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# NUMERICAL ANALYSES OF THERMAL PERFORMANCES OF THE CONVENTIONAL AND THE IMMERSION COOLING METHODS FOR LITHIUM-ION BATTERY PACKS

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## *Highlights*

- Transition to electric vehicles has surged to reduce carbon emissions and utilize accessible energy.
- Key challenges for electric vehicle adoption include limited battery capacity, lengthy charging times, thermal management during rapid charging/discharging, and thermal runaway risks.
- Inhomogeneous temperature distribution's negative impact on electric vehicles underscores the need for a thermal management system.
- Widely employed thermal management systems include air-cooled, cooling plate (pipe) systems and the increasingly prevalent direct dielectric cooling systems.
- This study focused on thermal analyses of various cooling methods using Ansys Fluent software.
- The newest method, direct dielectric cooling, exhibited a 12% performance improvement over other systems under normal operating conditions (1C).

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**ABSTRACT:** The transition from fossil fuel vehicles to electric has increased rapidly in recent years to reduce carbon emissions and use accessible energy. The main obstacles to the widespread use of electric vehicles are limited battery capacities, long charging times, thermal management in sudden charge and discharge situations and thermal runaway risks. The adverse effects of non-homogeneous temperature distribution on electrically driven vehicles have demonstrated the necessity of a thermal management system. The most used thermal management systems in practice are air-cooled, cooling plate (pipe) systems and direct dielectric cooling systems, which have recently become widespread. This study focused on the thermal analyses of the different thermal cooling methods. All analyses have been conducted using Ansys Fluent software. It has been observed that the dielectric direct cooling method, which is the newest method, has a performance value of 12% better than other systems at 1C normal operating conditions.

***Keywords:*** *Battery Pack Thermal Management, Dielectric Coolant, Efficiency and Performance, Electrical Vehicles, Energy, Finite Volumes Analysis*

## 1. INTRODUCTION

Transportation in the world is mainly provided by internal combustion engine vehicles. The limited and gradually decreasing oil reserves in the world, being open to global manipulations and more importantly, posing a threat to the sustainable future, such as air pollution and climate change, have directed the transportation sector to alternative energy sources. It seems that the most convenient alternative energy source for vehicles is electric energy. On the other hand, It cannot be said that using electricity in vehicles is completely clean. Nevertheless, the total greenhouse gas emissions associated with the production, charging and use of an electric car is lower than the total greenhouse gas emissions associated with a gasoline car [1], [2], [3].

Thermal management of EV battery systems is the key to solving current problems surrounding the EV industry [4] ,[5], [6]. In research on battery pack thermal management, the best operating conditions for Li-ion batteries are between 25 ºC and 40 ºC. Studies have shown that at temperatures above 50 ºC, the charging efficiency and the battery's working life will decrease considerably. Li-ion batteries lose 60% of their initial capacity after 600 cycles at 50 ºC and 70% after 500 cycles at 55 ºC [7].

The temperature distribution of the battery cells within the battery pack is of paramount importance for the performance of electric vehicles. Various cooling methods are available to ensure a homogeneous temperature distribution, among which the most prevalent are air-cooling and indirect liquid-cooling methods. The next generation immersion cooling method represents a promising alternative for achieving more effective thermal management in battery packs.

Air-cooled systems have a simple design and low operating and maintenance costs. However, these systems require more volumetric flow, more space and more power for sufficient heat transfer. Liquid-cooled systems are used in applications where high energy is required, so more heat transfer is needed.

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However, the reasons such as the complex designs of the indirect liquid cooling systems, the presence of more equipment, the increase in weight and the lack of thermal homogeneity in aggressive working conditions have led to the emergence of cooling systems with the direct immersion method [4], [6], [8].

In the direct immersion method, the battery cells are in direct contact by immersed in a dielectric liquid with specific thermal properties. Since the battery cells are in direct contact with the coolant, it is called a direct contact cooling method. The advantage of this method is that extremely high heat transfer rates can be achieved through direct contact of the cells with the immersion fluid. In addition, immersion fluids specially developed for electric vehicles can act as fire extinguishers and reduce the risk of thermal runaways [2], [9], [10].

Recent studies in battery pack thermal management have demonstrated that the direct immersion cooling method is a more effective solution compared to other cooling strategies for electric vehicle batteries. One notable study conducted by Zhang et al. found that the direct immersion method offers the fastest cooling rates, leading to improved battery performance and a longer lifespan under 1C working conditions [11]. In a similar comparative study conducted by Chen et al., the performance of different cooling methods on a lithium-ion battery pack was evaluated under a 1C working condition, where it was found that the direct immersion method resulted in the lowest temperature rise and the highest heat dissipation efficiency, making it the most effective thermal management strategy [12]. Furthermore, immersion fluids used in direct immersion cooling have been found to have fire extinguishing capabilities, as highlighted by a study conducted by Zhang et al. which significantly reduces the risk of thermal runaways in the event of battery failure [11]. Overall, the direct immersion method is a promising solution for efficient and safe thermal management of electric vehicle batteries, especially in aggressive working conditions.

Several academic studies [10, 13, 14] have compared the performance of different cooling methods for electric vehicle battery packs, including air-cooling, cold-plate liquid-cooling and immersion cooling. These studies have utilized both numerical simulations and experimental tests to evaluate the cooling efficiency, temperature uniformity and overall performance of each method. In the study conducted by Roe et al., the performance of three cooling methods was compared using indicators such as maximum temperature difference between battery cells and temperature standard deviation. The results showed that immersion cooling was the most effective method and had the least temperature difference between the cells. The air-cooling method performed the worst in terms of maximum temperature difference compared to the other two methods, while the cold-plate liquid-cooling method was in between.

