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Thermal Management and Optimization Study of Immersion Cooled Battery Pack Using Different Dielectric Fluids

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Abstract

Electric vehicles with green power system are viable alternatives to reduce greenhouse gas emissions and dependence on fossil energy resources. The power source such as Li-ion battery has high sensitivity to temperature, which is a challenge related to battery thermal management. Effective thermal management is crucial for enhancing the performance and lifespan of electric vehicle (EV) batteries. Developing a BTM system that is both safe and reliable has a vital research goal. Immersion cooling, which submerges the battery in a dielectric fluid, has the potential of increasing the rate of heat transfer by 10,000 times relative to passive air cooling. In the present work, immersion cooling technique with dielectric fluid for 39 cells (4.6Ah), form factor of 21700 battery pack (660Wh) for 2C, 3C and 5C discharge rate with 2LPM, 4LPM and 6LPM have been introduced. From CFD simulations study it's observed that Maximum cell avg. temperature [97.50 °C] can be observed at 2lpm_5C condition in 3M Novec dielectric fluid battery pack. Minimum cell avg. temperature [29.93] can be observed at 6lpm_2C condition in Ester mivolt dielectric fluid battery pack. The cell average temperature is 2.56%, 4.11% and 12.02 % lesser for Ester Mivolt DF7 than 3M NOVEC dielectric fluid at 2C, 3C and 5C discharge rate conditions respectively. Observing the results, its recommended to use Ester mivolt coolant instead of 3M Novec, for better thermal management. To examine the real battery module cells with bus bars and holders are taken into consideration, volumetric heat source for different discharge rate is calculated and given heat value. This work presents direct liquid contact cooling using dielectric fluids as a secure and effective thermal management technique for lithium-ion battery applications requiring high energy density and high current.

Keywords: *3M Novec, CFD simulations, Dielectric Fluid, Immersion cooling, Li-ion battery, BTM*

1. Introduction

Soft Battery and thermal management stand as pivotal aspects in various technological realms due to their multifaceted impact. Primarily, they ensure safety by mitigating the risk of overheating, thermal runaway, and potential hazards like fires or explosions. This holds profound significance, especially in devices such as electric vehicles and high-energy-density batteries used in portable electronics. By regulating and controlling temperatures within safe thresholds, these systems prevent catastrophic failures and ensure user safety, thereby underlining their fundamental role in the design and operation of such devices. Moreover, effective battery and thermal management contribute significantly to the optimization of performance and longevity of batteries. Maintaining batteries at their ideal temperature ranges preserves their capacity, power output, and overall efficiency. Various cooling systems have been developed for li battery pack, including air, liquid, phase change material (PCM), heat pipe, and hybrid cooling systems. Air-based BTMS is famous for its economic viability and widespread availability, yet forced air cooling systems encounter drawbacks such as pressure loss and uneven temperature distribution.[3] In contrast, direct liquid cooling demonstrates high efficiency, particularly in two- phase heat transfer scenarios. Immersion cooling emerges as a specialized solution, immersing battery cells or packs in dielectric fluids engineered to efficiently transfer heat [4]. This introduction highlights the critical need for effective BTMS solutions to address thermal management challenges and ensure the reliability and performance of lithium-ion batteries in EV applications.nNumerous researchers have investigated the experimental and numerical examination of the LIB's fire hazards under various abuse settings in order to address the safety concern [5]. To provide recommendations for the best thermal management system, a variety of cooling techniques important to the creation of the BTMS are covered. These include liquid, air, PCM, HP, and hybrid-based cooling strategies. The most recent studies for each sector are also highlighted [3]. Air cooling systems are commonly utilized in BTMS because of its many advantages, including their low cost, easy maintenance, high dependability, and simple structure, However, one significant drawback of the air-cooling system is its inadequate thermal management, or lack of appropriate cooling impact [2]. Compared to the indirect liquid cooling method, which increases thermal resistance unavoidably, the direct liquid cooling strategy is far more efficient [4]. Dielectric immersion cooling for a battery pack is perhaps the ultimate method of controlling cell temperatures. Dielectric Fluid: an electrically non-conductive liquid that has a very high resistance to electrical breakdown, even at high voltages [6]. In the present study, Immersion cooling is studied with different dielectric fluids and C-rates; namely, Ester mivolt-DF7 and 3M NOVEC. Simulation have been conducted at different discharge rates, namely 2C, 3C and 5C. This paper mainly focuses on using two dielectric fluid and comparison on different discharge rate varying the flow rate. The novelty aspects of present research work are the following:

i. Thermal management of Li-ion battery with dielectric fluids like Ester Mivolt and 3M Novec industrial fluid is investigated.
ii. Comparative analysis of fluid is done at different discharge faster C-rates and flow rates.
iii. For high-energy density and high-current lithium-ion batteries, the use of dielectric fluids as a direct immersion cooling method is a secure and effective thermal management technique

