

RESEARCH ARTICLE

Battery thermal management system analysis on electric vehicles

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Abstract - Battery thermal management systems (BTMS) on electric vehicles are crucial for efficiently managing battery temperature. The development of BTMS has been a crucial part of the commercialization of electric vehicles. The efficiency of the BTMS has become a bottleneck to increasing the battery's charging and discharging rates. Hence, this study aims to examine the impact of cell arrangement and the type of coolant used on the BTMS performance, and also to identify the most suitable setup for the current module. This study uses Ansys as the Computational Fluid Dynamics (C) software to simulate the cooling of a battery module with 96 units of 21700 cylindrical cells by immersion cooling BTMS. Two cell arrangements and three types of coolant have been simulated to identify the impacts on the performance of the BTMS. The flow speed of the coolant is set to 0.0020 m s^{-1} , 0.0045 m s^{-1} , 0.01 m s^{-1} , 0.015 m s^{-1} , and 0.02 m s^{-1} to analyse the impact of the setup at different inlet velocities. The inlet velocity is set to a constant at the inlet of the module without considering the pressure loss coming from the pump to simplify the study. The result indicates that the aligned module has reduced the maximum module temperature and module temperature gradient by 7.91% and 24.64%, respectively. For the coolant, water shows its superior cooling performance, which reduces the maximum temperature and temperature gradient of the module by 17.61% and 63.77%, respectively. The Analytic Hierarchy Process indicates the same decision, where water is the most suitable alternative for the given criterion in this study. However, water has significant safety issues where it can cause battery circuit shortage when it is polluted with ions. The study recommends that future studies consider additional criteria in terms of safety and lifespan for the AHP, and also to apply more detailed geometry for the module in order to achieve more practical results.

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1. Introduction

Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) have been gaining popularity in recent years due to their low or zero emissions [1]. Lithium-ion Batteries (LIBs) have been applied to EVs as the popular energy source due to their high energy density, low self-discharge rate, and long lifespan [2]. It is worth noting that in the cycle of charging and discharging process, a significant amount of heat can be dissipated from the battery module. The increasing charging rate, particularly fast charging, can cause higher heat dissipation [3], [4]. Lithium-ion batteries (LIBs) are sensitive to temperature and high temperature fluctuations. To address the heat dissipation issue, the battery pack in EVs is integrated with a Battery Thermal Management System (BTMS). In a battery pack, the smallest unit is a cell. The cells link together to form a module. The modules are then linked together to produce a high-voltage battery pack. Figure 1 displays the position of cells and modules in a battery pack [5].

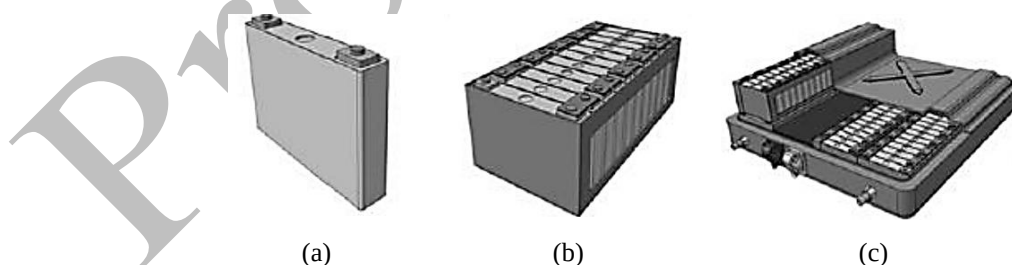


Figure 1. Terms and respective parts of a battery pack (a) cell (b) module (c) pack [5]

The large-scale development of EVs is limited by several critical factors that can contribute to significant issues in daily usage for the driver. In terms of convenience, EVs need to overcome charging and discharging rates to reduce the drivers' waiting time at charging stations [5]. Besides, the safety factor is the utmost factor in the development of EVs [6]. Currently, the thermal runaway of the battery pack inside EVs is uncontrollable, which is a critical fire hazard in EVs. In addition, the lifespan of the battery is one of the bottlenecks that limit the large-scale development of EVs [7]. The efficiency of the BTMS decides the maximum charging and discharging rate allowed, and the number of battery modules that can be supported for an EV [9], [10]. There are several types of BTMS, including air cooling and liquid cooling systems, which are also recognized as active BTMS [11], [12], [13]. Air-based BTMS has the advantages of a simple

structure, low manufacturing cost, and low energy consumption compared with liquid-based BTMS. Nevertheless, a large-capacity battery and fast charging require a higher heat transfer coefficient to efficiently remove the heat from the battery pack [13],[14]. The liquid-based BTMS is more capable of removing more heat than the air-based BTMS in the same volume, as the liquid-based BTMS has higher specific heat capacitance [15]. It is worth noting that the active BTMS consumes electrical energy from the battery, which reduces the EV battery's mileage[17]. Thus, it is crucial to study and utilize BTMS to enhance efficiency.

A lithium-ion battery has a narrow range of optimum operating temperature, ranging from 15°C to 35°C, and a tolerance of a 5°C temperature difference within a multi-cell module [18], [19]. The flow structure, mass flow rate, pressure loss, and heat coefficient are the main factors to be studied. As mass flow rate increases, pressure loss increases, leading to significant power consumption in the BTMS system. The high mass flow rate will also increase the risk of BTMS failure, especially coolant leakage, which can cause a circuit shortage within the battery module. The past study has focused on optimizing the air-cooled BTMS via cell arrangement and airflow path design, with limited focus on optimizing the direct liquid-cooled BTMS. The previous study also did not focus on optimizing the parasitic power from the BTMS. Thus, this study is conducted to analyse the impact of cell arrangement on BTMS cooling performance, evaluate the effects of coolant materials on BTMS performance under different velocity values, and determine the suitable configuration of the parameters for the current module.

2. Methods and Material

The following sub-chapters discuss the methods and materials used in the study. The materials used in this study were referred to the setup used by Mazyar *et al.* in their study [20]. The mesh and simulation setup were converted to be compatible with Ansys Fluent, as the original setup was set for STAR-CCM. The simulation study focused on two components, which were the cooling material and cell arrangements. The final goal of the simulation was to determine the most efficient setup for the current BTMS under various coolant velocities. To limit the variables, the battery's heat generation was assumed to be a simple, constant heat source. In addition, the study was simplified to be time-independent. To compare the results for each material and cell arrangement, temperature colour contours and plotted graphs were prepared. In addition, the AHP was done to further analyse the performance of each cooling material based on the preference of each factor.

2.1 Materials in the Study

This study focused on the analysis of direct liquid-cooled BTMS, comprising 96 units with 21,700 cylindrical cells, one enclosure, and different coolants. Table 1 shows the properties of a 21,700-cell. The dimensions of the 21700 cells can be inferred from their code: “21” represents the cell diameter is 21 mm, “70” represents the cell height is 70 mm, and “0” indicates the cell has a cylindrical shape [1], [20]. In this study, the heat generation of each cell was assumed to be constant at 4.4 W. This baseline assumption is informed by empirical heat generation curves from previous literature and the practical operational boundaries of electric vehicles (EVs) [20]. For instance, the 2017 Tesla Model 3 adopted 21700 cylindrical cells within its battery pack. According to manufacturer specifications, 21700 cells are designed to operate continuously between 0.5C and 2.0C on average [21], representing the permissible continuous discharge rate during vehicle operation. By definition, C-rate quantifies the number of times a battery can be fully charged or discharged in one hour. Prior research demonstrated that through the dielectric immersion cooling method, Novec fluid was able to control the internal temperature gradient within 5°C inside the 21700 battery module. At this upper cooling boundary, the cell generated 4.4 W of heat at an operating rate of approximately 2.62C. Consequently, this 4.4 W thermal load models a sustainable high-stress scenario, such as high-speed highway cruising or A/C maximum charging operation.

