Journal of Physics: Conference
Series

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To cite this article: A Z A Akmal *et al* 2023 *J. Phys.: Conf. Ser.* **2643** 012015

ICADME-2023 IOP Publishing
Journal of Physics: Conference Series **2643** (2023) 012015 doi:10.1088/1742-6596/2643/1/012015

Numerical Investigation of Immersion Cooling Performance for Lithium-ion Polymer (LiPo) Battery: Effects of Dielectric Fluids and Flow Velocity

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Abstract. This study investigates the enhancement of immersion cooling performance for a single 14.6 Ah lithium-ion polymer (LiPo) battery cell by using air, palm oil, and engineered fluid (3M Novec 7000) as dielectric fluids. The research aims to observe the temperature distribution and rate of heat transfer on the battery cell at a 3C discharge rate, while varying the fluid velocity flow (0 mm/s, 1 mm/s, and 50 mm/s) and fluid types. Computational fluid dynamics (CFD) simulations were performed using ANSYS Fluent software, with heat generation from the LiPo battery simulated using the Newman, Tiedmann, Gu, and Kim (NTGK) semi-empirical electrochemical model. Results revealed that palm oil demonstrated the optimum cooling effect, reducing peak temperature to safe operating temperature region by 62.4% within 1020 seconds. Fluid flow velocity strongly influenced temperature distribution and heat transfer rates, with 50 mm/s resulting in a more uniform temperature distribution compared to 1 mm/s and 0 mm/s. The rate of heat transfer was highest at 1 mm/s and intermediate at 50 mm/s. Considering the abundance of palm oil in Malaysia, utilizing it as the dielectric fluid with a 50 mm/s flow velocity yields the best cooling effect for the 14.6 Ah LiPo battery at a 3C discharge rate.

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1. Introduction

The Lithium-ion Polymer (LiPo) battery is a type of rechargeable battery that utilizes Lithium-ion (Li-ion) technology with a high-conductivity semisolid gel polymer electrolyte instead of the liquid electrolyte found in other Li-ion batteries. Solid electrolytes, such as gel polymers, offer enhanced safety and thermal stability due to their physical barrier layer that separates positive and negative electrodes [1], [2]. In various applications, most Li-ion batteries undergo many charge-discharge cycles until they need to be replaced, which sometimes can be accelerated due to abnormal operating behaviours [3]–[6]. The two (2) major concerns regarding Li-ion batteries are finding the optimal operating temperature and addressing the uneven temperature distribution during the discharging process [7], [8]. To tackle these challenges, an effective battery thermal management system (BTMS) is commonly employed to regulate the battery's temperature and control heat distribution [9].

One of the promising concepts in direct cooling involves immersing the battery cells in a coolant such as dielectric fluids to release the heat generated from the battery during operating conditions [10], [11]. Immersion cooling can be further classified into stationary liquid BTMS and circulating liquid BTMS [12]. In this research, both types of immersion cooling have been numerically investigated to observe their effects on the heat distribution and temperature uniformity of the studied LiPo battery. By conducting a comprehensive investigation into the immersion cooling methods, our aim is to optimize the LiPo battery's temperature regulation and address the challenge of uneven temperature distribution. This research will contribute to the development of efficient battery thermal management system (BTMS), ultimately enhancing the performance and longevity of LiPo batteries in various applications.

2. Battery Modelling and Specifications

A geometrical model of a LiPo battery has been developed using ANSYS Fluent software. To address the diverse physics involved in simulating the battery under different operating conditions, a Multi-Scale & Multi-Domain (MSMD) approach is adopted. For capturing the electric and thermal behaviours of the battery cell during the simulation, the Newman, Tiedmann, Gu, and Kim (NTGK) semi-empirical electrochemical model is employed. The specific battery used in this study is a 14.6 Ah Lithium-ion battery, featuring a configuration with a $LiMn_2O_4$ cathode, a graphite anode, and a plasticized electrolyte [13]. To generate the battery behaviour, the modelling procedure follows the approach proposed by Kwon et al., which calculates the potential and current density distribution of the electrodes [14]. The dimensions of the LiPo battery model utilized in the simulation are illustrated in Figure 1, with a thickness of 2 mm [4].