1.1. Objective & Scope

Study the Impact of different dielectric fluids on Battery thermal performance at different flow and discharge conditions. Analyse battery pack average and maximum temperature and optimize the battery pack thermal performance at different C rate conditions. [7]

2. Numerical Model

To study and examine the effectiveness of Immersion cooled battery pack. A battery pack consist of 39 cylindrical lithium iron phosphate cells with 21700 form factors are considered. Lithium iron phosphate LiFePO4 is used because of its longer life span, higher energy density, low self-weight, better discharge, and high thermal runaway temperature. Two dielectric fluids namely Ester Mivolt DF-7 and 3M Novec 2. [9, 10]

2.1. Battery Pack Details

LiFeP04 21700 cells are used in simulation for study. Cells are arranged in 13S 3P arrangement with bus bars attached and cell holders to examine the real case are shown in Fig1. Properties of cell, bus bar and cell holder are given in table 1. A dimension of, battery module, space between each cell is 2mm, casing details, and inlet and outlet flow pipe diameter 15mm. The cooling configurations used in the present work is shown in schematically. For immersion-cooled battery module, the Li- ion cells are contained within an enclosure made of polycarbonate with outer dimensions of 283mm × 73mm × 80mm. The module enclosure has one inlet and one outlet port for the flow of a dielectric coolant (Figure 1). The entire battery module is assumed to be tightly sealed such that there is no coolant leak. All the Li-ion cells are exposed to the dielectric liquid are submerged up to full height. Bus bar of copper are used to connect the cells and cell holder of aluminum to hold the cells. Full detailed geometry description is given in figure.

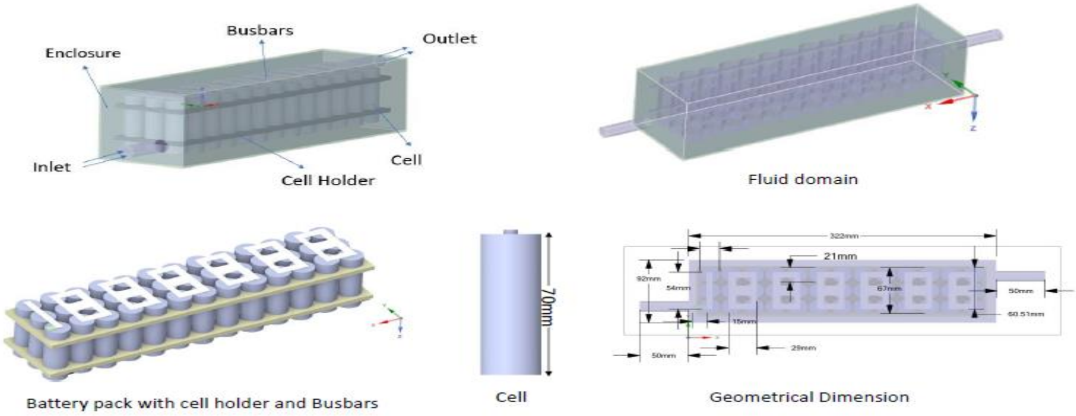

Figure 1 Geometrical Description Cell

Table 1 Battery Pack Specifications

Battery Pack Details	
Cell Type	21700
Cell Chemistry	LFP
Cell Specifications	
Nominal Voltage (V)	3.7
Nominal Capacity(Ah)	4.6
Battery Pack Capacity (Wh)	660
Battery Pack Voltage (V)	48
Battery Pack Current (Ah)	13.75
Pack Configuration	
No.of Cells in Series	13
No. of Cells in Parallel	3

2.2. Battery and Working Fluid Modeling

To assess the Battery pack thermal performance, computational fluid dynamics (CFD) has been used. Based on the design, the battery pack includes different domains such as cells, cell holder, enclosure, and dielectric fluid. The following assumptions are considered:

- The coolants (ESTER MIVOLT DF-7 and 3M NOVEC) are incompressible and Newtonian.
- The coolant flow's buoyancy impact is neglected.
- Heat transfer modes inside the battery pack are convection and conduction. The effect of radiation is neglected.
- Heat generation by the Li-ion cells due irreversible Ohmic heating is considered.