Table 1. 21700 lithium-ion cell properties [41]

Property	Value
Rated discharge capacity (1C-rate)	3.2 Ah
Nominal voltage	3.56 V
Rated discharge energy	11.4 Wh
Density	560 kg m ⁻³
Heat capacity	1000 J kg ⁻¹ K ⁻¹
Radial thermal conductivity	1 W m ⁻¹ K ⁻¹
Axial Thermal conductivity	25 W m ⁻¹ K ⁻¹
Tangential thermal conductivity	25 W m ⁻¹ K ⁻¹
Internal resistance	50 mΩ

The 21700 cells were arranged in two different arrangements, as shown in Figure 2. The first arrangement was constructed by placing the cells in two different patterns: the 3 rows of cells were positioned closer to the inlet, and the rest were positioned 12.5 mm behind. On the other hand, the aligned cell arrangement allowed the cells to be spaced equally. Both cell arrangements left a 2 mm gap between cells.

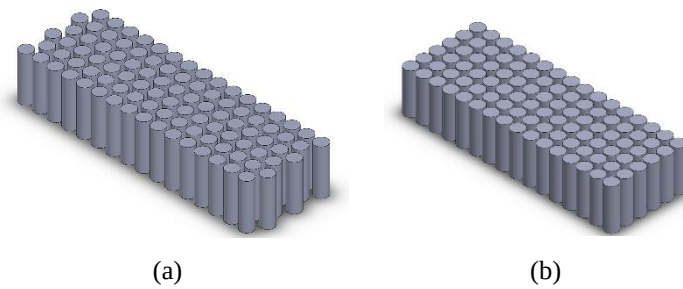


Figure 2. Isometric views of the cell configuration for: (a) staggered cell module; (b) aligned cell module

The cells were sealed in a module that consisted of walls, one inlet, and one outlet, as shown in Figure 3. The flow direction was consistent throughout the simulation for any cell arrangement or any coolant. The enclosure had equal height with the cell, which restricted the coolant to only flow around the side wall of the cell.

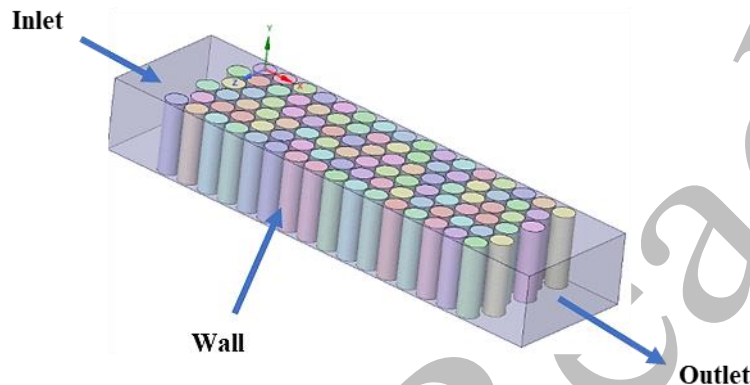


Figure 3. Dimensions of the enclosure

In Table 2, the properties of the coolants used in the study are listed. The coolants were selected based on common coolants available in the industry. The coolants were applied only one type at a time in the simulation with different inlet velocities for comparison.

Table 2. Material properties of fluids

Materials	Density (kg m^{-3})	Specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	Dynamic viscosity ($\text{Pa}\cdot\text{s}$)
Novec	1660	1130	0.06	0.000870
Ester	804.06	2155	0.1589	0.008290
Water	998.2	4182	0.6	0.0010016

2.2 Mesh independence study

Different mesh element sizes can cause CFD results to differ, even when the parameter setup is constant. A finer mesh can lead to more accurate results, as it better resolves steep gradients in flow variables and features. A coarser mesh tends to smooth out the important flow features, which reduces the accuracy of the results. Due to the computational cost, the element size cannot be extremely fine. The element size must be chosen wisely to achieve acceptable computational cost and an accurate result. To obtain stable simulation results with minimum mesh resolution, the simulation parameter is fixed, and the simulation is repeated with different element sizes and temperatures [22]. Table 3 Includes the physical parameters that are used for the simulation and the tested element size. The simulation result is compared in terms of maximum coolant and module temperature.

Table 3. Parameter setup for the validation test

Parameters	Description
Thermal condition	1 source term, 181400 W m^{-3}
Inlet velocity	0.0045 m s^{-1}
Inlet temperature	20°C
Gravity	y-axis, -9.81 m s^{-2}
coolant	Novec
Element size	1 mm, 3 mm, 5 mm, 7 mm, 9 mm

Through the simulation, the result for each element size was demonstrated as shown in Figure 4. The module temperature re was significantly reduced with the smaller element size. On the other hand, the coolant temperature was

much more stable regardless of the element size. When the element size shifted from 5 mm to 3 mm, the module temperature dropped from 43.13°C to 41.47°C, resulting in a 3.84% temperature reduction. When the element size shifted from 3 mm to 1 mm, the temperature rose from 41.47°C to 41.70°C, increasing the module temperature by 0.5%. In addition, the coolant temperature rose from 26.85°C to 27.33°C and dropped to 26.74°C when the element size shifted from 5 mm to 3 mm and 1 mm, which means the element size only contributed almost 2% of the difference in coolant temperature. The result showed that the 3 mm element size is the ideal option to conduct grid independence simulation with the lowest computational cost. The graph of module temperature against the element size also showed that the temperature curve was almost flat.

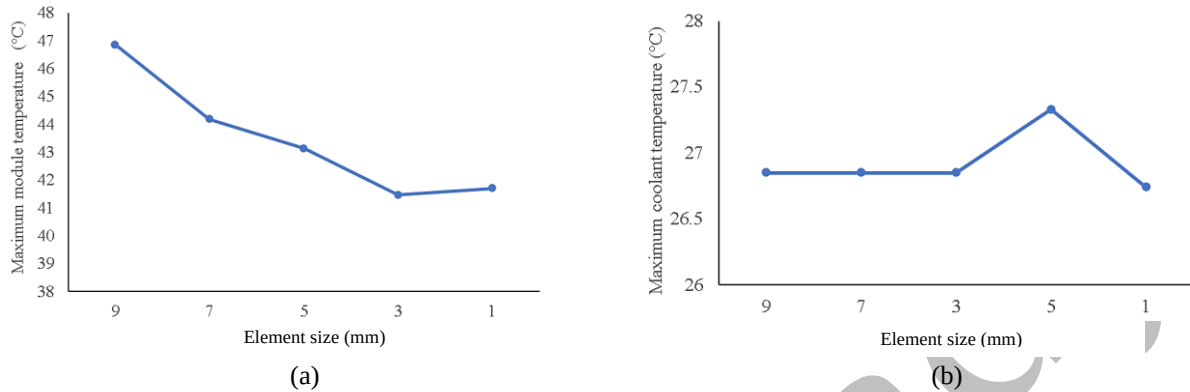


Figure 4. The maximum temperature against mesh size for: (a) the module; (b) the coolant

To verify the result, the simulation result was compared with one past study conducted by Mazyar *et al.* [20]. In the identical module geometry and simulation setup. In Figure 5, the module temperature contour is compared side by side. The comparison proved that both contours exhibit an identical pattern, in which the module temperature rose smoothly from the inlet to the outlet. The cells that were next to the outlet have obviously higher temperatures due to turbulence flow formed at the outlet. The maximum module temperature for past study and current study was 37.873 °C and 41.47 °C, respectively. The maximum module temperature for the current study was 9.51% higher compared to the past study. The setup for the current study was acceptable, as the error in the result was controlled within 10%. The difference in the study could result from differences in the software used in the simulation and the slight difference in the inlet and outlet path length.