The use of electric vehicles (EVs) has been on the rise in recent years due to growing environmental concerns and the need to reduce greenhouse gas emissions. However, effective and safe management of their batteries remains a significant challenge. Thermal management is critical to the performance and durability of electric vehicle batteries, especially during extreme weather conditions or high-demand driving scenarios. Various thermal management strategies have been proposed and tested to address this issue, such as liquid cooling, air cooling, phase-change materials and direct immersion cooling. Direct immersion cooling has gained increasing attention due to its promising performance in terms of cooling efficiency, safety and simplicity. In this context, this study aims to design and analyze a battery pack for a passenger electric car using the direct immersion cooling method and to evaluate its thermal performance through numerical simulations using the finite volume method. The performance of the immersion cooling method will be compared to other cooling methods, such as air-cooling and cold-plate liquid cooling, by analyzing factors like temperature uniformity, cooling efficiency and maximum temperature difference between battery cells.

## 2. MATERIAL AND METHODS

To conduct a thermal analysis of the indirect liquid cooling system, the dimensions of battery packs in a commercial vehicle were used as a reference. The thermal performance of the currently used cooling system for this vehicle [15] was compared with the direct cooling system designed in this study. The module is made of Al6061 T1 material and has dimensions of 1854 x 292 x 66 mm, which are approximately the same size as the original commercial vehicle's module.

The analysis model shown in Figure 1a was used in the indirect liquid cooling analysis, while the model in Figure 1b was used for analyzing direct cooling methods and the model in Figure 1c was used for analyzing direct cooling with air method.

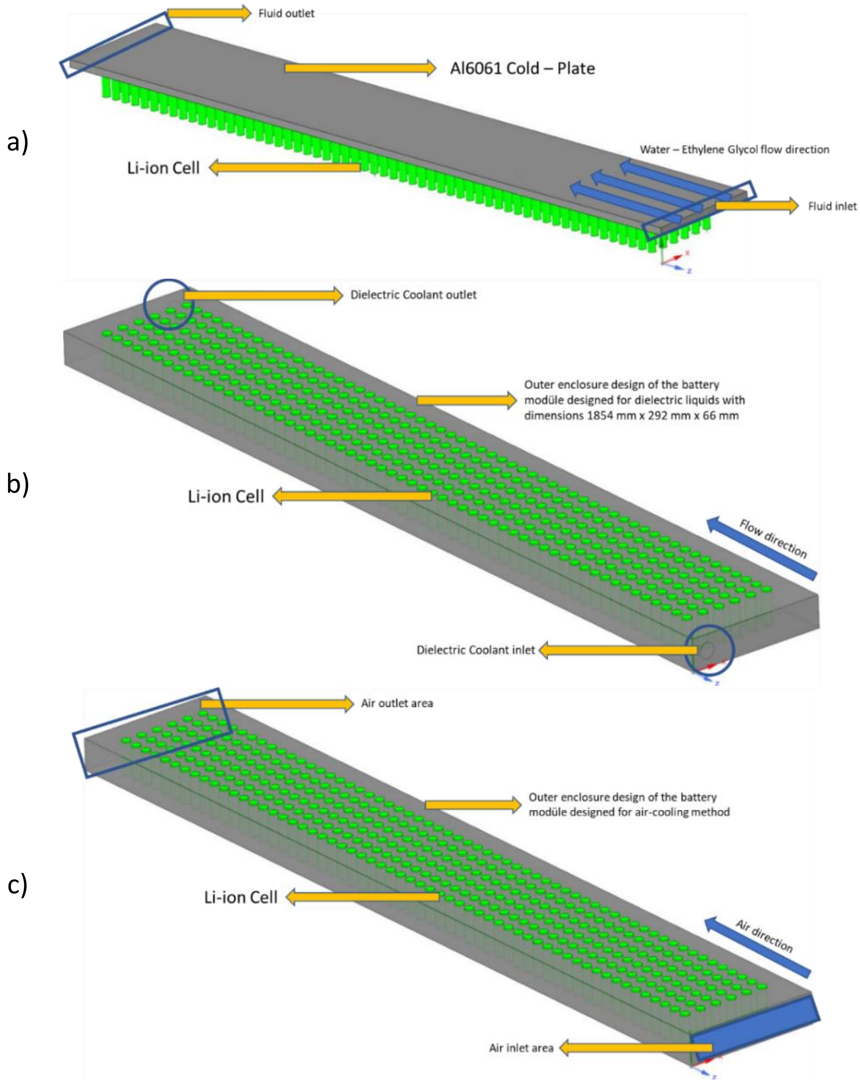


Figure 1. CAD Design of 1 Module a) Indirect Liquid Cooling b) Direct c) Air-cooling CAD Model

### 2.1. Battery Selection

Lithium-ion battery cells are commonly used in electric vehicles due to their reliability and high energy density per unit mass [16], [17]. For this reason, the Panasonic NNP Series NCR-18650A Li-ion batteries were selected for this study. The technical specifications of these batteries are presented in Table 1 [18].

**Table 1.** Technical Specifications and Calculations of Panasonic NNP Series NCR-18650A Battery Cell [18].

| | |
|---|---|
| Battery Cell Voltage (Nominal) | 3.75 V |
| Group (1 Module) Voltage | 22.5 V (6S – 6 x 3.75 V) |
| Battery Cell Current Rating (Nominal) | 3750 mAh |
| Group (1 Module) Current Capacity | 217.5 Ah (58P – 58 x 3750 mAh) |
| 1 Module Power Capacity | 22.5 V x 217.5 Ah = 4.89 kWh |
| 1 Battery Pack (16 Modules) | 16 x 4.89 kWh = 78.24 kWh |
| Dimensions of Battery Cell | Diameter: 18.6 mm Length: 65.2 mm |

### 2.2. Fluid Selection

Various methods exist for the thermal management of battery packs, with the air and liquid cooling method being the most used. To determine the best cooling method for the battery pack, the required thermal load must be calculated. Generally, the air-cooling method is used in vehicles that require less power density [16]. However, with increasing demand for more powerful vehicles and longer ranges, the need for advanced liquid cooling methods is growing. Different liquids are used based on the design and power density of the battery model. In the indirect liquid cooling method, the most used cooling liquid is a 50/50 Water Ethylene Glucose solution, while dielectric liquids are used in the direct liquid cooling method [18].