Table 2 Material Properties

Partname		Cell	Enclosure	Bus Bar	Immersion Coolant1	Immersion Coolant2	Immersion Coolant3
Property	**Unit**						
Material type	NA	LFP	Ploy Corbonate	Copper	Ester (MIVLOT DF7)	3M NOVEC 7000	NO.10 TRANSFORMER OIL
Density	(kg/m3)	2846	1200	8940	916	1510	895
Specific Heat	(J/kgK)	885	1200	385	1907	1300	1971
Thermal Conductivity	(W/mK)	A-12, R-1	0.2	305	0.13	0.08	0.106
Viscosity	(mm2/s)				16.4	0.3	9
Dielectric strength	(V/m)				176	7.4	2.135
Flash Point	Deg.C				194	195	140
Breakdown Voltage	kV				>90kV	>65kV	>30kV

2.3. Governing equations

For Li ion cells Bernardi and Pawlikowski proposed a model for estimating the heating rate inside battery cells based on temperature changes. The sum of reversible and irreversible heat generation is expressed as Q, the overall heat generation rate, Qirr, or irreversible heat creation, is always exothermic and is provided by Eq.1 The reversible heating, Qr, component includes the enthalpy of mixing effects, entropy change, heat capacity effects, and phase change terms Eq 2. There will be some loss of heat by convection, Qcon, from the cells to the environment, which is provided by Eq. 3,[8]

$$Q\mathrm{irr} = \mathrm{I2\ Ri} \qquad (1)$$

$$Q\mathrm{r} = \mathrm{I\ T}\ dV\ /dT \qquad (2)$$

$$Q\mathrm{con} = \mathrm{-h\ A(Tc\text{-}Ta)} \qquad (3)$$

This leads to the development of an energy balance equation [4]

$$\partial / \partial t\,(\rho \mathrm{cell} C\mathrm{p,cell} T\mathrm{cell}) = \nabla \bullet (K\mathrm{cell} \nabla T\mathrm{cell}) + \dot{}\, Q\mathrm{cell} \quad (4)$$

For coolant The continuity equation, momentum equation, and energy equation for the coolant are given in Eqs., respectively [8].

$$\nabla . \vec{u}_c = 0 \qquad (5)$$

$$\rho_c \frac{\partial \vec{u}_c}{\partial t} + \left(\vec{u}_c . \nabla\right) \vec{u}_c = -\nabla p + \mu_c \nabla^2 \vec{u}_c + \rho_c \vec{g} \qquad (6)$$

$$\frac{\partial T_c}{\partial t} + \left(\vec{u}_c . \nabla\right) T = \frac{K_c}{\rho_c C_{p,c}} \nabla^2 T_c \qquad (7)$$

2.4. Boundary and Initial Conditions

At the start of the solution, the temperature for all the computational domains (solids, fluids) is initialized to 25 °C. For the parametric simulations we consider three different flow rates of 2 LPM,4 LPM and 6 LPM. Here, LPM denotes the flow rate in units of liters-per-minute of coolant. For the parametric simulations, we consider three different module discharge C-rates of 2 C, 3 C and 5C and for immersion. The estimated heat generation is then applied as a volumetric heat source in the for each 21700 Li-ion cells considered in the simulations. Table 2,3 shows Material Properties and Heat Input to Battery Pack.

Table 3 Heat Input to Battery Pack

Heat Input			
C rate	**2**	**3**	**5**
per cell [A]	9.2	13.8	22.9
Heat Value [W]	2.54	5.71	15.73
Heat Value [W/m3]	107489.7	241851.9	665981.7

Table 4 Simulation DOE Plan

Sl No	Case No	Fluid Temp [℃]	Ambient Temp [℃]	Dielectric Fluid	Flow Rate	C rate
1	Case1	25	25	Ester mivolt	2	2
2	Case2	25	25	Ester mivolt	2	3
3	Case3	25	25	Ester mivolt	2	5
4	Case4	25	25	Ester mivolt	4	2
5	Case5	25	25	Ester mivolt	4	3
6	Case6	25	25	Ester mivolt	4	5
7	Case7	25	25	Ester mivolt	6	2
8	Case8	25	25	Ester mivolt	6	3
9	Case9	25	25	Ester mivolt	6	5
10	Case10	25	25	3M Novec	2	2
11	Case11	25	25	3M Novec	2	3
12	Case12	25	25	3M Novec	2	5
13	Case13	25	25	3M Novec	4	2
14	Case14	25	25	3M Novec	4	3
15	Case15	25	25	3M Novec	4	5
16	Case16	25	25	3M Novec	6	2
17	Case17	25	25	3M Novec	6	3
18	Case18	25	25	3M Novec	6	5

2.5. Numerical Technique

The battery module's geometric model is created in ANSYS Space claim 2023R1, for meshing as well as simulation purpose ANSYS fluent 2023 R1 is used. Ansys Fluent's numerical method is based on discretizing the governing equation in a finite volume employing a 2nd order accurate spatial solver and a 1st order accurate temporal solver based on algebraic multigrid's. SIMPLE algorithm is used for the solution. This program leverages the relationship between velocity and pressure corrections to obtain the pressure field and enforce mass conservation. Standard K-e model is used and CHT approach is used for adding heat source to the battery for different C-rates. The battery module's geometric model is created in ANSYS Space claim 2023R1, for meshing as well as simulation purpose ANSYS fluent 2023 R1 is used. Ansys Fluent's numerical method is based on discretizing the governing equation in a finite volume employing a 2nd order accurate spatial solver and a 1st order accurate temporal solver based on algebraic multigrid's. SIMPLE algorithm is used for the solution. This program leverages the relationship between velocity and pressure corrections to obtain the pressure field and enforce mass conservation. Standard K-e model is used and CHT approach is used for adding heat source to the battery for different C-rates. Table 4 shows Simulation DOE Plan

