liquidus temperature(K)	321.3
Phase change latent heat (J/kg)	178780
Specific heat (J/kg K)	2200
Density (kg/m ³)	857
Thermal conductivity (W/m K)	0.157
Viscosity (Kg/m s)	0.0067
Coefficient of thermal expansion $\beta(K^{-1})$	0.0006

Table 2. Properties of Lauric acid.

Property	Value
Solidus temperature(K)	311.15
Liquidus temperature(K)	316.15
Phase change latent heat (J/kg)	165000
Specific heat (J/kg K)	200
Density (kg/m ³)	820
Thermal conductivity (W/m K)	0.2
Viscosity (Kg/m s)	0.02
Coefficient of thermal expansion $\beta(K^{-1})$	0.0001

NUMERICAL MODEL

The battery material melting of phase change material (PCM) process has been simulated and modelled using the ANSYS (Fluent) 2022 R2 software. ANSYS Fluent's melting and solidifying scenario has been utilized, employing the enthalpy porosity method for simulating the solidification and melting processes. This methodology provides a comprehensive understanding of the physical phenomenon, enabling accurate predictions of the thermal behaviour during the phase change process. By implementing this advanced approach, the simulation results obtained are reliable and can aid in optimizing the design of PCM-based systems. In this method, the exact moment the material transitions from solid to liquid form is not explicitly recorded. Instead, each cell within the PCM domain is assigned a specific value known as a liquid fraction, representing the proportion of the cell volume that exists in liquid form. The liquid fraction is calculated following each iteration, taking into account the overall enthalpy balance.

This process results in a phase shift interface that is characterized by a mushy zone, wherein the liquid fraction value fluctuates between 1 to 0. This mushy zone can be likened to a porous, zone in which the porosity gradually decreases from 1 to 0. Once the material has fully hardened, the porosity within this zone becomes zero, and the velocity within the area also falls to zero.

Assumption

In the numerical modelling, it was assumed that melting is a transient phenomenon that can be represented as a two-dimensional process. This assumption suggests that the melting process occurs over a short period and can be approximated by a simplified mathematical model that only considers the two-dimensional aspects of the process. By making this assumption, the model can more easily predict the changes in the phase transition of the PCM.

The second assumption used in the numerical modelling is that the liquid motion of the PCM is incompressible, non-Newtonian, and turbulent. This implies that the fluid's velocity does not change as it passes through different areas of the system, and its viscosity and turbulence behaviour are consistent. These assumptions were made to make the mathematical model easier to understand, making it easier to simulate the fluid's behaviour.

In the numerical modelling, the PCM's density, viscosity, and thermal conductivity were assumed to change in a piecewise linear fashion. This assumption suggests that the PCM's properties change gradually, and the changes can be approximated as a series of linear steps. This allows the model to simulate the changes in the PCM's properties over time accurately.

The fourth assumption used in the numerical modelling is that viscous heating and volume expansion are not taken into account. This implies that the energy generated by the fluid's viscosity and the increase in volume due to the melting of the PCM is not included in the model. This simplifies the mathematical model and makes it easier to predict the changes in the PCM's properties.

Finally, it was assumed that the PCM does not generate any heat. This assumption implies that the PCM's energy is constant throughout the process, and no heat is produced or lost. This assumption is used to simplify the mathematical model and make it easier to simulate the changes in the PCM's phase transition.

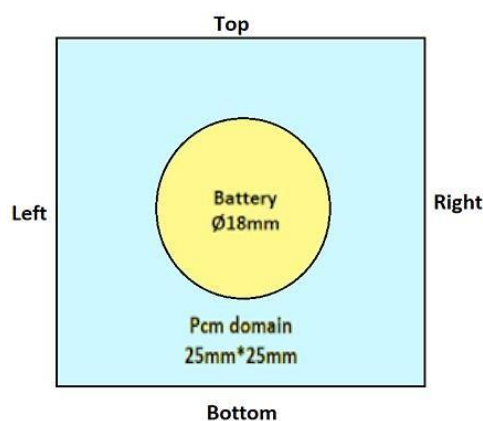


Figure 1. Schematic Diagram of the Model.

Model Description

The "Figure 1" below depicts a geometric representation of the battery thermal management area used for simulation. The current study addresses a two-dimensional planar rectangular domain of PCM, which has a length and height of 25 mm each. The domain holds a battery with an 18 mm diameter. The purpose of this inquiry is to examine the practises of the Phase Change Material (PCM) within the provided domain when linked to a battery. The PCM domain's boundary is defined by all

four walls, including the top, bottom, right, and left, which are exposed for free convective and have a heat transfer coefficient of $15 \text{ W/m}^2\text{K}$. It is anticipated that the battery would keep a constant temperature of 60 degrees Celsius.