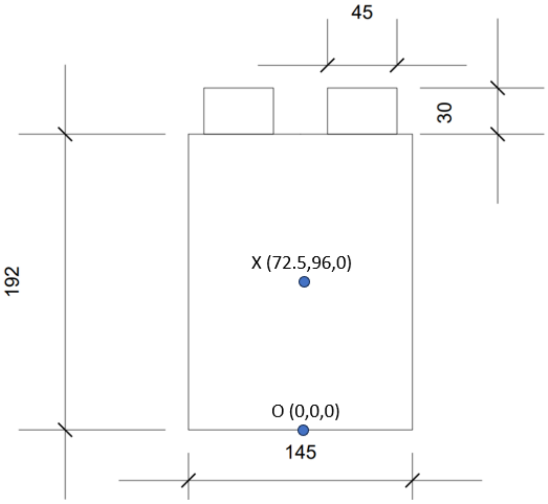

Figure 1. Studied dimensions for LiPo battery model (mm).

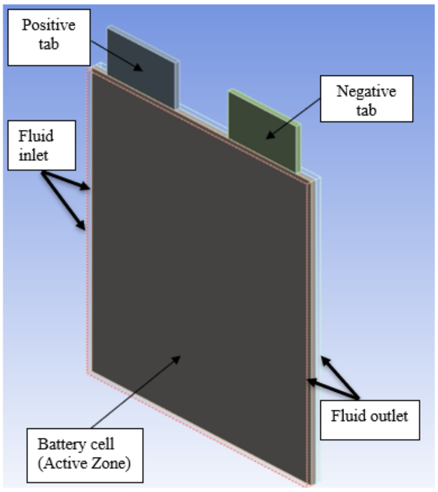

Figure 2. Simulation battery model with fluid cooling channel.

3. CFD Simulation and Boundary Conditions

Based on Figure 2, the battery structure consists of a single-cell LiPo battery with cooling section at both sides of the battery. The tabs are not bounded by the fluid domain as the focus for heat transfer evaluation is on the active cell zone. The fluid channel domain has a thickness of 2 mm [9], with length and height matching the cell's dimensions. When modelling the immersion cooling system, the fluid channel inlets and outlets are set on the planes of the cell's side surfaces.

Table 1. Thermal and physical properties of selected dielectric fluids.

Type of Dielectric Fluids	Density (kg/m^3)	Kinematic Viscosity $(N \cdot s/m^2)$	Specific Heat Capacity $(J/kg \cdot K)$	Thermal Conductivity $(W/m \cdot K)$
Air	1.225	1.789e-05	1006.43	0.0242
Palm Oil	887.5	0.08697	1861	0.1721
3M Novec 7000	1400	0.0003	1300	0.0800

For the simulation, the studied type of dielectric fluids listed in Table 1 are assumed to be single-phase with an ideal incompressible fluid for the immersion cooling process. The initial temperature is set to a constant value of 23°C, and the outlet pressure is set to be at atmospheric condition [9]. The wall condition of the battery cell follows a non-slip condition, with the SST k-omega viscous model used for the simulation. The flow rate of the fluid is set at 1 mm/s for circulating immersion cooling BTMS. The thermophysical parameters of the dielectric fluids, including specific heat, thermal conductivity, and viscosity, are assumed to be constant. In this simulation, transient analysis is also considered, as the behaviour of the LiPo battery is dependent on the discharge rate, which is a function of time. The time step is set at 10 s, with a maximum of 20 iterations for each time step. The total number of time steps is set to be 120, as the battery discharges for 20 minutes. The convergence criteria value on the residuals of the continuity equation, velocity, and energy equation are assigned to 10^{-6}.

4. Mesh Independence Test

The mesh independence study involved observing the average temperature value located at the centre of the battery surface (point X) with respect to the origin coordinate as shown in Figure 1. Five (5) different mesh runs were considered, each having a different number of nodes. The results from the mesh independence analysis are presented in Figure 3. There are only slight differences in temperature readings between mesh run 3, mesh run 4, and mesh run 5. Specifically, the relative error between mesh run 5 and mesh run 4 is 1.26% in terms of temperature reading. As the error is less than 5%, the model is deemed capable of accurately predicting the output from the simulation. Therefore, mesh run 5 was selected for the simulation in this study.