2.5.1.Mesh Details and Grid Independence Test

While performing numerical simulations, one of the most important aspects to consider is the grid resolution that is used to discretize the computing domains. A high-quality grid must be generated to ensure accurate results for cell temperature and fluid flow for immersion cooling. To generate a high-quality mesh, we use Ansys fluent Meshing, polyhedral elements are generated for both fluid and solid domains with growth rate of 1.2 and 5 layers are formed for near wall gradients. There are 1.8 million volume cells created for this case. Figure and table show the number of elements generated for the computational domain. For saving computational time and cost it is recommended to perform the grid independence study. In computational fluid dynamics (CFD) analysis, a grid independence test is a technique used to make sure the outcomes are independent of the simulation grid. It enables precise comparisons with experimental data and other numerical predictions. Figure 2 shows Polyhedral Meshed Battery Model, Figure 3 shows Simulation Methodology.

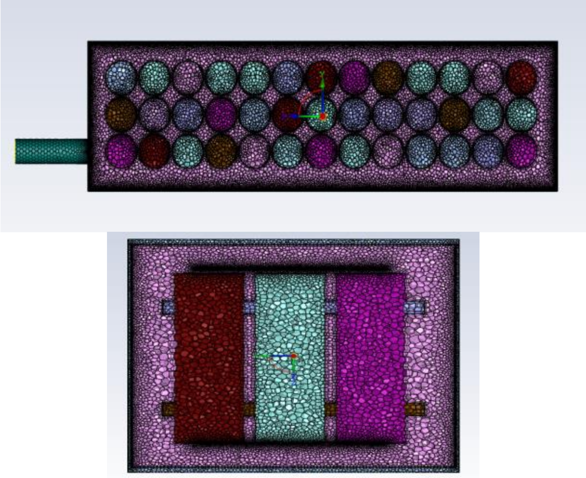

Figure 2 Polyhedral Meshed Battery Model

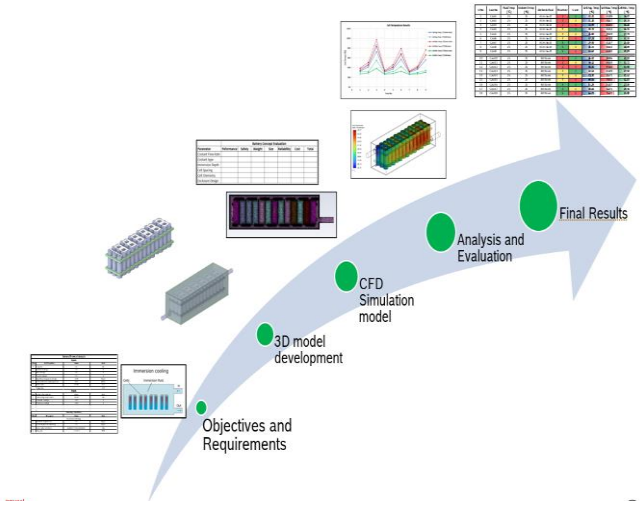

Figure 3 Simulation Methodology

3. Results and Discussion

The results of simulation carried out to compare the cooling capabilities of two different cooling liquids, namely, EsterMiVoltDF-7 and 3M Novec and comprehend numerical simulations results overview is given has below. Table 5 shows Simulation Results Overview, Figure 4,5,6 shows Cell Average, Min Temperature and Maximum Temperature Comparison of ESTER MIVOLT DF-7 and 3M NOVEC Coolants.

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Table 5 Simulation Results Overview