Due to the widespread use of the immersion cooling method, special chemicals have been developed to produce dielectric liquids. The most used dielectric liquids are Novec and Engineered Fluids. Table 2 presents the necessary equations to calculate the thermo-physical properties of the dielectric liquid at 20°C in the given operating range, as well as the thermo-physical properties of the dielectric liquid calculated using these equations.

**Table 2.** Thermo-physical property equations of dielectric fluid [18].

| Thermo-Physical Properties | Equations | Working Range | Calculated Values |
|---|---|---|---|
| ϱ [kg/m3] | $-2.0845 \times T\,[°C] + 1665.8$ | 20 °C ≤ T ≤ 70 °C | 1624.11 |
| μ [Pa sec] | $1\times10^{-7}\times T^2[°C] - 3\times10^{-5}\times T[°C] + 0.0018$ | 20 °C ≤ T ≤ 70 °C | 1.24 x 10-3 |
| Cp [J/ (kg K)] | $1.4982 \times T[°C] + 1091$ | 20 °C ≤ T ≤ 70 °C | 1120.96 |
| k [W/ (m K)] | $4\times10^{-7}\times T^2[°C] - 0.0002\times T[°C] + 0.069$ | 20 °C ≤ T ≤ 70 °C | 0.06516 |

For the analysis of the indirect liquid cooling method, 50/50 Water-Ethylene Glycol solution will be utilized. Table 3 provides the necessary equations to calculate the thermo-physical properties of the 50/50 Water-Ethylene Glycol solution at 293.15 K, as well as the thermo-physical properties calculated using these equations.

**Table 3.** Thermo-physical property equations of 50-50 Water Ethylene Glycol Solution liquid [18].

| Thermo-Physical Properties | Equations | Working Range | Calculated Values |
|---|---|---|---|
| ϱ [kg/m3] | $-0.615 \times T[K] + 1259.5$ | $293.15 K \leq T \leq 353.15 K$ | 1079.2 |
| μ [Pa sec] | $2.48\times10^{-8}\times T3[K]+2.47\times10^{-5}\times T^2[K]-8.22\times10^{-3}\times T[K]+0.92$ | $293.15 K \leq T \leq 353.15 K$ | 1.259 |
| Cp [J/ (kg K)] | $3.06 \times T[K] + 2574.8$ | $293.15 K \leq T \leq 353.15 K$ | 3471.84 |
| k [W/ (m K)] | $-2\times10^{-7}\times T^3[K]+0.0002\times T^2[K]-0.048\times T[K]+5.38$ | $293.15 K \leq T \leq 353.15 K$ | 3.457 |

The thermo-physical properties of the fluid air to be used in the air-cooling method are readily available in the Fluent library [20] and are given in Table 4.

**Table 4.** Thermo-physical property values for air [20].

| Thermo-Physical Properties | Values from Fluent Library |
|---|---|
| ϱ [kg/m3] | 1.125 |
| μ [Pa sec] | 1.7894 x 10-5 |
| Cp [J/ (kg K)] | 1006.43 |
| k [W/ (m K)] | 0.0242 |

### 2.3. Thermal Analysis of Battery Pack Modules with Liquid Cooling System Using Finite Volume Method

To start the analysis of direct liquid cooling, the meshing process was applied to the simplified CAD model with dimensions of 1854 x 292 x 66 mm. The creation of a smooth and high-quality mesh is critical for obtaining accurate results. However, as the complexity of the geometry increases, it becomes challenging to achieve this mesh quality. One method for verifying numerical studies is the mesh independence test, where a specific value is determined for the number of mesh structures required to obtain accurate results [20]. In this study, a summary of the mesh independence tests conducted is shown in Table 5. To create the desired number of mesh structures at various skewness ratios, both triangular and quadrilateral meshes were modified by changing their minimum and maximum dimensions. The analysis was carried out using the same turbulence models and mesh independence studies were conducted with seven different mesh numbers. As Table 5 shows, the temperature values of the battery cell obtained in the number of 2,112,173 elements were like each other. Therefore, this number of elements was determined as the appropriate value for achieving minimum error levels.

**Table 5.** Mesh Independent Study with Dielectric Liquid at 20 °C

| | Number of Elements | Battery Cell Minimum Temperature [°C] | Battery Cell Maximum Temperature [°C] |
|---|---|---|---|
| 1 | 546066 | 19.665 | 25.078 |
| 2 | 555354 | 19.8 | 24.5 |
| 3 | 822385 | 20.01 | 22.079 |
| 4 | 1322101 | 20 | 20.134 |
| 5 | 2112173 | 20 | 20.179 |
| 6 | 3294243 | 19.99 | 20.180 |
| 7 | 6207887 | 20 | 20.183 |

The skewness value was assessed to evaluate the mesh quality level, revealing an average value of approximately 0.21. Considering that skewness values below 0.4 are typically deemed acceptable in the literature [1], the analysis was conducted using this mesh generation. Additionally, the orthogonal quality value of the model was scrutinized, exhibiting an average value of 0.83. Given these findings, it was concluded that the mesh quality was adequate for obtaining precise outcomes.