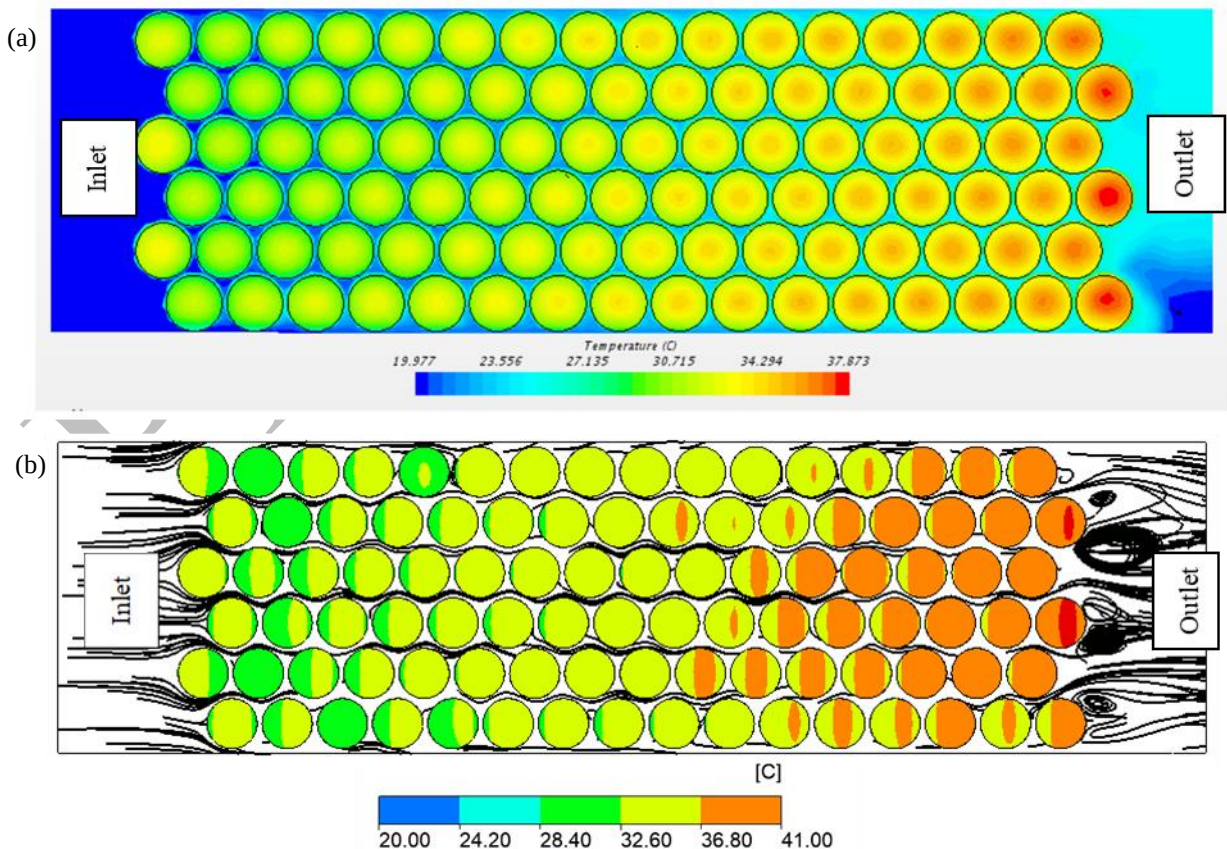


Figure 5. The module temperature contour from: (a) the referred past study [20]; (b) the actual result

In summary, the mesh independence and validation study were executed as shown in Figure 6. The geometry for the module and the enclosure were drawn and set inside the Ansys Workbench Geometry section. The mesh was set with 9 mm of element size in the beginning to let the simulation start with minimum computational power. The simulation environment was set to a fixed value to let the module release heat and the coolant flow at a fixed rate within 350 iterations. The coolant and module temperature values and contour were collected at the end of the simulation. The simulation was repeated by reducing the element size by 2 mm until the element size was reduced to 1 mm. Once all the data were collected, the module and coolant temperature curves against element size were plotted. The largest element size at which the temperature curve flattened was chosen as the grid independence value. The result of that element size was validated with the past study. If the error was less than 10%, the simulation was accepted; the simulation setup would be checked and adjusted until the error was reduced to less than 10%.

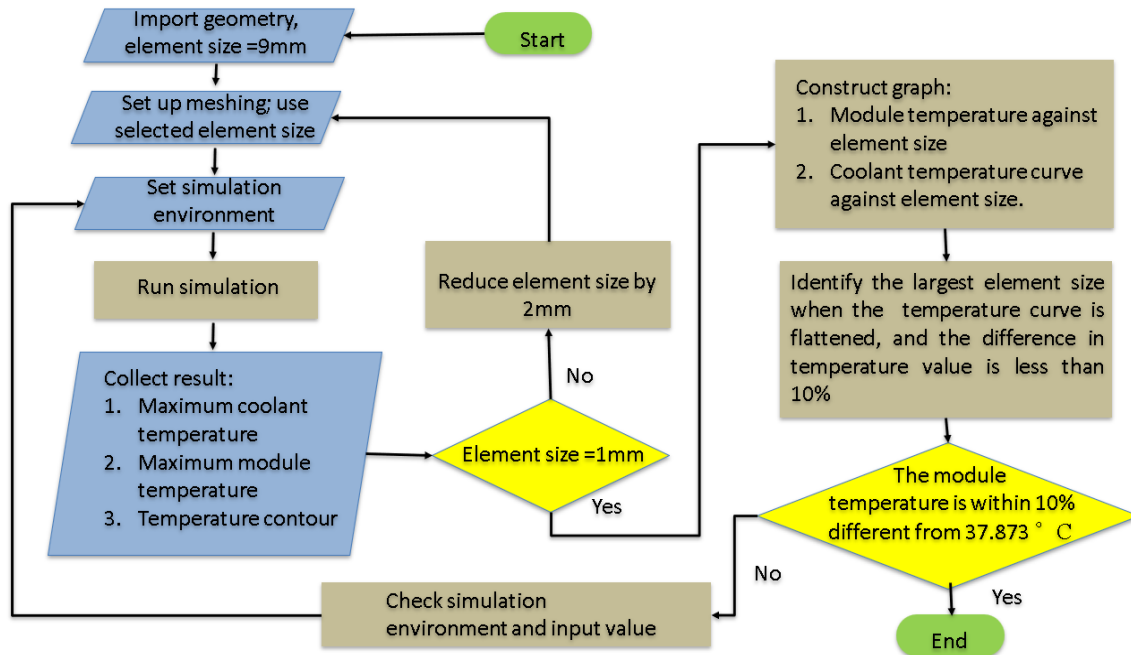


Figure 6. The flow chart used to conduct mesh independence and validation study

In Figure 7, the final setup of meshing is shown. The element size for the mesh was set at 3 mm with 741,072 cells. Multizone was used to configure the mesh setup for the fluid zone (the area excluding the cell) and the cell separately [23]. An inflation layer was applied on the cells' cylindrical face to allow capture of thermal effects near the wall [24], [25]. The mesh setup is consistently applied for each case of study to ensure the accuracy of the result.