Sl No	Case No	Fluid Temp [℃]	Ambient Temp [℃]	Dielectric Fluid	Flow Rate	C rate	Cell Avg. Temp [℃]	Cell Max. Temp [℃]	Cell Min. Temp [℃]
1	Case1	25	25	Ester mivolt	2	2	32.31	34.09	26.87
2	Case2	25	25	Ester mivolt	2	3	41.38	45.37	29.19
3	Case3	25	25	Ester mivolt	2	5	72.99	83.50	38.28
4	Case4	25	25	Ester mivolt	4	2	30.72	32.42	26.15
5	Case5	25	25	Ester mivolt	4	3	36.80	40.49	27.73
6	Case6	25	25	Ester mivolt	4	5	57.23	67.28	32.43
7	Case7	25	25	Ester mivolt	6	2	29.93	31.57	25.85
8	Case8	25	25	Ester mivolt	6	3	36.44	40.15	26.89
9	Case9	25	25	Ester mivolt	6	5	55.64	65.84	30.29
10	Case10	25	25	3M Novec	2	2	36.82	38.86	30.82
11	Case11	25	25	3M Novec	2	3	46.32	50.30	31.72
12	Case12	25	25	3M Novec	2	5	86.85	97.50	54.90
13	Case13	25	25	3M Novec	4	2	32.53	34.29	27.92
14	Case14	25	25	3M Novec	4	3	41.80	45.74	31.52
15	Case15	25	25	3M Novec	4	5	69.06	79.40	42.07
16	Case16	25	25	3M Novec	6	2	31.29	33.07	27.05
17	Case17	25	25	3M Novec	6	3	38.82	42.71	29.46
18	Case18	25	25	3M Novec	6	5	66.01	76.24	33.80

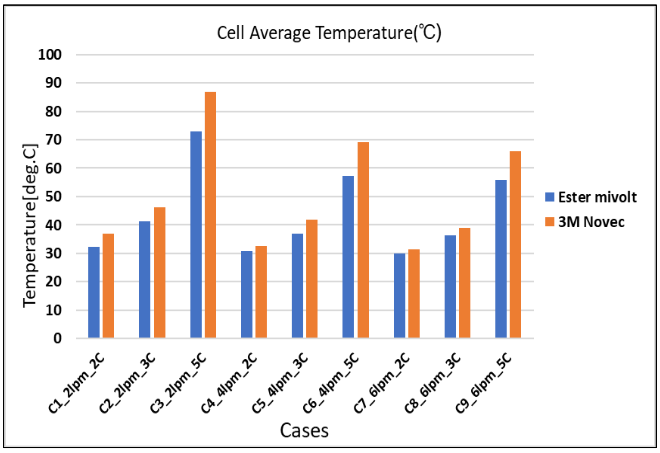


Figure 4 Cell Average Comparison of ESTER MIVOLT DF-7 and 3M NOVEC Coolants

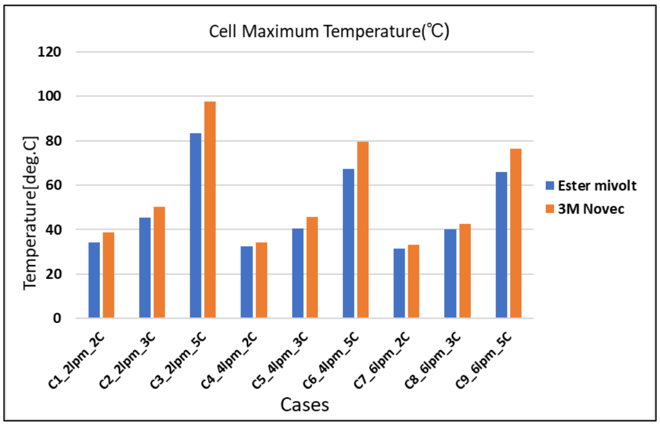


Figure 6 Maximum Temperatures Comparison of ESTER MIVOLT DF-7 and 3M NOVEC Coolants

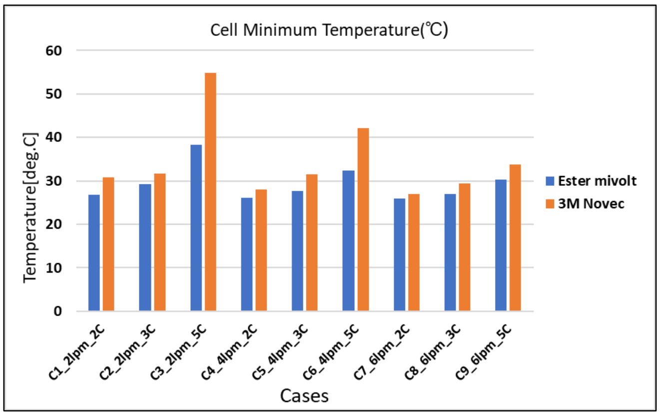


Figure 5 Minimum Temperatures Comparison of ESTER MIVOLT DF-7 and 3M NOVEC Coolants