Once the mesh preparations are finished and the mesh sizes are determined, the meshing process is completed. The geometric model, as displayed in Figure 2a, was designed for the dielectric direct liquid cooling and air-cooling methods and is composed of 975,648 nodes and 2,112,173 elements. On the other hand, the geometric model created for the cold plate indirect liquid cooling method, as seen in Figure 2b, contains 2,224,287 nodes and 7,262,536 elements. A detailed representation of the mesh structure on the battery cell is shown in Figure 2c.

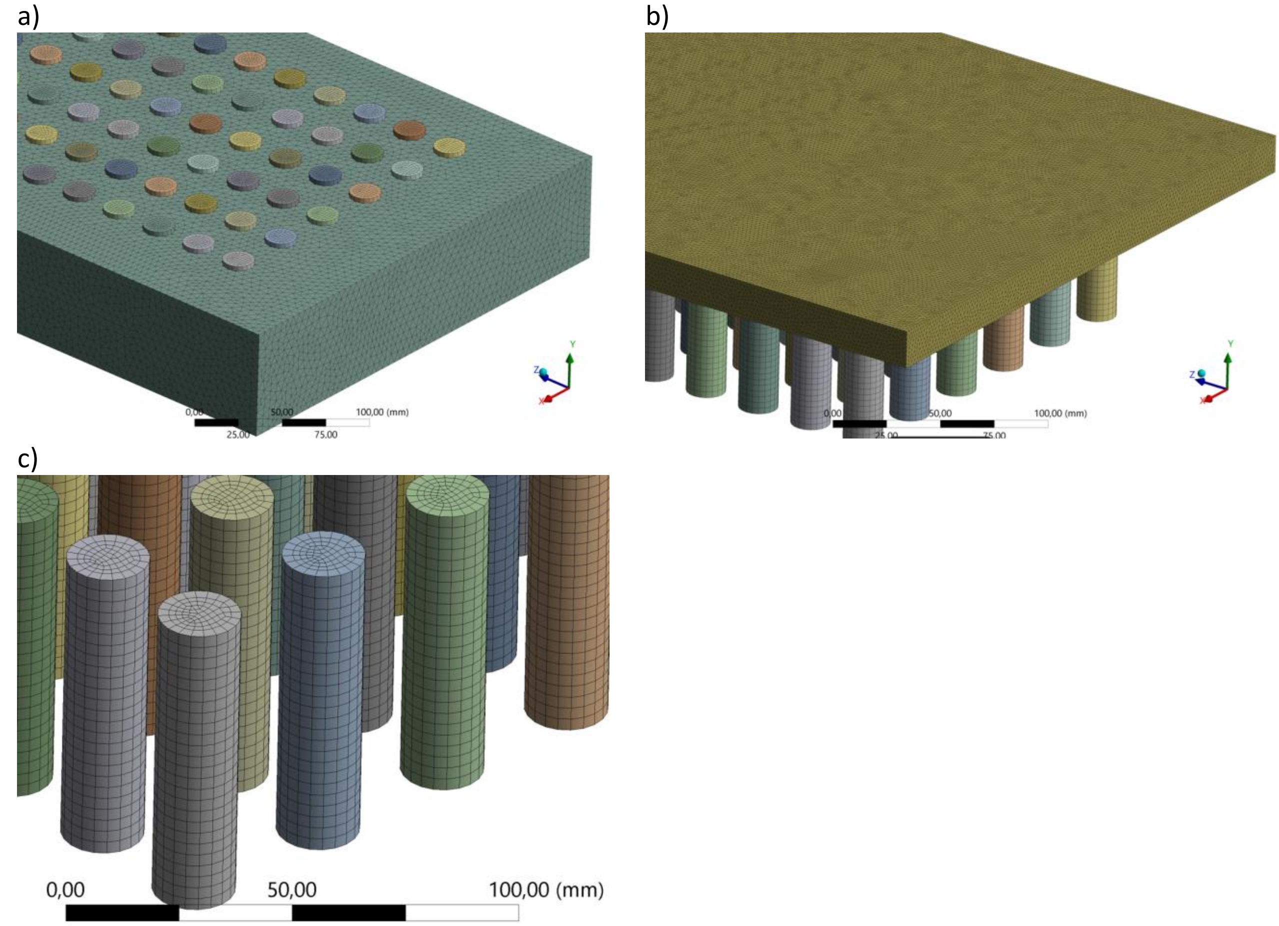


**Figure 2**. Mesh Structure a) for dielectric direct cooling and air cooling method b) for cold plate indirect cooling method c) detailed view of cells.

The energy equation shown in Equation 1, the continuity equation shown in Equation 2and the momentum equation shown in Equation 3 were solved by the program for thermal analysis the battery pack by the finite volumes.

$$\frac{\partial(\rho e_t}{\partial t} + \nabla\, x\, [V x(\rho e_t + p)] = \nabla\, x\, [k\nabla T + (\tau\, x\, V)] + S_g \quad (1)$$

$$\rho_1\, x\, v_1\, x\, A_1 = \rho_2\, x\, v_2\, x\, A_2 \quad (2)$$

$$F = \frac{d(mV)}{dt} = m\frac{dV}{dt} = m\, x\, a \quad (3$$

In the analysis study to be conducted, the definition of boundary conditions has been explained in detail:

Firstly, a significant portion of total heat production in battery cells is generated due to the ohmic resistance [11]. The heat produced through ohmic resistance heats up the surface of the battery cell through conduction. This heat generated on the surfaces of the battery cell is removed by convective heat transfer with the help of the coolant fluid. The amount of heat generation occurring in a battery cell due to ohmic resistance is calculated by $I^2 x\ R$, where I represent the standard capacity under working conditions and R is defined as the internal resistance of the battery cell. The heat amount produced by the battery cell with this formula is also the minimum amount of heat transfer that needs to be exceeded by convection. Table 1 shows that 6S58P (348 pieces of 18650 Li-ion battery cells) are used in the analysis model. In this case, the total heat energy that will occur in a module can be calculated. Under 1C operating conditions, the heat production occurring in one battery cell is calculated as $3.1^2 x * 0.1 = 0.96\ W$. The total heat production due to ohmic resistance in a module is found to be 335.04 W by multiplying 0.96 with 349. Therefore, a heating boundary condition of 0.96 W for each battery cell through conduction is defined.