Mesh Generation and Simulation Approach

The finite volume method using ANSYS (Fluent) 21 software has been employed to solve the problem. A crucial step in the pre-processing stage is selecting the appropriate mesh size. The mesh model used in this study consists of 10416 nodes and 10080 elements, as shown in "Figure 2" below. The momentum and energy equations' convective terms are discretized using a second-order upwind interpolation scheme. The coupling between pressure and velocity is achieved using a SIMPLE algorithm, while pressure interpolation uses the PRESTO method. The commercial CFD code provided by ANSYS (Fluent) 2022 R2 was used for the calculations. To accomplish this, the time study and grid independence test are carefully carried out to assess any influence on the solution, and they are shown in "Figure 3" "Figure 4" The energy, momentum, and continuity equations set to be in the limit of 10^{-6} , 10^{-3} , and 10^{-3} . After the time test, we take the value of the time step is 0.1 and 10 iterations per time. The imitation was executed through a 2.4 ghz intel core i5 processor with 8 gb ram.

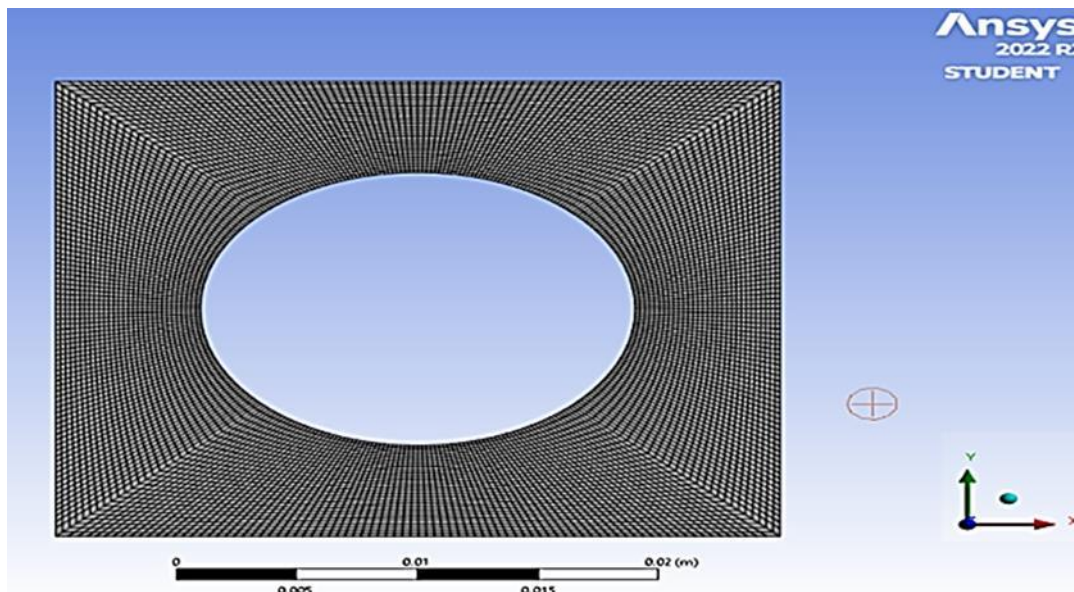


Figure 2. Schematic diagram of the meshed PCM domain.

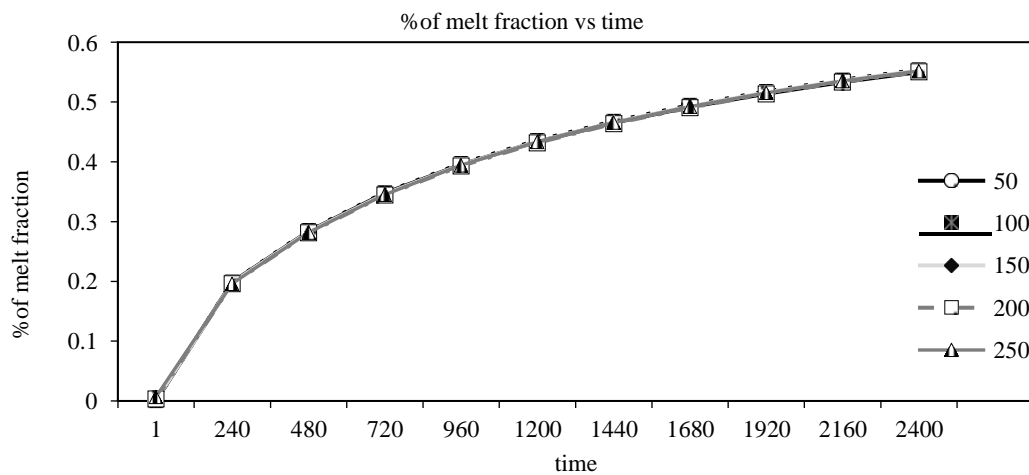


Figure 3. Grid independence study.