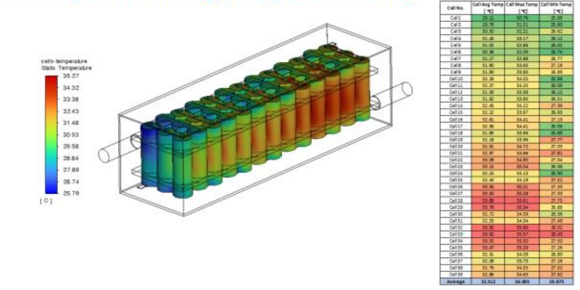
- Maximum cell avg. temperature [97.50 ℃] can be observed at 2lpm_5C condition in 3M Novec dielectric fluid battery pack; Minimum cell avg. temperature [29.93] can be observed at 6lpm_2C condition in Ester mivolt dielectric fluid battery pack.
- Since cell cutoff temperature is 65 ℃, it is recommended to use higher flow rates for 3C and 5C rate conditions.
- Observing the results, its recommended to use Ester mivolt coolant instead of 3M Novec, for better thermal management.
- Overall, the cell average temperature is 2.56%, 4.11% and 12.02 % lesser for Ester

Mivolt DF7 than 3M NOVEC dielectric fluid at 2C, 3C and 5C discharge rate conditions respectively.