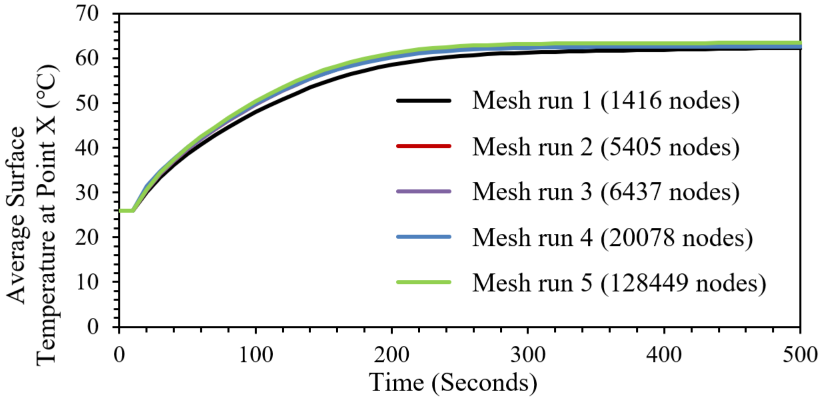

Figure 3. Mesh independence test results.

5. Results and Discussion

Based on Figure 4, the temperature plots for the studied fluids (Air, Palm Oil, and 3M Novec 7000) followed a similar pattern, except for natural cooling. In the case of natural cooling, where no fluid medium is involved, it is expected that the temperature will continue to rise as the battery discharges because there is no moving fluid to carry the heat generated from the battery surface to the environment. For immersion cooling, the battery's temperature is expected to rise during the initial stage of the discharging process. During this phase, the temperature will rise, and small amount of heat generated are being absorbed by the moving fluid due to rapid discharge of current (high voltage potential). At the peak, the battery surface temperature reached maximum temperature and reduced significantly as larger amount of heat are being absorbed after it reach the peak temperature. Once the battery surface temperature reaches a steady state, the temperature is expected to drop.

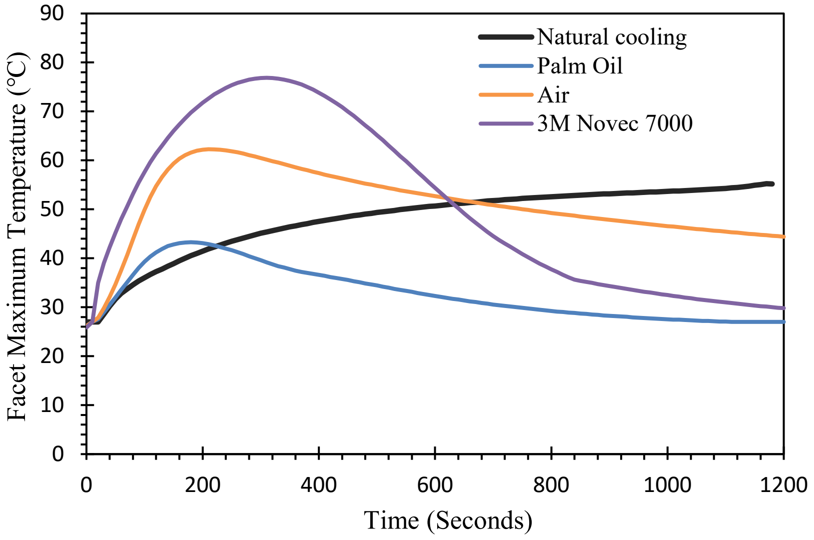

Figure 4. Maximum Facet temperature obtained on the battery cell surface through natural cooling, palm oil, air, and 3M Novec 7000 at 1 mm/s inlet velocity.