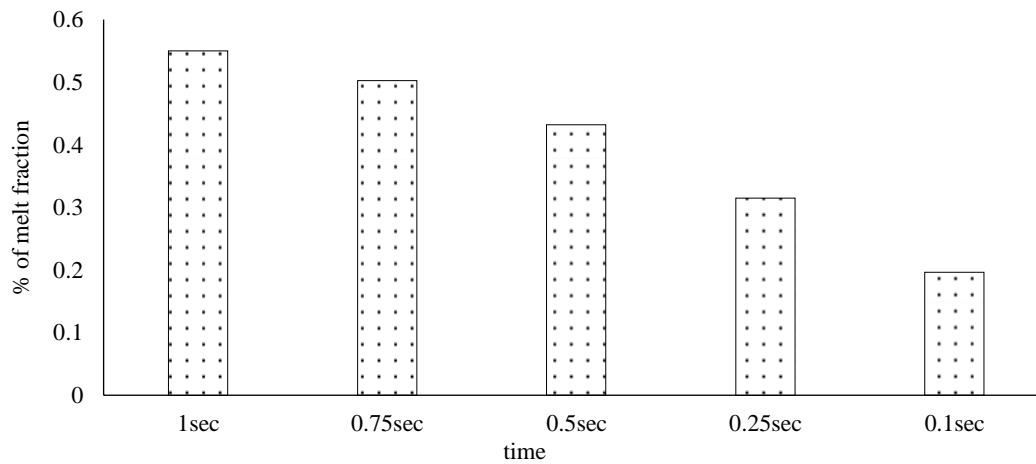


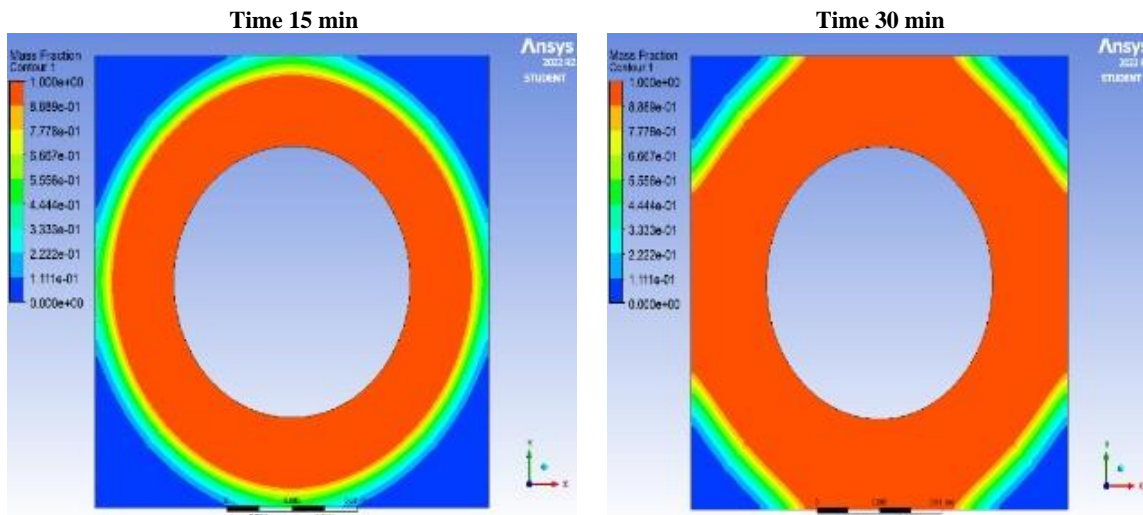
Figure 4. Time Step Study.

RESULTS AND DISCUSSIONS

Battery thermal management often involves studying the melting behaviour of materials such as paraffin wax and lauric acid. In this study, a numerical simulation was conducted to observe the melting process within a rectangular domain measuring 25 mm × 25 mm. The domain was subjected to constant heat from the battery and all the outer sides of PCM is exposed to natural convection. The outcomes of the model were captured at intervals of fifteen minutes over the period of a 60-minute melting cycle. The resulting data was analyzed and presented as contour plots of liquid fraction and temperature.