This heat needs to be removed through convection. The heat transfer coefficients for the forced air, dielectric liquid and water ethylene glycol solution that will be used in the analysis model are determined as shown in Table 6. For forced air, 70 W/m²K, for forced water ethylene glycol solution, 600 W/m²K and for dielectric liquid, 1750 W/m²K, are defined under the convective boundary condition [21]. As a result of the research conducted, it was found that the coolant fluids in vehicles are usually circulated within the range of 1-9 LPM [22]. In the analysis study, this value was accepted as 6 LPM and the flow rate was defined as the flow rate in the analysis program.

**Table 6.** Convective Heat Transfer Coefficient [22].

| **Convection Type** | **Convective Heat Transfer Coefficient** | |
|---|---|---|
| | **Btu / (hxft2R)** | **W / (m2K)** |
| Air, Free Convection | 1 – 5 | 2.5 – 25 |
| Air, Forced Convection | 2 – 100 | 10 – 500 |
| Liquid, Forced Convection | 20 – 3000 | 100 – 15000 |
| Boiling Water | 1000 – 20000 | 2500 – 25000 |
| Condensing Water Vapor | 1000 – 20000 | 5000 – 100000 |

Convective heat transfer will help to balance this generated heat. Numerically, if we calculate this example:

The internal resistance of a classical 18650 Lithium-ion battery cell can be selected as an average of 0.1 Ohm [11]. The heat generated in one Lithium-ion battery cell is found to be $I^2 x\ R$, which is 0.96 W under 1C operating conditions. The minimum amount of heat energy that needs to be removed is determined by multiplying this value by the number of battery cells. It is found to be 335.04 W by multiplying 0.96 W with 349, which is the number of cells used in the analysis model. This heat generation must be removed from the surface of the battery cells to the fluid through convective heat transfer. The expression for this is shown in Equation 4.

$$Q = h\ A\ (T_{surface} - T_{fluid}) \quad (4)$$

Q : Heat Transfer Rate

h : Heat transfer coefficient

A : Surface Area

$T_s$ : Surface Temprature

$T_w$ : Fluid Temprature

The surface temperatures expected in different fluids are approximately as follows:

The surface temperature of the battery cell in the module cooled using dielectric liquid:
$335.04\ W = 1750\frac{W}{m^2 x} 1.36\ m^2\ x(T_s - 20)$ → $T_s = 20.14\ ^oC$

The surface temperature of the battery cell in the module cooled using water ethylene glycol:
$335.04\ W = 600\frac{W}{m^2 x} 0.56\ m^2\ x(T_s - 20)$ → $T_s = 21\ ^oC$

The surface temperature of the battery cell in the module cooled using air cooling:
$335.04\ W = 70\frac{W}{m^2 x} 1.3\ m^2\ x(T_s - 20)$ → $T_s = 23.7\ ^oC$

The numerical calculations reveal that the best thermal performance is achieved with the dielectric liquid cooling method. The verification of these values and results against the boundary condition defined in the analysis will be examined in Section 3.

## 3. RESULTS AND DISCUSSION

Battery packs in electric vehicles directly influence the battery's service life and, thus, the car's performance, depending on the cooling method [23]. Sudden rises in temperature in the battery cells are one of the cases that adversely affect the battery's life and safety [23]. A sudden rise in temperature in the battery pack or a decrease in thermal homogeneity between battery cells causes the risk of thermal runaway and explosion [7].

The temperature distribution results performed under normal operating conditions using forced air as the refrigerant in the direct cooling method are shown in Figures 3a and 3b. The difference between the inlet and outlet temperature values of the battery cells has reached approximately 20%.

In Figure 3, the difference in temperature between the battery cells is relatively high (approximately 21%), so it doesn't seem good enough. For this reason, it is thought that the air-cooling method wouldn't supply sufficient thermal homogeneity in fully electric vehicles. Similar results have been demonstrated by Kaba et al. [16]. One of the reasons for the temperature differential among battery cells in an air-cooled battery thermal management system is a lack of sufficient heat transfer coefficient. Heat transfer coefficient is a measure of how effectively heat is transferred between the surface of the battery cells and the cooling air. If the heat transfer coefficient is not sufficient, some cells may not receive enough cooling air, leading to higher temperatures and a temperature differential among the cells. To ensure uniform cooling and minimize temperature differentials among the cells, it is important to optimize the heat transfer coefficient in the battery thermal management system. This can be achieved through careful design of the cooling channels and flow rates, as well as regular maintenance and cleaning of the cooling system.