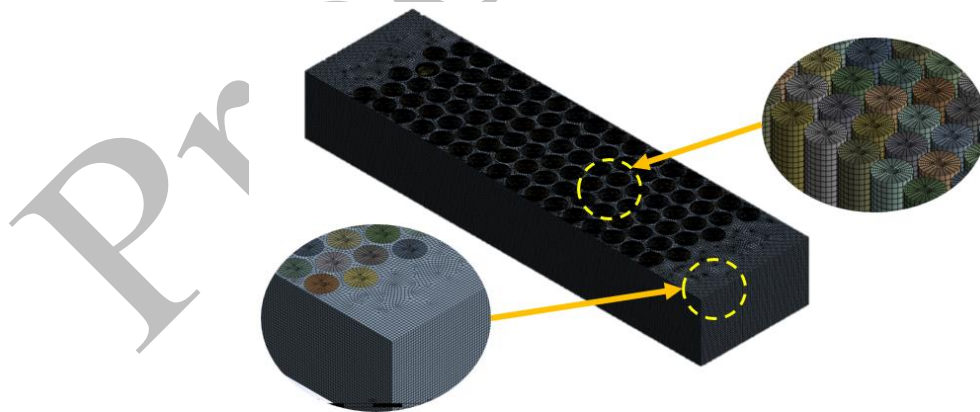


Figure 7. Mesh arrangement of the module

2.3 Methodology

In Figure 8, the process of the study has been illustrated in a flow chart. The simulation study was started after the model passed the mesh independence test. The first aim of the simulation study was to compare the two cell arrangements in order to acquire the best-performing model. The second simulation study focused on the cooling performance comparison for different types of coolant. The best-performing model was transferred and applied to the second simulation study. The AHP was then carried out to select the suitable coolant in the current module based on the given criterion and the goal.

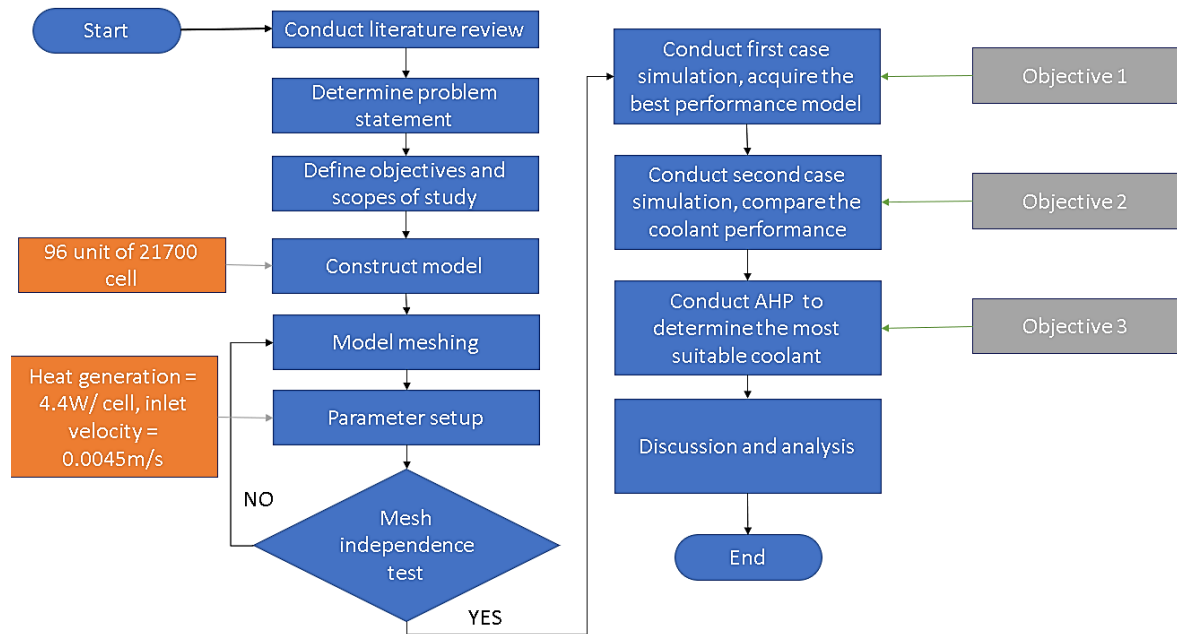


Figure 8. Test configuration

After completing the mesh generation, the setup was configured to determine the temperature and pressure distribution within the model. The Reynolds-Averaged Navier-Stokes (RANS) methodology was applied to analyse the flow structure inside the model. Comprehensive details regarding the solver configuration were presented in Table 4. The turbulence effects were modelled using the standard K-epsilon approach, with enhanced wall treatment, RNG model, and curvature correction set at 1. The energy equation was enabled. The Green-Gauss cell-based technique was employed to compute spatial gradients, enabling precise representation of flow field variables [26]. The simulation used internal flow which the wall of the module and the surface of the cylindrical cell acting as the boundary [27]. In all cases, the heat generation rate remained constant, with each cell releasing heat at a rate of 4.4 W. 350 iterations indicated 350 steps taken throughout the solution process. The iteration number was controlled to prevent excessive processing time for the analysis and ensure the simulation result converged. Table 4 shows the parameters for the RANS approach.

Table 4. Parameters for the RANS approach used in simulation

Parameters	RANS
Model	k-epsilon
Type	Standard
Wall treatment	enhanced wall treatments
Solver type	Steady
Number of iterations	350

The staggered and aligned modules are applied separately in the simulation. The first 5 cases of the simulation were simulated with the staggered cell, followed by the aligned module. The simulations use 4.4 W of heat generation per cell and 5 different inlet velocities, ranging from 0.002 m s^{-1} to 0.020 m s^{-1} . Table 5 shows the configuration of the tests in the first case study.

Table 5. Test configuration for the second case study

Test number	Module	Heat generation per cell (W)	Inlet velocity (m s^{-1})
1	Staggered	4.4	0.0020
2	Staggered	4.4	0.0045
3	Staggered	4.4	0.0100
4	Staggered	4.4	0.0150
5	Staggered	4.4	0.0200
6	Aligned	4.4	0.0020
7	Aligned	4.4	0.0045
8	Aligned	4.4	0.0100
9	Aligned	4.4	0.0150
10	Aligned	4.4	0.0200

In the second case study, the module with the best performance was transferred and applied. The Novec, water, and ester were then used to simulate the BTMS cooling process. In the simulation test, the heat generation was set to 4.4 W per cell, and the inlet velocity was set from 0.0020 m s^{-1} to 0.020 m s^{-1} for every type of coolant. Table 6 shows the simulation configuration for each type of coolant.

Table 6. Test configuration for the second case study

Test number	Coolant	Heat generation per cell (W)	Inlet velocity (m s^{-1})
1	Novec	4.4	0.0020
2	Novec	4.4	0.0045
3	Novec	4.4	0.0100
4	Novec	4.4	0.0150
5	Novec	4.4	0.0200
6	Water	4.4	0.0020
7	Water	4.4	0.0045
8	Water	4.4	0.0100
9	Water	4.4	0.0150
10	Water	4.4	0.0200
11	Ester	4.4	0.0020
12	Ester	4.4	0.0045
13	Ester	4.4	0.0100
14	Ester	4.4	0.0150
15	Ester	4.4	0.0200

After the simulations were conducted, the simulation results were analyzed for the coolants. The AHP was then conducted based on the results produced in the simulation. The goal of the AHP was to determine the most suitable coolant in the current module. In order to achieve the goal, the coolant was evaluated based on its velocity required to maintain the module temperature below 35°C , the inlet velocity required to maintain the module temperature gradient within 5°C , and the pressure drop of the coolant when the velocity was set at 0.02 m s^{-1} . Table 7 showed the list of components in the AHP, and Figure 9 showed the hierarchy structure of the AHP.