Counters of the liquid fraction

"Figure 5" depict varying of liquid fraction with time of paraffin wax and lauric acid, allowing us to analyse the form of a body and motion of the melting interfaces over time. The colour red shows the condition when the PCM is completely liquid ($\beta=1$), while the colour blue represents the condition when the material is fully solid ($\beta=0$). The mushy zone represents the melting front, separating the liquid and solid regions. The results shown that the initial stages of melting process (time=0–15 min), the melting interface is almost parallel to the centre, which suggests that heat transfer at this stage is primarily by conduction. However, as time progresses to 60 minutes, the liquid PCM with a maximum temperature and minimum density rises and moves from the centre to adjacent sides, continuing for more cycles.



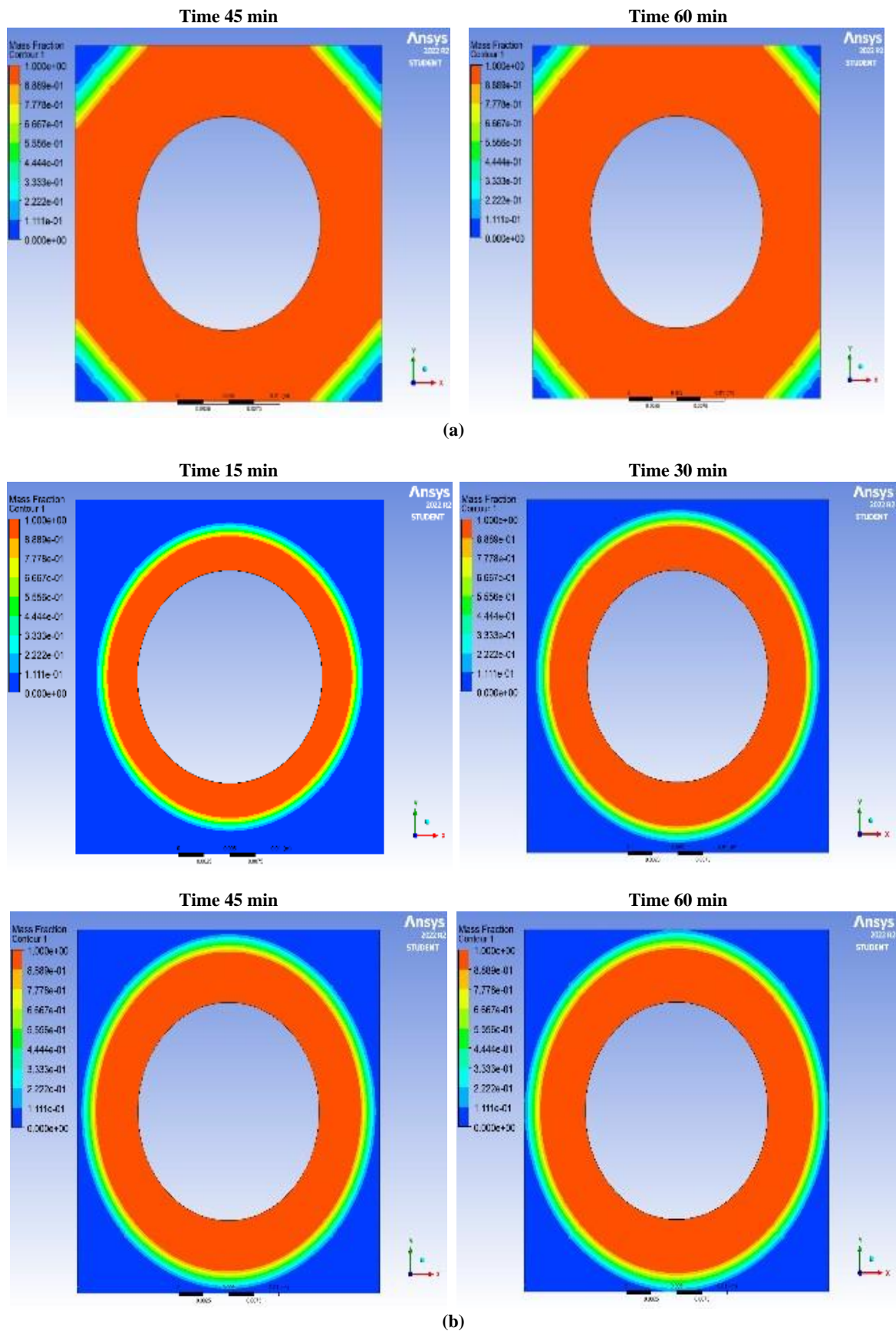


Figure 5. Counter of Liquid Fraction of (a) Paraffin Wax And (b) Lauric Acid.