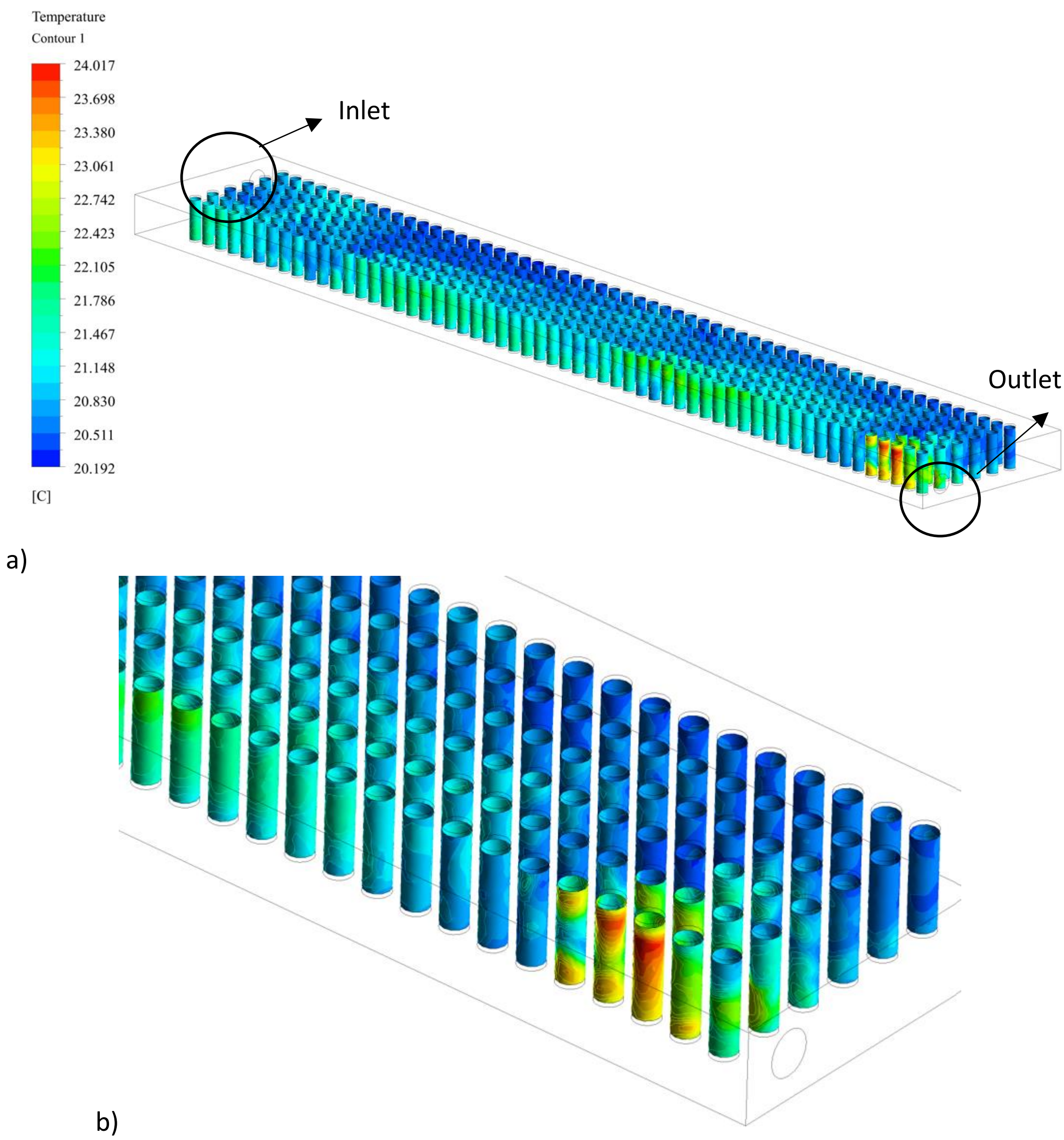


**Figure 3.** Air Cooling Method Temperature Distribution a) General View b) Detail View

In indirect cooling thermal management systems, the heat is carried by a heat sink plate or pipes. Unlike the direct liquid cooling system, the coolant doesn't contact the battery cells in this method. The post-analysis temperature distribution of the indirect cooling system modeled in this situation is shown in Figures 4a and 4b. The analysis made by passing a water-glycol solution through the cooling plate, it is seen that the maximum temperature difference between battery cells is approximately 10%. Also, the difference between inlet and outlet coolant temperatures was about %13. Although this is a better performance value compared to the air-cooled system, the indirect liquid cooling method may not provide sufficient performance values in systems that require high power density [23], [24].