Table 7. List of the goal, alternatives, and criteria

Item	Criteria	Definition
Goal	-	The optimum coolant.
Criteria	A	The inlet velocity required to maintain the maximum module temperature is approximately 35°C .
	B	The inlet velocity required to maintain the module temperature gradient within 5°C .
	C	The pressure drop of the coolants at maximum inlet velocity (0.02 m s^{-1}).
Alternatives	1	Novec.
	2	Water.
	3	Ester.

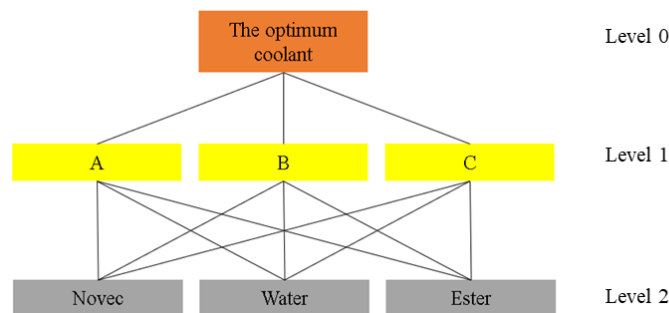


Figure 9. The structure of the hierarchy

The test rig of this study is demonstrated in Figure 10. In the simulation, only one module was simulated, which contained 96 units of cells. The cell was set to release heat equally at the rate of 181400 W m^{-3} . The pump moved the water in one direction and ensured the coolant reached the desired velocity at the inlet of the module. The coolant was

cooled to 20°C when entering the module, and absorbed the heat coming from the cells. The heat was totally removed at the radiator to continuously supply the coolant into the module at a constant 20°C.

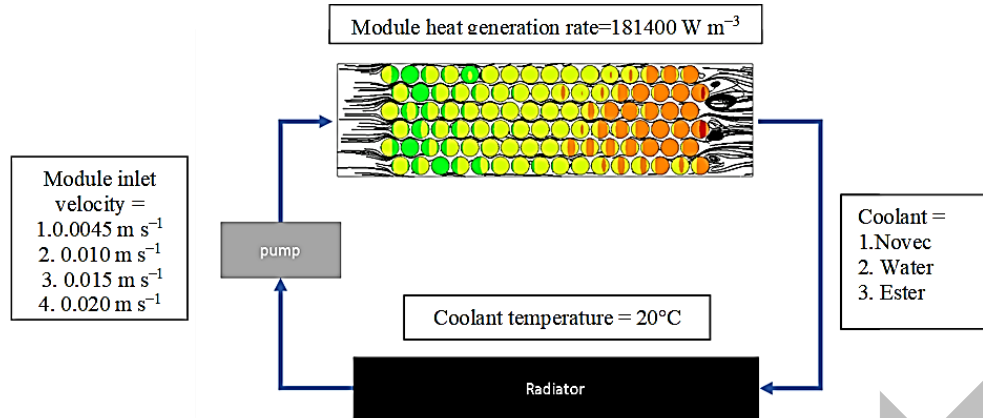


Figure 10. The test rig for the study

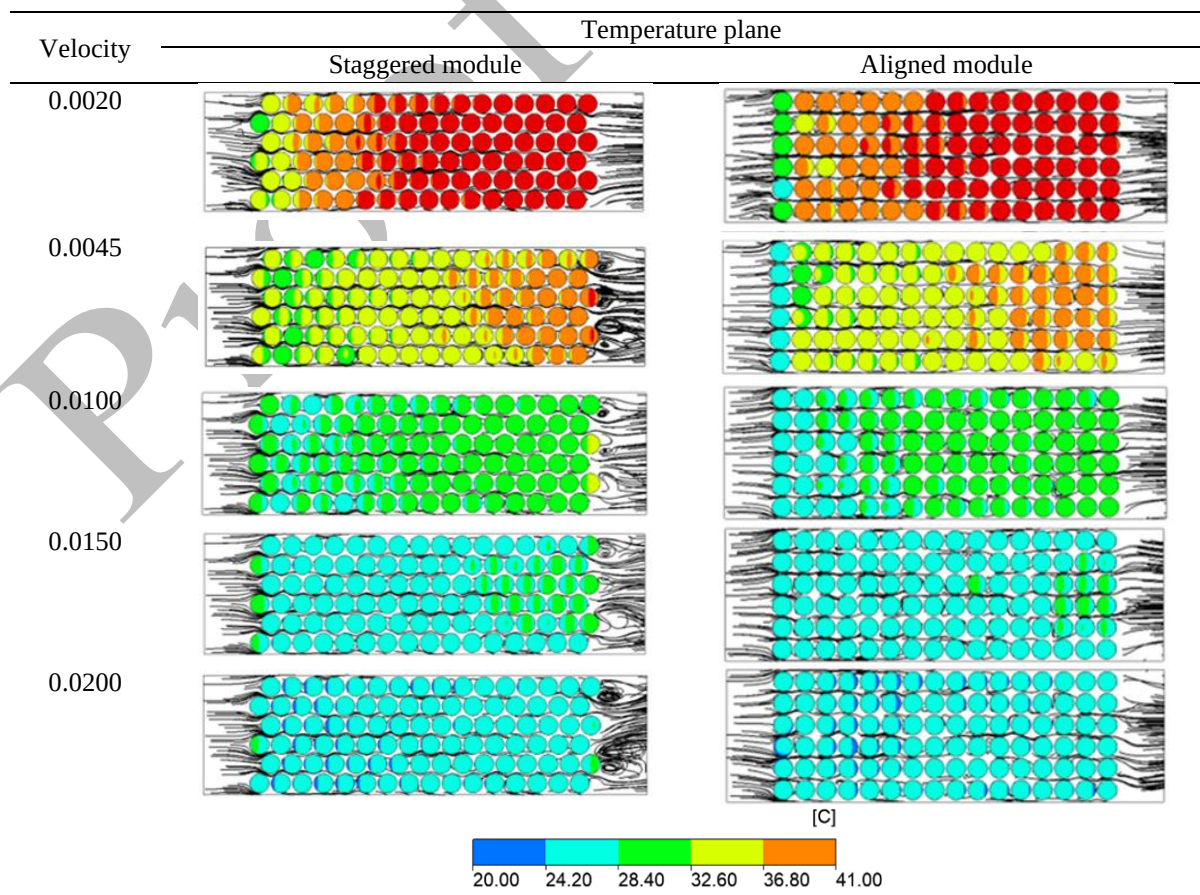
3. Result and Discussions

In the following sub-chapters, the simulation results for the impact of cell arrangements and coolant materials on BTMS performance were discussed. The AHP process was then conducted after the result analysis to determine the suitable coolant.

3.1 Impact of Cell Arrangement on BTMS Performance

In the streamlined pattern, the staggered module differed significantly from the aligned module. The streamlines show the formation of turbulence in the outlet region of the staggered module. The formation of turbulence became dominant as the inlet velocity increased. This was due to the coolant flow direction changing randomly within the staggered module. The fluid flowing in random directions interacted with each other in the outlet region and formed turbulence. As a result, the formation of turbulence caused poor cooling for the cells next to the outlet. On the other hand, the fluid flow pattern remains consistent in the aligned module regardless of the inlet velocity. This was due to the fluid's consistent flow direction within the aligned module. As a result, the fluid could evenly interact with each cell to absorb the heat.