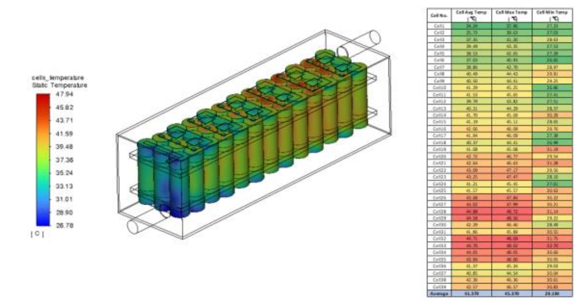
3.1. Simulation Temperature Contours

1. Immersion Coolant1 Ester (MIVLOT DF7

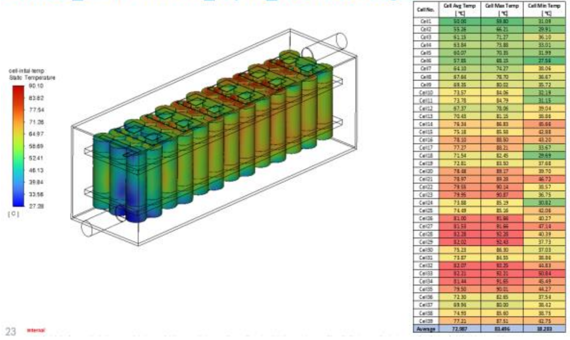
Case1_Ester mivolt_2lpm_2C discharge



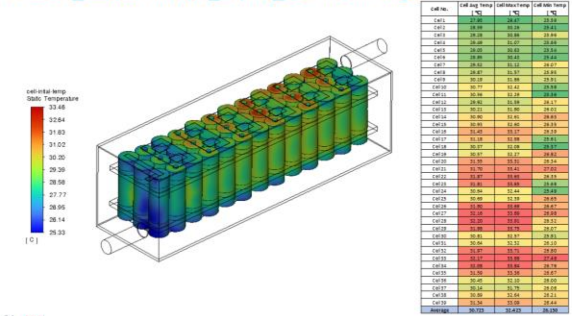
Case2_Ester mivolt_2lpm_3C discharge



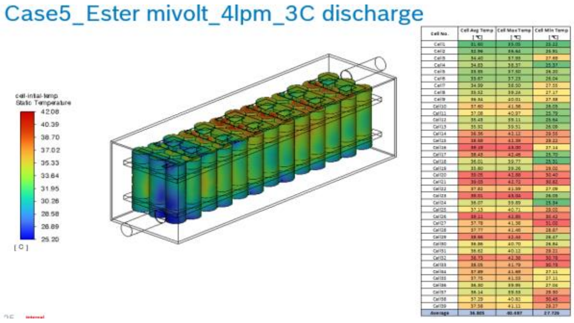
Case3_Ester mivolt_2lpm_5C discharge



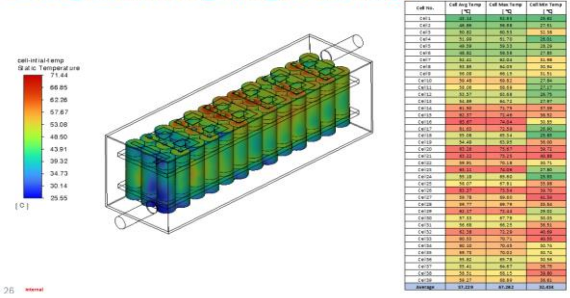
Case4_Ester mivolt_4lpm_2C discharge



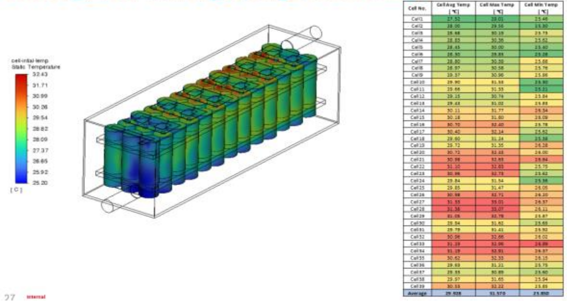
Case5_Ester mivolt_4lpm_3C discharge



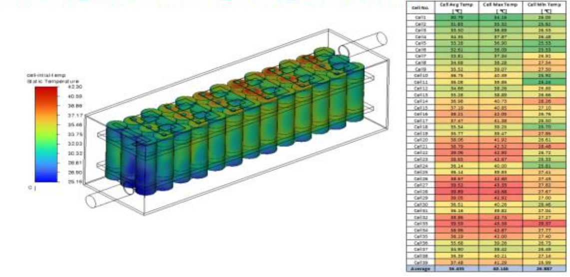
Case6_Ester mivolt_4lpm_5C discharge



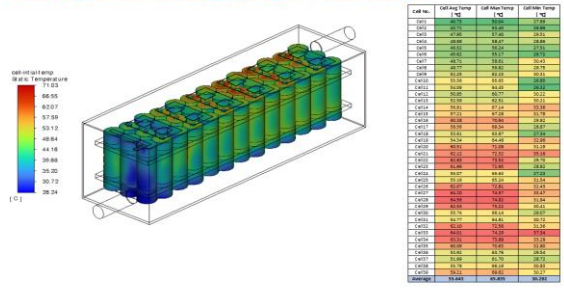
Case7_Ester mivolt_6lpm_2C discharge



Case8_Ester mivolt_6lpm_3C discharge



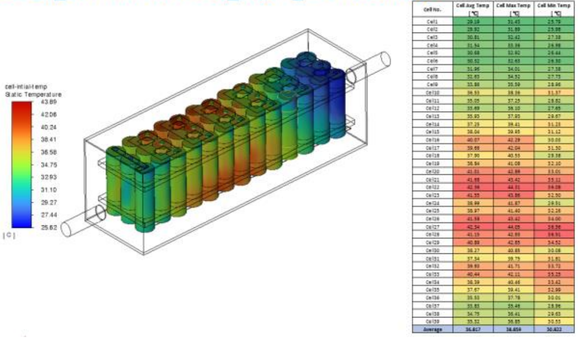
Case9_Ester mivolt_6lpm_5C discharge



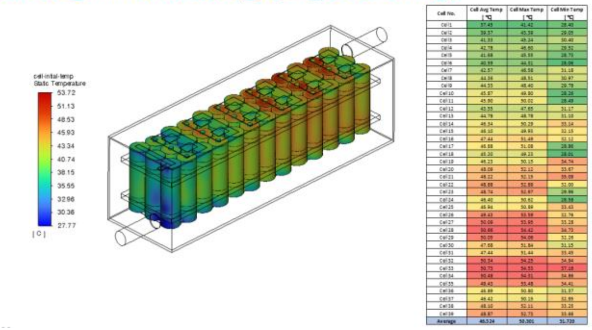
3.1 Simulation Temperature Contours

2. 3M NOVEC 7000

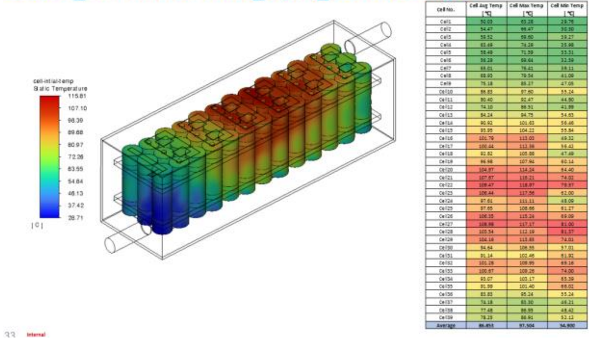
Case1_3M Novec7000_2lpm_2C discharge



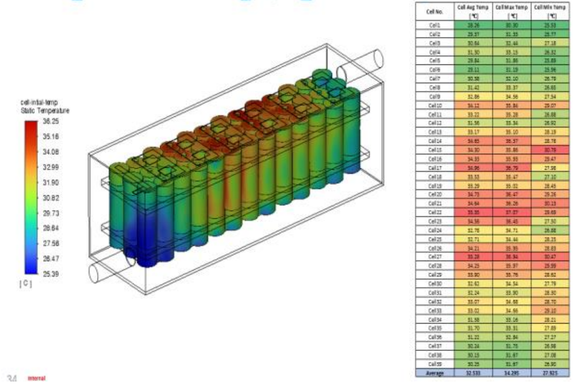
Case2_3M Novec7000_2lpm_3C discharge



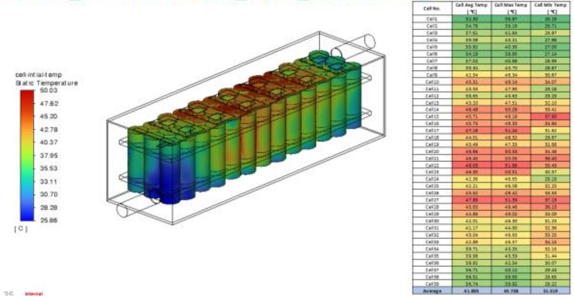
Case3_3M Novec 7000_2lpm_5C discharge



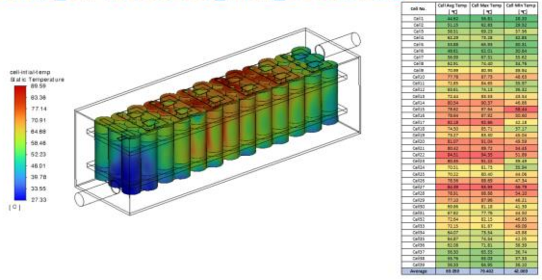
Case4_3M Novec 7000_4lpm_2C discharge



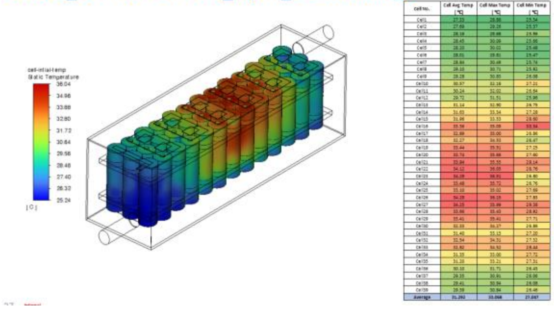
Case5_3M Novec7000_4lpm_3C discharge



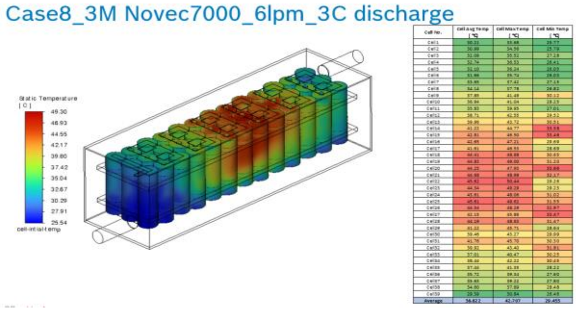
Case6_3M Novec7000_4lpm_5C discharge



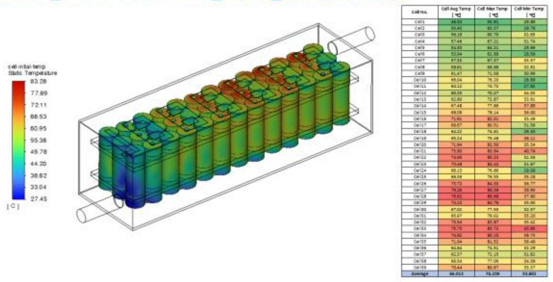
Case7_3M Novec7000_6lpm_2C discharge



Case8_3M Novec7000_6lpm_3C discharge



Case9_3M Novec7000_6lpm_5C discharge



Conclusion and Observation