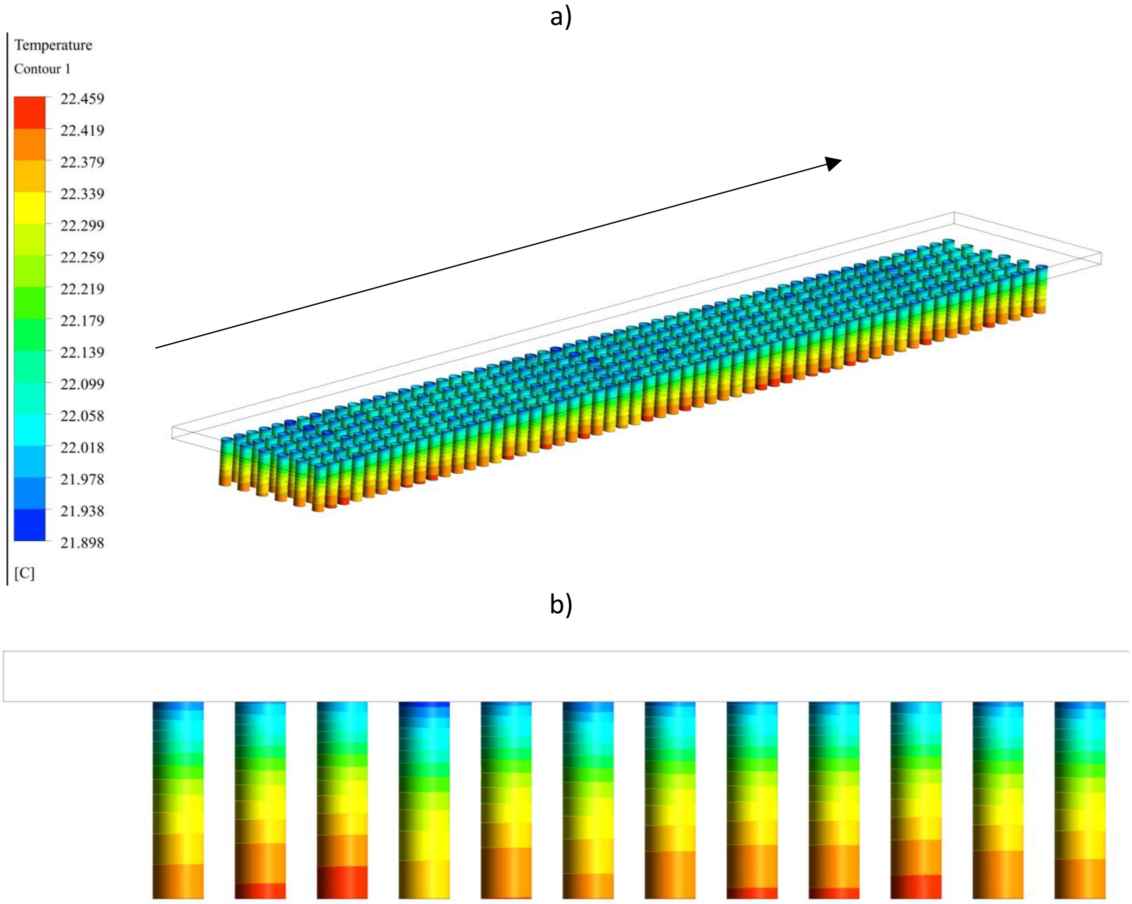


**Figure 4.** Cold Plate Cooling Method Temperature Distribution a) General View b) Detail View

In the Cold plate liquid-cooled battery thermal management system, a cooling fluid is circulated through Cold-plate in contact with the battery cells to remove heat. However, due to the geometry and placement of the cells, not all cells receive the same amount of cooling fluid, leading to temperature variations among the cells. This variation in cooling leads to a temperature differential between the cells with some cells being cooler than others. The heat generated is not uniform among the cells and cells that are generating more heat will become hotter than those generating less heat. This uneven heat generation can exacerbate the temperature differential between cells, especially if the heat transfer coefficient is not optimized.

The results of direct cooling analysis have been demonstrated in Fig 5a and Fig 5b. The maximum temperature difference between the battery cells was found to be approximately 0.89%. Since the temperature difference between the battery cells is so low compared to the other methods and the thermal homogeneity is good, it can be expected that the battery pack has superior thermal performance, decrease the risk of thermal and leakage and directly increase vehicle performance. The summary of the results of the finite volume analyses performed for the dielectric liquid direct cooling method, the air direct cooling method and the cold plate cooling method was shown in Table 7. Looking at the difference between the inlet and outlet temperatures, it is seen that the most homogeneous thermal distribution is the direct immersion method with the dielectric liquid, the indirect cooling system with the help of the plate and the air-cooling method, respectively.