"Figure 6" illustrates the varying in the melting fraction, defined as the percentage of PCM that has to be melted with increase in the time. At the initial time of 0 minutes, the domain PCM is in completely solid state, hence the liquid fraction is zero. As time progresses and the PCM is heated, it undergoes a change of state from solid to liquid, resulting in an increase in the melting fraction. The melting fraction values of paraffin wax were recorded at various time intervals, with respective values of 66%, 85%, 91% and 94% obtained at the melting time of 15, 30, 45, and 60 minutes. The melting fraction values of lauric acid were recorded at various time intervals, with respective values of 39%, 51%, 55% and 60% obtained at the melting time of 15, 30, 45, and 60 minutes. The melting rate is observed to be constant in the beginning of the process and it has been increased more in middle and towards rest of the process. When lauric acid absorbs more heat compared to paraffin wax by liquid fraction rate. Conducted a simulation of PCM melting using ANSYS (Fluent) [29–30].

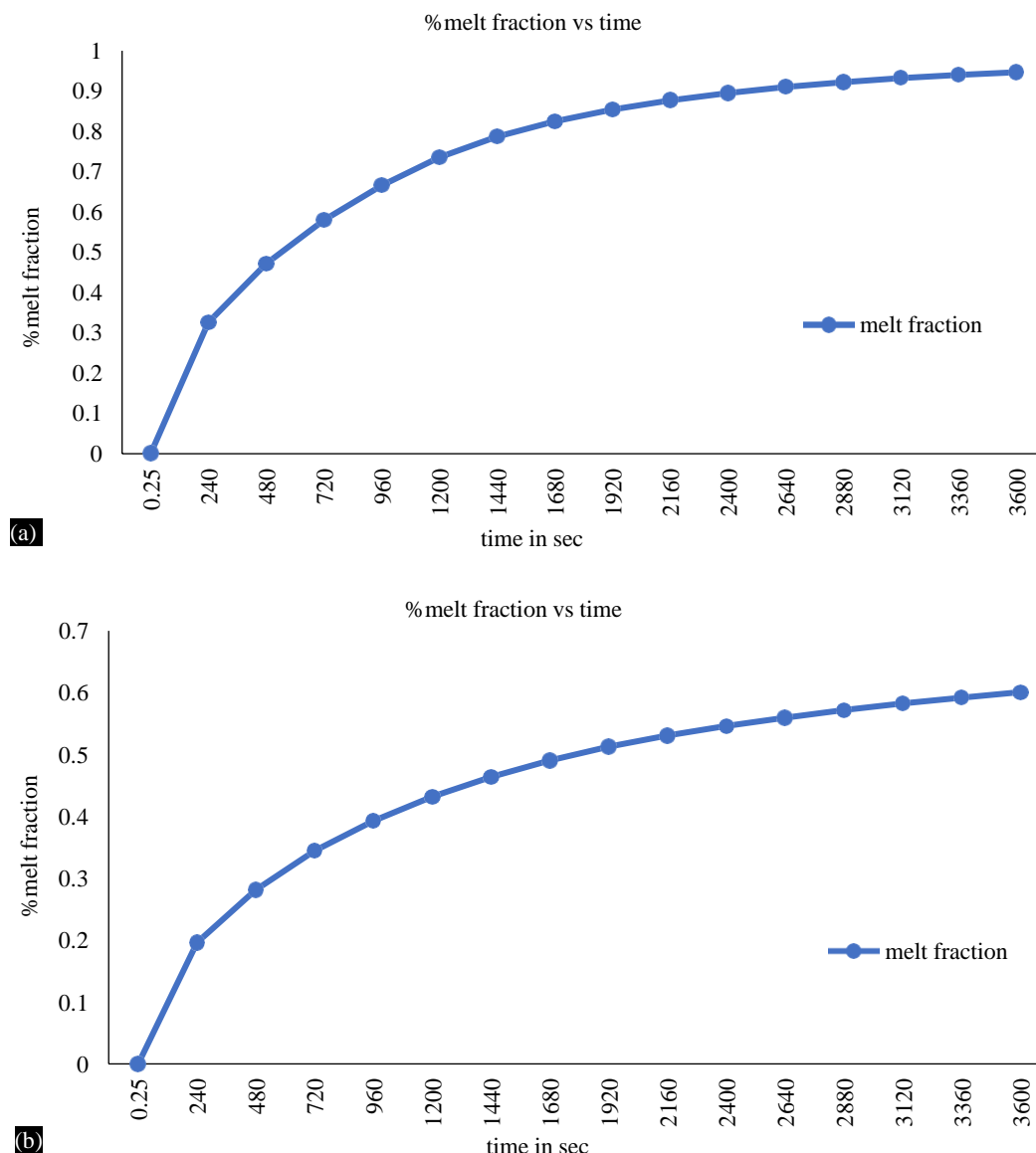
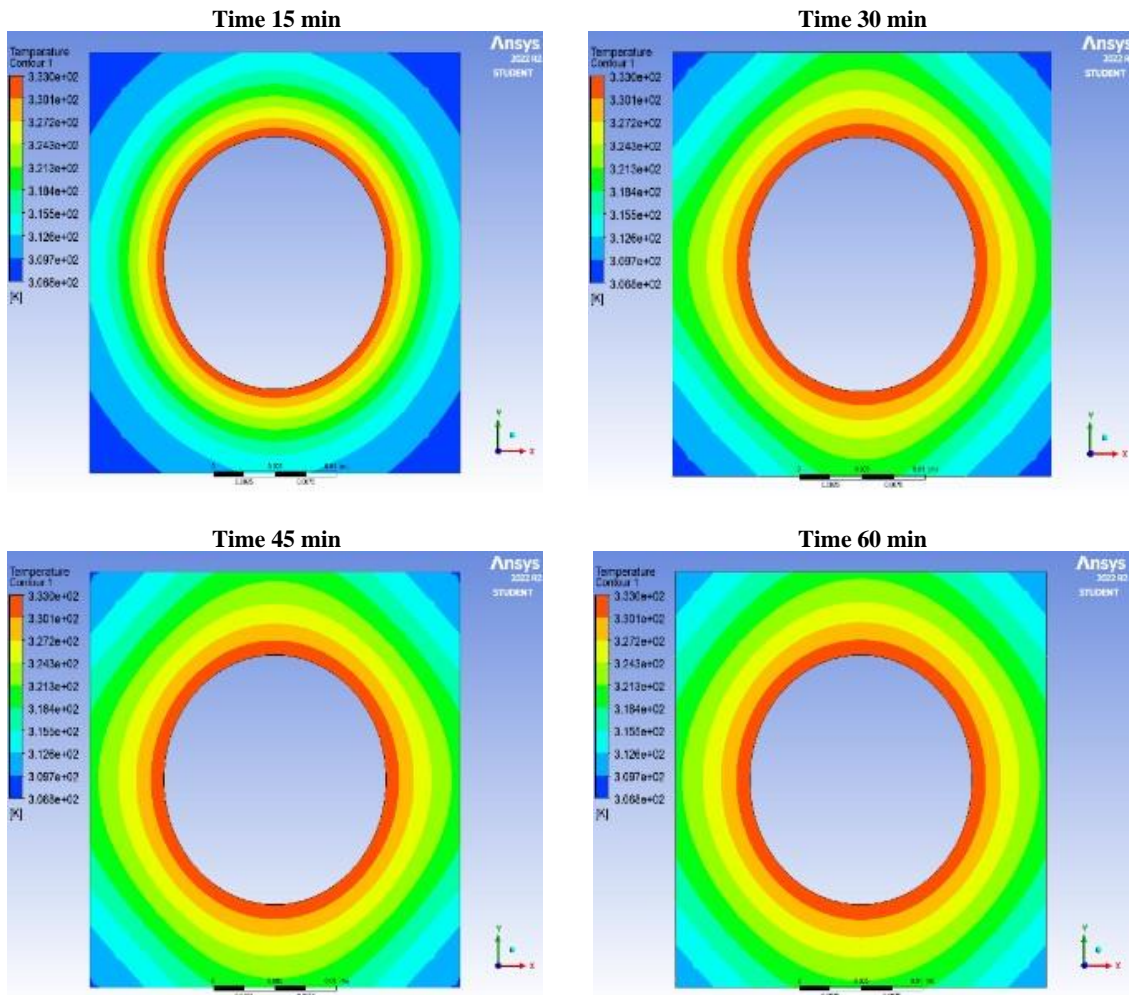


Figure 6. Variation of melting fraction with a time of (a) paraffin wax and (b) lauric acid Acid.