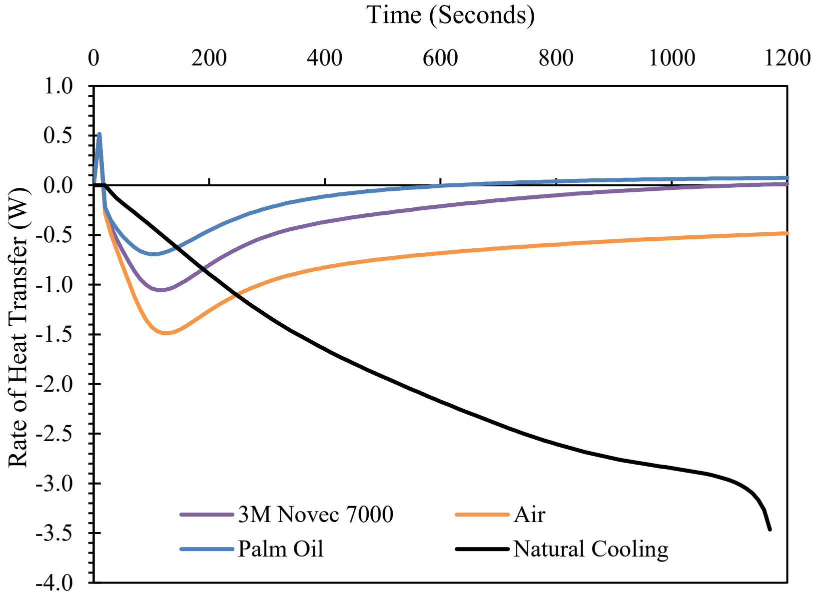

Figure 5. Rate of heat transfer obtained between the battery cell surface and the fluid channel through natural cooling, palm oil, air, and 3M Novec 7000 at 1 mm/s inlet velocity.

Comparing all types of fluids used for immersion cooling, palm oil demonstrated the most effective cooling effect, as it exhibited the smallest temperature change on the battery surface during the 3C discharge rate. Palm oil also showed the quickest initiation of the cooling effect on the battery surface compared to other fluids. These findings align with the results obtained by Bhattacharjee et al., where the temperature started to drop once it reached the peak temperature for the specified LiFePO4 battery [15]. Palm oil successfully reduced the temperature by 62.4% from its peak to the steady-state temperature at the end of the discharge process, falling within the optimum cooling range of 15°C to 35°C [16] for the battery at the 3C discharge rate.

In Figure 5, the rate of heat transfer plots for air, palm oil, and 3M Novec 7000 exhibited similar trends (reversal trend), while natural cooling showed a different pattern (downtrend). Both palm oil and 3M Novec 7000 fluids showed positive values for the rate of heat transfer at 630 seconds and 1130 seconds, respectively, indicating that heat started to flow from the dielectric fluids to the cell battery surface. For the palm oil and 3M Novec 7000 fluids, the rate of heat transfer showed a change in direction, indicating a reversal of heat flow (coming into the battery). In contrast, for the air, the heat did not change in direction (unable to reach positive region). This behaviour is attributed to the sign convention obtained from the simulation. In general, the equation for the rate of heat transfer for convection is given as

$$\dot{Q}_{\mathrm{conv}} = hA(T_s - T_\infty) \tag{1}$$

Based on Equation 1, the rate of heat transfer is directly proportional to the temperature difference and the heat transfer coefficient, *h*, while the surface area, *A*, of the battery remains constant. The value of *h* strongly depends on fluid properties, the roughness of the solid surface, and the type of fluid flow. In this study, the value of *h* was set to an ideal constant case. As a result, the rate of heat transfer depends solely on the temperature difference. This explains why the rate of heat transfer plots for air, palm oil, and 3M Novec 7000 are similar. Regarding cooling, both palm oil and 3M Novec 7000 are potential candidates as both fluids can effectively cool the battery until the rate of heat transfer becomes positive. This indicates that heat starts flowing from the fluid to the cell battery surface. Therefore, both palm oil and 3M Novec 7000 have the potential to achieve sufficient cooling for the battery.

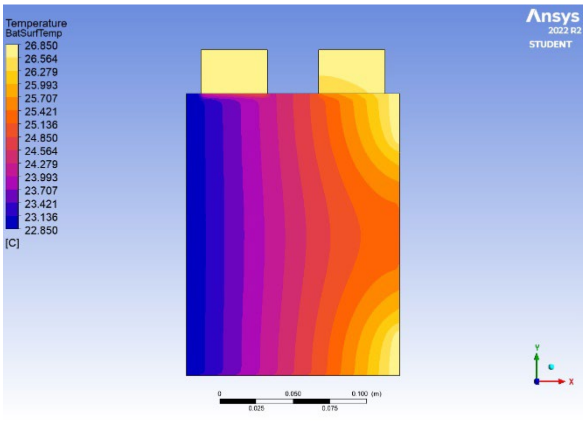

Figure 6. Temperature contour plot for palm oil at inlet velocity of 0 mm/s.

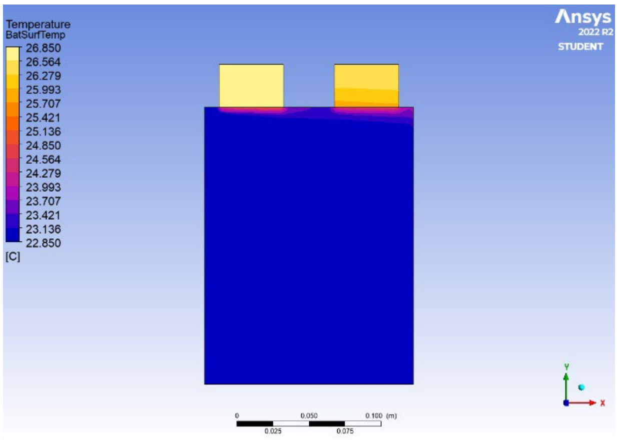

Figure 7. Temperature contour plot for palm oil at inlet velocity of 1 mm/s.