In conclusion, the proper design considerations for immersion-cooling battery systems are different yet more straightforward than conventional liquid-cooling battery systems. Essentially, an immersion-cooling battery system integrates the cooling system into the battery housing itself, without extensive coolant channels, cold plates, and coolant pipes. Managing heat is a big challenge for efficient and safe battery systems in electric vehicles and energy storage system. Overheating can cause device failure, reduced efficiency, and fire risk. Most thermal management systems are complex and expensive, but immersion cooling is an innovative and adaptable method that can prevent thermal runaway and increase battery lifespan.

From present work we can conclude that immersion cooling strategy outperforms in managing the battery temperature.

- In immersion cooling methods, the Ester MiVolt-DF7 coolant shows better control of the maximum temperature of the battery module compared to 3M NOVEC due to the high specific heat capacity.
- From the above graphs and contours we can infer that as we increase the flow rate the maximum temperature is decreasing. On increasing the C rate, the temperature is increasing.
- Maximum cell avg. temperature [97.50 °C] can be observed at 2lpm_5C condition in 3M Novec dielectric fluid battery pack and Minimum cell avg. temperature [29.93] can be observed at 6lpm_2C condition in Ester mivolt dielectric fluid battery pack.
- Overall, the cell average temperature is 2.56%, 4.11% and 12.02 % lesser for Ester Mivolt DF7 than 3M NOVEC dielectric fluid at 2C, 3C and 5C discharge rate conditions respectively.
- It recommends that to keep the battery in safe operating temperature range at 2C, 3C and 5C rate conditions, the minimum coolant flow rate at inlet of the battery pack should be 2LPM, 2-4 LPM, 6LPM respectively.

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