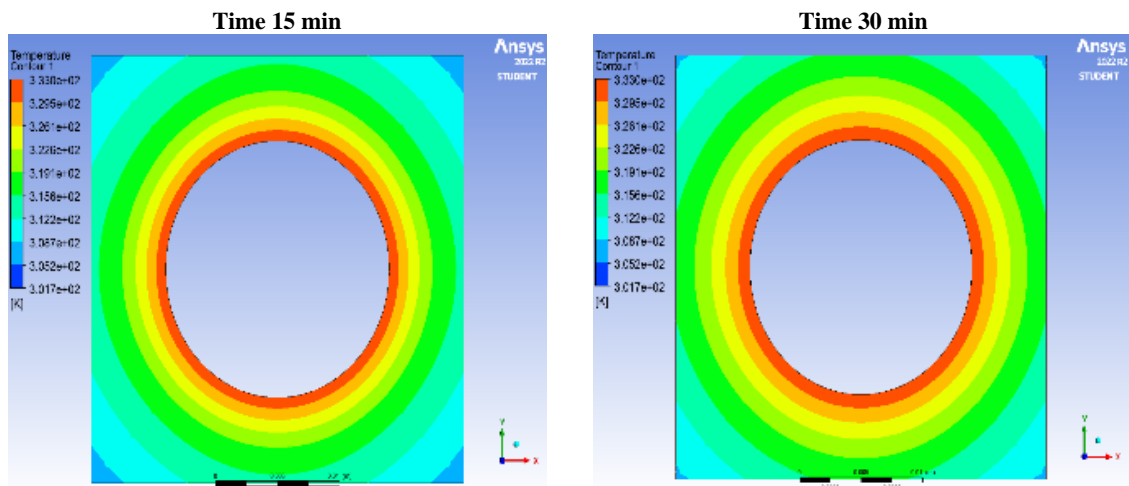
Counters of Temperature

"Figure 7" illustrate the contours of the temperature of lauric acid and paraffin wax and its variation over time at regular 15-minute intervals. The maximum temperatures observed during the melting process were 300K at the starting, 321K in middle, and 330K at later stages. The low-temperature

zone, indicated by the blue colour, exhibited a solid PCM-like shape, as seen in Figures 5 and 6. As time progressed, a red zone began to emerge closer to the center of the PCM domain, gradually increasing in size. This can be attributed due to turbulent impacts within liquid PCM. Through natural convection, the PCM's temperature dissipates into the environment, as indicated by the temperature contours. Heat travels evenly in this process.



(a)



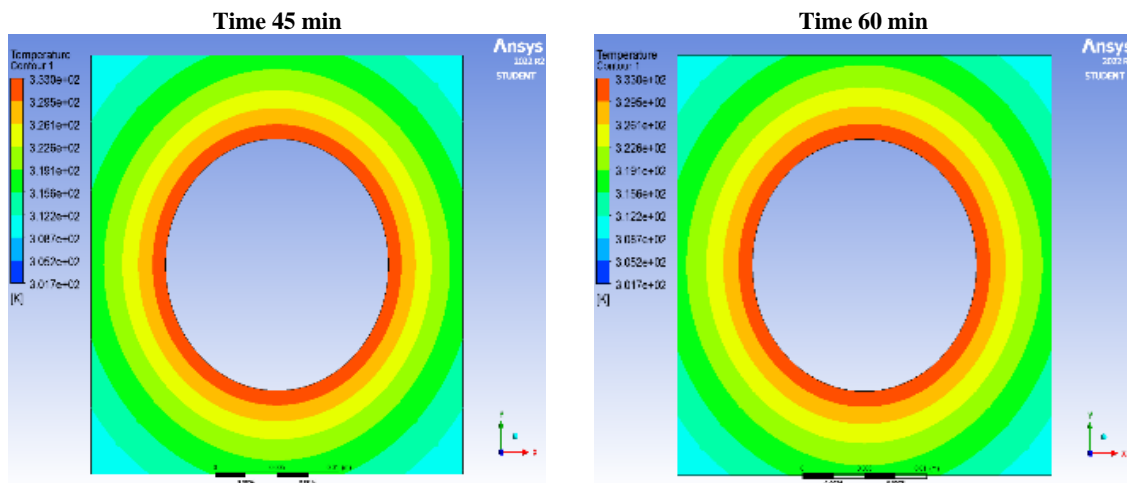


Figure 7. Counter of Liquid Temperature of (a) Paraffin Wax and (b) Lauric Acid.

When the temperature raises more at the initial stages after some time it will make little inclination for the remaining time as shown in "Figure 8".