Table 8. Temperature contour with streamline for the staggered and the aligned module



In terms of temperature distribution, the temperature contours for each module showed a similar pattern: the cell temperature increased from the inlet and peaked at the outlet. When the inlet velocity was set below 0.0150 m s^{-1} , the cells next to the inlet could be cooled more effectively in the aligned module compared to the staggered module. The difference between the aligned module and the staggered module became insignificant when the inlet velocity exceeded 0.0100 m s^{-1} . In Table 8, the temperature planes for the aligned and staggered modules display the cell and coolant temperature distributions from a side view. At 0.0020 m s^{-1} , the staggered module maintained more cells at a lower temperature than the aligned module. However, the aligned module could reduce the temperature gradient lower than the staggered module as the velocity increased from 0.0045 m s^{-1} . The significant difference in the temperature contours between the two modules occurred in the cells near the outlet. The cells near the outlet of the staggered module had much higher temperatures due to the formation of turbulent flow. In contrast, the cells in the aligned module showed a smooth temperature transition.

Figures 11 (a) – (c) compare the performances of each module. Figure 11 (a) shows the maximum module temperature for two cell arrangements. For the maximum module temperature, the performance of each module was similar. However, the aligned module managed to keep the maximum module temperature lower than that of the staggered module at any velocity. The aligned module maintained a lower maximum coolant temperature starting at 0.0045 m s^{-1} . At maximum inlet velocity, the maximum module and coolant temperatures of the aligned module were 7.91% and 0.74% lower than those of the staggered module. Figure 11 (b) showed the module and coolant temperature gradient for two types of cell arrangement. The coolant temperature showed no significant difference under the same range of coolant velocity. Starting at 0.01 m s^{-1} , the coolant temperature gradient could be maintained within 5°C . In terms of module temperature gradient, the aligned module required a coolant velocity of 0.0020 m s^{-1} to fall below 5°C , whereas the staggered module could not fall below 5°C at the maximum coolant velocity. Figure 11 (c) showed the graph of pressure drop against coolant inlet speed for two modules. The pressure drop increased with velocity for both modules. The pressure drop in the aligned module was always higher than in the staggered module. The difference in pressure drops between the two modules became more significant as the velocity increased. At maximum velocity, the pressure drop inside the aligned module was 25.34% higher than that of the staggered module. This indicated that the aligned module had lower efficiency compared to the staggered module, particularly at high inlet velocity.

Overall, the study of cell arrangement has shown a similar trait in the study conducted by Yang et al., where the cooling efficiency increased when the cells were arranged in an aligned pattern [6]. However, the simulation yielded different findings: the pressure drop would increase, and the maximum temperature would decrease when the cells were arranged in an aligned pattern. This may be due to the model used in the previous study having a much shorter flow length and fewer cells. The findings of this study can assist future BTMS development for cylindrical-type cells.