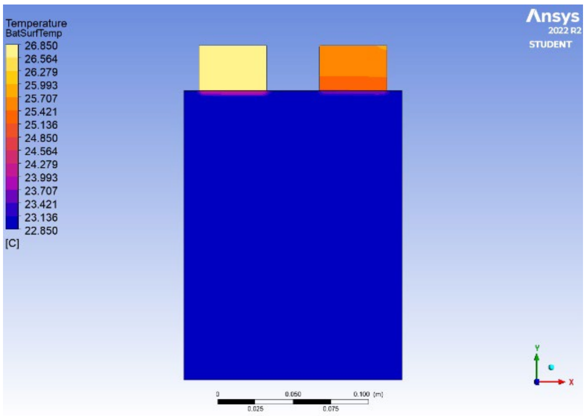

Figure 8. Temperature contour plot for palm oil at inlet velocity of 50 mm/s.

Figure 6 shows the stagnant immersion case, while Figure 7 and Figure 8 illustrate the circulating immersion cases. Based on the previous results, palm oil is selected to study fluid velocity effect on the immersion cooling performance of the battery. At 0 mm/s, the fluid remains static, fully submerging the battery surface. The stationary fluid only exchanges heat with the cell, and other thermal boundary conditions of the coolant are adiabatic. As a result, during the discharging process, most of the heat is absorbed by the fluid, causing uneven temperature distribution. For the circulating immersion case, the temperature distribution obtained using palm oil with inlet velocity of 50 mm/s showed the most uniform temperature distribution.

Whereas at 1 mm/s, the temperature distribution is slightly distorted near the location of the battery tabs. Notably, at the fluid outlet, there is a temperature difference between the 1 mm/s and 50 mm/s cases, which amounts to 0.857°C. This difference is relatively small, as higher fluid velocity leads to a higher heat transfer rate between the surface and the fluid. Therefore, based on this simulation study, using a higher inlet velocity for cooling the battery is expected to result in a better temperature distribution on the battery surface [17].

6. Conclusion

In conclusion, the battery model successfully predicted the temperature distribution on the battery surface by numerical investigation. The first case study focused on heat transfer characterization with various types of dielectric fluids. Among them, palm oil demonstrated the most effective cooling effect, reducing the battery surface temperature to 27°C, which is the lowest temperature compared to natural cooling, air, and 3M Novec 7000. Palm oil managed to reduce the peak temperature by 62.4%, reaching a steady-state temperature within 1020 seconds on the battery surface. In the second case study, heat transfer characterization was examined with different flow rates of the selected dielectric fluid, which palm oil was used for this investigation. It was observed that as the fluid velocity increased from 1 mm/s to 50 mm/s, the temperature distribution on the battery surface improved. In the stagnant case, the temperature distribution was uneven due to the absence of fluid flow. Therefore, the best configuration for the 14.6 Ah LiPo battery using immersion cooling BTMS is achieved through palm oil at an inlet velocity flow rate of 50 mm/s. This configuration provides optimum performance for the battery at a 3C discharge rate. These findings highlight the significance of using palm oil as the dielectric fluid in immersion cooling to enhance the overall performance and temperature distribution of LiPo batteries. Considering the growing demand for high-performance LiPo batteries in various applications, such as electric vehicles and renewable energy storage systems, the utilization of palm oil as a dielectric fluid in immersion cooling presents a promising solution for enhancing battery performance, safety, and longevity. Moreover, this research provides valuable insights for engineers, scientists, and policymakers in the field of energy storage technology, encouraging further exploration and development of eco-friendly cooling solutions using abundant and locally available resources like palm oil.

Acknowledgements

The authors would like to acknowledge the financial support under Universiti Teknologi Malaysia (UTM) through the UTM Encouragement Research Grant (UTMER/PY2022/03943) (Q.J130000.3824.31J30). A gratefully acknowledge for collaborators from Universiti Malaysia Perlis (UniMAP) for their insightful ideas and contributions to the research.

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