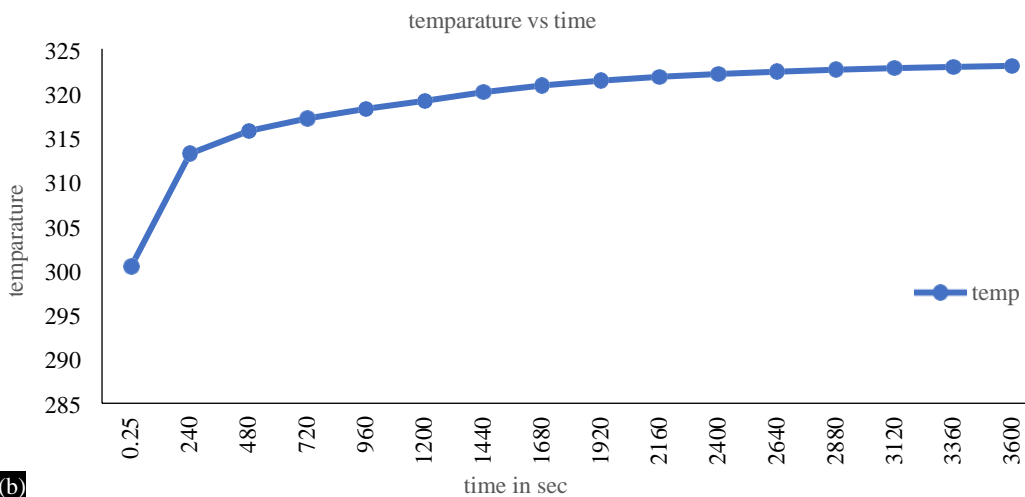
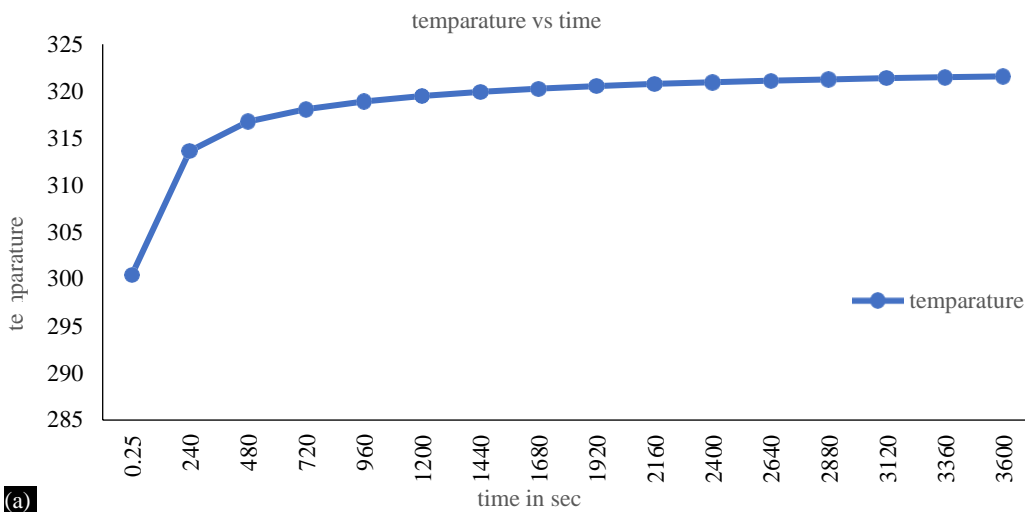


Figure 8. Variation of Temperature With Time of (a) Paraffin Wax and (b) Lauric Acid.

CONCLUSIONS

Several conclusions may be obtained from computational simulation and modelling of the PCM melting procedure under constant heat flux circumstances.

- It was observed that the liquid fraction rate increases as time progresses. In the initial stages, the rate remains relatively constant and then accelerates in the centre and the later stages of the melting process.
- Heat transmission occurs mostly by conduction upon the initial phases (0–30 minutes) of the melting process, and natural convection became the primary method of heat transfer after additional heating.
- To simulate the melting problem on ANSYS (Fluent) without encountering divergence errors during the solution, proper meshing and time step selection are necessary.
- It is concluded that the liquified of PCM can be simulated by ANSYS (Fluent) software with the help of proper settings.
- It was found that the combination of paraffin wax and lauric acid produces effective heat control in battery cooling applications, with lauric acid exhibiting higher heat absorption capacity than paraffin wax.

Finally, based on the aforementioned results, it can be inferred that lauric acid is the most suitable material for battery cooling in this technique in this study.

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