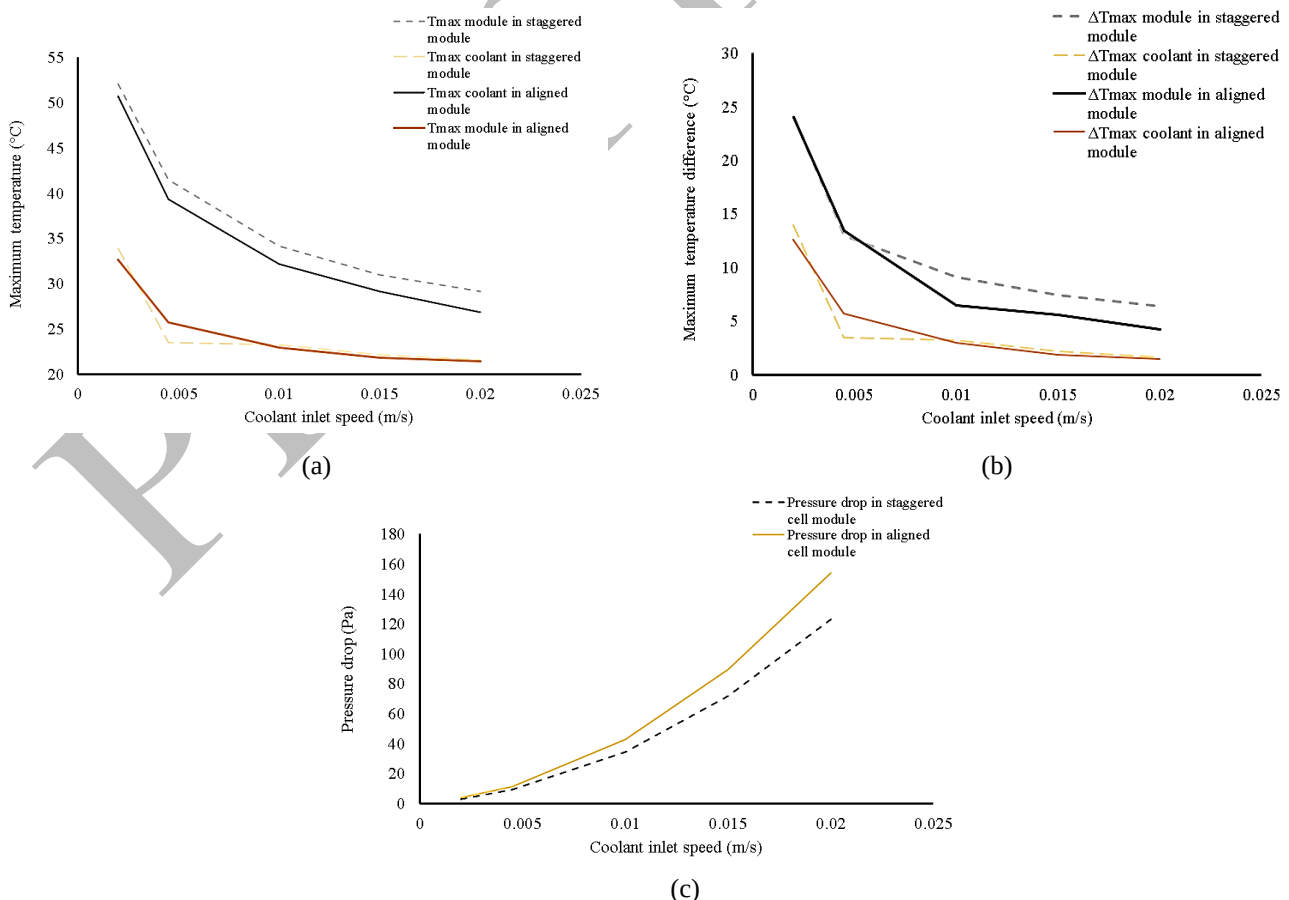


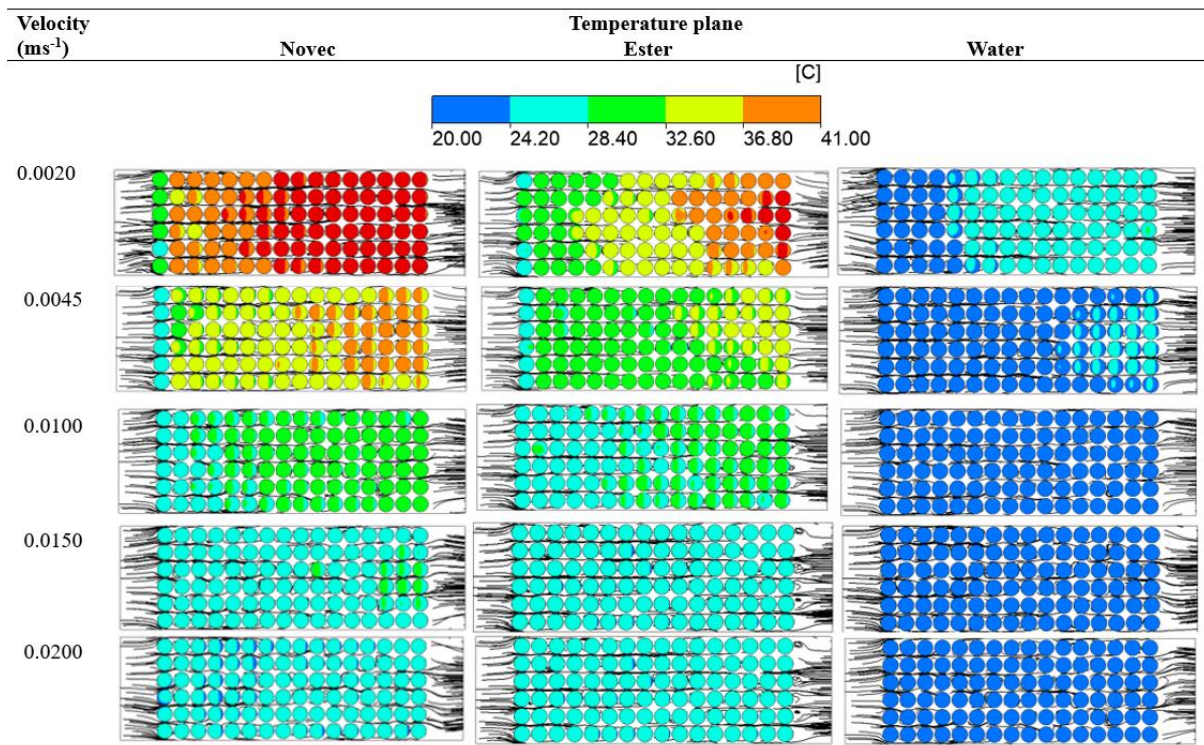
Figure 11. The comparisons of the modules in terms of: (a) maximum temperature; (b) temperature gradient; (c) pressure drop

3.2 Impact of coolant material on BTMS performance

Coolant is one of the significant factors that determines the maximum limit of a BTMS. For EVs, the coolant has stricter standards for its coolant. Novec, ester, and water were used to simulate the BTMS cooling process inside the aligned module. In Table 9, the temperature contours of the module for Novec, ester, and water were compared. In general, the streamline patterns were consistent regardless of coolant type or inlet velocity. The streamlines showed that the fluid flowed smoothly in the gap between each row of the cells and exited at the outlet. The cells' temperature rose starting from the inlet and peaked at the outlet.

For the Novec, the temperature contour showed inconsistency in the temperature distribution in the cells at minimum velocity. This indicated insufficient coolant flow speed to even the cell temperature. As a result, almost 50% of the cells' temperatures stayed above 41°C, about 20% stayed between 36.80°C and 41°C, and the rest stayed between 20°C and 36.80 °C. This could cause serious, long-term temperature-aging issues due to uneven temperature distribution. As a result, the module's reliability and lifespan drop. At 0.0100 m s⁻¹, about 75% of the cells' temperatures stayed between 28.40°C and 32.60, while the rest stayed between 24.20°C and 28.40°C. To keep all cells' temperatures within the same range, the inlet velocity was required to rise to 0.0200 m s⁻¹.

Table 9. Temperature contour for different types of coolants



In the case of the ester, the temperature contours also showed uneven temperature distribution in the cells at minimum velocity. 23.95% of the cells' temperature fell between 28.40°C to 32.60°C, followed by 41.67% stayed between 32.60°C to 36.80, 21.88% stayed between 36.80°C to 41°C and the rest fell below 28.40°C or above 41°C. At low inlet velocity, the ester was also unable to absorb the heat evenly from the cells, which led to uneven aging. The cells near the inlet aged more slowly than those further away. At 0.0100 m s⁻¹, about 50% of the cells' temperature fell between 24.20°C and 20.00°C, while the rest stayed between 28.40°C and 32.60°C. To keep all cells' temperatures within the same range, the inlet velocity needs to be increased to the maximum value.

For the water, the cells' temperature was more evenly distributed at the minimum velocity than at the other velocities. In the module, 72.92% of the cells' temperature fell between 24.20°C and 28.40°C, whereas the rest fell between 20.00°C and 24.20°C. Under this condition, the difference in aging speed between the cells would be much smaller than that of the ester and the Novec. However, the front cells would still age more slowly than the rear cells, resulting in a shorter module lifespan. To address this issue, the inlet velocity of the water needed to be increased to at least 0.01 m s⁻¹ to keep all cells within the same temperature range.

Regardless of coolant type, the maximum module temperature decreased as the inlet velocity increased. The maximum module temperature for the Novec dropped drastically when the velocity increased from 0.0020 m s⁻¹ to 0.01 m s⁻¹. The difference in module temperature between the Novec and the ester decreased as the velocity increased. At 0.0020 m s⁻¹, the Novec could maintain a lower module temperature than the ester. The module temperature was relatively stable when water was used. The module temperature became almost constant when the water inlet velocity was set to 0.01 m s⁻¹. At maximum velocity, the module temperature was 17.61% lower when water was used and 4.84% higher when ester was used compared to Novec.

In Figure 12(b), the graph of the module temperature gradient against velocity showed that the temperature gradient of the module dropped regardless of the type of coolant used. The module temperature gradient for the Novec dropped

significantly when the velocity increased from 0.020 m s^{-1} to 0.01 m s^{-1} . At the same time, the difference in temperature gradient between the ester and the Novec became smaller. Above 0.01 m s^{-1} , the Novec was able to reach a lower module temperature gradient compared to the ester. The water showed a relatively smooth and lower temperature curve in the graph. At maximum inlet velocity, the module temperature gradient was 63.77% lower when the water was applied, and 2.90% higher when the ester was used compared to the Novec.