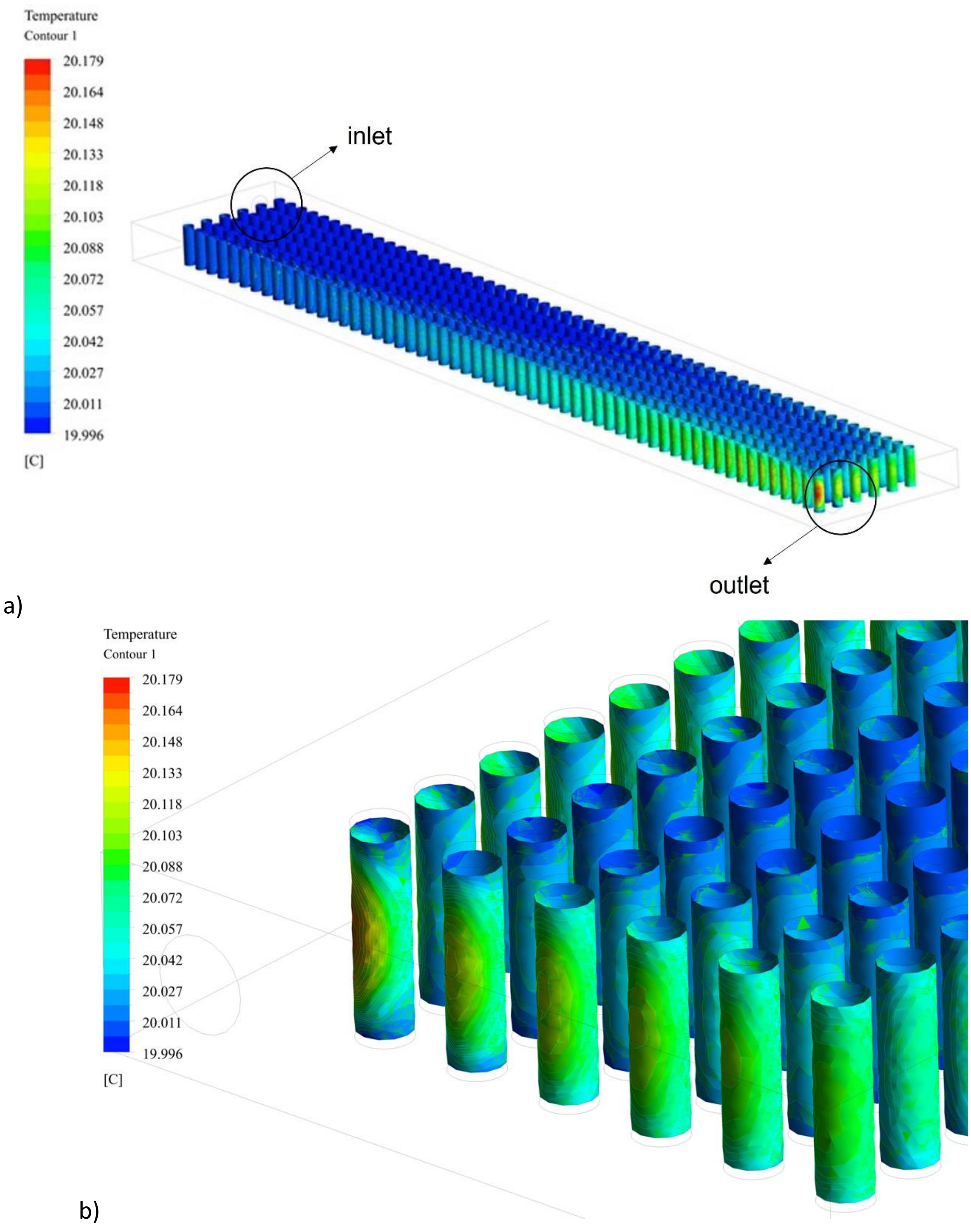


**Figure 5.** Dielectric Liquid Cooling Method Temperature Distribution a) General View b) Detail View

In a dielectric liquid-cooled battery thermal management system, a dielectric fluid is circulated through channels in contact with the battery cells to remove heat. Dielectric fluids have higher heat transfer coefficients compared to air and can more effectively transfer heat from the battery cells to the cooling system. This results in more uniform cooling across the battery pack and reduces temperature variations among the cells. In a dielectric liquid-cooled system, the heat transfer coefficient is higher than in an air-cooled system and cold-plate based system due to the higher thermal conductivity of the dielectric fluid. This allows for more efficient heat transfer between the battery cells and the cooling system, resulting in a more uniform temperature distribution across the battery pack.

In summary, the higher heat transfer coefficient of dielectric liquid cooling methods can provide more uniform cooling and reduce temperature variations among battery cells, leading to improved battery pack performance and longevity. It is desirable that the temperature difference between the battery cells be as low as possible. Thermal runaway is a very serious problem that will cause the surrounding battery cell ignites and explode if even a single cell in the battery pack gets too hot. Having better thermal homogeneity of Lithium-Ion batteries, which are the most widely used in electric vehicles, leads directly affects vehicle performance and minimizes the risk of thermal runaway and explosion.

**Table 7.** Comparison of the minimum and maximum temperature values of battery cells according to the analysis results.

| | Inlet Temperature | Minimum Temperature | Maximum Temperature | Temperature Difference Between Battery Cells |
|---|---|---|---|---|
| Air Cooling | 20°C | 20.192 °C | 24.017 °C | 3.825 °C |
| Indirect Cooling with Cold Plate | 20°C | 21.898 °C | 22.459 °C | 0.561 °C |
| Direct Cooling with Immersion Cooling | 20°C | 20.011 °C | 20.179 °C | 0.168 °C |

## 4. CONCLUSIONS

During charging or discharging of a battery cell, ohmic heat is generated due to the resistance of the cells. This heat can cause an increase in the temperature of the battery, which can be detrimental to the cells. Convective heat transfer helps to balance this heat by transferring it away from the battery cells. Direct liquid cooling uses a dielectric cooling fluid to directly cool the heat-generating battery cells, while indirect liquid cooling uses a coolant to first cool a cold plate, which in turn indirectly cools the battery cells. In this study, the thermal performance of different cooling methods in a battery module under 1C operating conditions was compared based on the total heat generation and convective heat absorption. When the direct cooling method was examined in detail, it was found to have a lower surface temperature output value for the battery cells in a battery module than all other methods under the determined conditions and dimensions. This provides the desired homogeneity output and demonstrates the suitability of this study for further academic research.

- ✓ The research findings indicate that the immersion liquid cooling technique offered superior thermal uniformity in comparison to the other methods investigated. This method has been shown to be particularly effective in high-power-density vehicles, as it can efficiently dissipate heat and prevent localized temperature hotspots that may lead to thermal runaway or other safety hazards. In contrast, the air-cooling method, while being an eco-friendly and cost-effective alternative, demonstrated inadequate thermal management performance in high-power-density applications. This method is less efficient in dissipating heat due to the low thermal conductivity of air and thus may lead to localized hotspots that can negatively impact battery performance and longevity. Additionally, the indirect liquid cooling method, which involves cooling the battery through a coolant flow in a separate circuit, requires additional design and auxiliary equipment, thereby making it more challenging to maintain and potentially more expensive. Overall, the results highlight the importance of selecting an appropriate cooling method based on the specific application and design requirements to ensure optimal thermal management performance and battery safety.
- ✓ The maximum temperature difference between the immersion cooling method and the liquid plate cooling method was determined to be 12%. This temperature difference, however, may vary depending on the type of cooling method used, as XING Mobility, a new venture company in the field of dielectric cooling, claims that their method can achieve temperature differences of up to 20% to 30%. It is worth noting that the use of air cooling and indirect liquid cooling methods may result in localized temperature increases in the battery cell, which can potentially lead to thermal runaways and even explosions, as reported in various studies [1], [7], [25], [26], [27].

In the next research, by taking this study as a reference, the thermal performance of the battery cells and battery module can be examined in sudden charge and discharge situations (4C and 5C standards), which require the change of the thermal parameters of the finite volume model.

**Declaration of Ethical Standards**

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

**Credit Authorship Contribution Statement**

Conceptualization, F.E. and K.T.; methodology, F.E. and K.T.; FEM analysis, F.E; validation, K.T.; investigation, F.E. and K.T.; data curation, F.E. and K.T.; writing—original draft preparation, F.E. and K.T.; writing—review and editing, M.R. and K.T.; visualization, M.R. and K.T.; supervision, M.R. and K.T.; funding acquisition, F.E. and K.T. All authors have read and agreed to the published version of the manuscript.

**Declaration of Competing Interest**

The authors declared that they have no conflict of interest.

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**Data Availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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