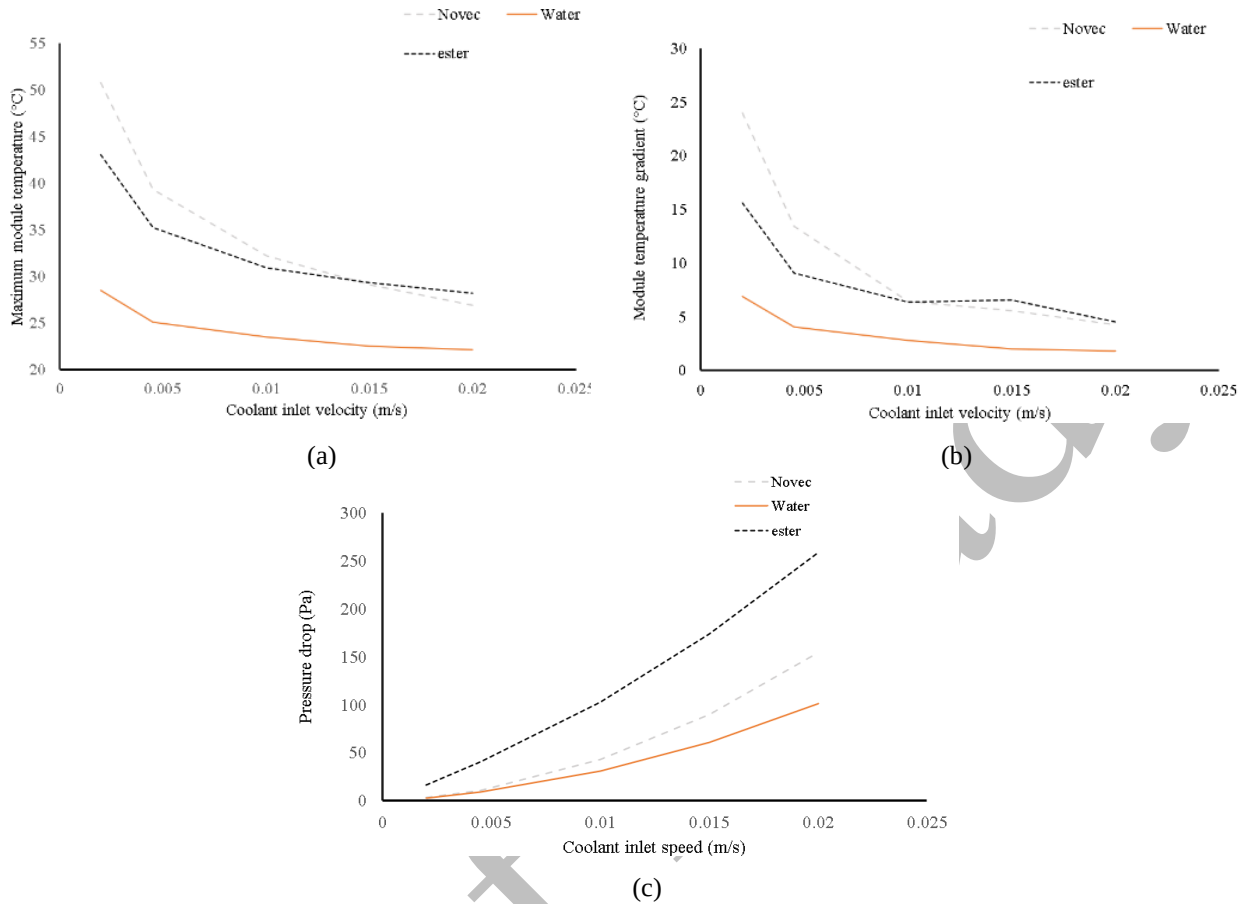


Figure 12. The comparison between coolants in terms of: (a) maximum module temperature against inlet speed; (b) module temperature gradient against inlet speed; (c) pressure drop against inlet speed

In Figure 12(c), the pressure drop for different types of coolant against velocity was plotted. The ester had a significantly higher pressure drop with increasing velocity, followed by the Novec and the water. The pressure curve for the Novec was much closer to that of water. The difference in pressure drop between each coolant increased with the velocity. At maximum inlet velocity, the pressure drop was reduced by 34.55% when water was used and increased by 67.66% when the ester was used, compared to the Novec.

In summary, the findings of the study in terms of coolant material showed a different perspective of analysis compared to the previous study conducted by Mazyar et al. [20]. The previous study conducted by Mazyar et al. had focused on comparing different types of BTMS. To be highlighted, they used 3M Novec and air in their active cooling BTMS for the same module geometry. This study added 2 more types of coolant in the simulation to evaluate the impact of coolant on BTMS cooling performance. This step was necessary to explore the new possibility of cooling material in direct liquid cooling BTMS.

3.3 AHP for the coolant

In Table 10, the comparison matrix for each criterion with respect to the goal was conducted. Through the calculation, criterion B occupied the largest priority vector, which was 58.13%. The second largest criterion was criterion A, which occupied 30.92% of the priority vector. Criterion C had the smallest priority vector, which occupied only 10.96%. The calculated CR value was 0.42%, which indicated the comparison matrix was very consistent.

Table 10. Paired comparison matrix level 1 with respect to the goal

	A	B	C	Priority vector (%)
A	1	1/2	3	30.92
B	2	1	5	58.13
C	1/3	1/5	1	10.95
Total	10/3	17/10	9	
$\lambda_{\max} = 3.005$, CI = 0.0025, CR = 0.42% < 10% (acceptable)				

In Table 11, the overall preference of each alternative with respect to the criterion was determined by calculating the total score. Criterion B had the biggest weightage, which was 58.13%, followed by criterion A with a weightage of 30.92%, and criterion C with a weightage of 10.96%. Among the selected criteria, the water had the highest score, with a score rated at 43.86% out of 58.13% in criterion B. This indicated the water was an excellent choice when the temperature gradient of the module was the most crucial criterion. The ester had the best score in criterion A compared to its scores in criteria B and C, respectively. This indicated that the ester had better advantages if maintaining the module temperature below 35°C was considered more crucial. On the other hand, the Novec had the best score in criterion C compared to its performance in the other criteria, which was 3.39% out of 10.96%. This indicated the Novec had a better advantage in terms of efficiency compared to its performance in maintaining module temperature below 35°C or maintaining the temperature gradient. By combining each score, the water scored 71.87% out of 100%, which indicated that the water was the most optimum alternative when all criteria were considered. The Novec had a slightly higher score than the ester, with the total score rated at 15.61%. The ester only scored 12.53% in total.

Table 11. Total score of each alternative

Criteria	Criteria Weight (%)	Novec	Water	Ester
A	30.92	3.29	21.64	5.98
B	58.13	8.93	43.86	5.34
C	10.96	3.39	6.37	1.20
Total score (%)		15.61	71.87	12.53

In the study, the water was the ideal solution to dissipate heat efficiently from the battery pack. However, water in reality is a hazard that can severely damage the battery. For pure water, there are no ions that can conduct electricity. Nevertheless, when the water is exposed to the carbon dioxide in the air, the water will react with carbon dioxide and form carbonic acid. In addition, ions coming from the worn metal in the pump can also pollute the deionized water. The presence of ions is barely avoidable in the actual operation of an immersion cooling BTMS. An electrical circuit shortage inside the battery pack can trigger thermal runaway inside the battery pack. In the event of thermal runaway, the water will be broken down into hydrogen and oxygen gas. The mixture of heat and flammable gas can trigger an explosion in a short moment. Thus, the practical usage of water in the immersion cooling BTMS is almost non-existent in the current stage of BTMS development. Further improvement in the safety factor is required for water-based immersion cooling BTMS.

4. Conclusions

In conclusion, this research provides a thorough analysis of the impact of cell arrangement and types of coolants on BTMS performance through CFD simulations. The simulations were conducted in steady-state, with constant heat generation and various inlet velocities. The aims were to analyze the temperature distribution, flow structure, and pressure drops in the modules and the coolants, and to recognize the effect of cell arrangement and the types of coolant on BTMS performance. The first objective highlights the impact of cell arrangement on temperature distribution and pressure drop inside the module and the coolant. The result reveals that the aligned module has a more organized flow pattern and better temperature distribution in comparison to the staggered module. The second objective reveals that the application of different coolant materials has a significant impact on the cooling performance of the BTMS. In general, the maximum temperature and temperature gradient for the module and the coolant drop when the inlet velocity increases for every coolant. On the contrary, the pressure drop increases with the inlet velocity. The third objective revealed that the best configuration for the current BTMS is using the aligned module and water as the coolant to achieve the best performance. The selection of the coolant was conducted through the MCDA. The AHP method, which is one kind of MCDA, provided a good insight into evaluating the coolant under each criterion. The first-level comparisons between the criteria with respect to the goal show that the inlet velocity required to maintain the module temperature gradient within 5°C is the most crucial criterion, which occupies 58.13% of the priority vector. Water was always most preferred under the given criterion. The water scored 71.87% in total, whereas the Novec scored 15.61%, and the ester scored 12.53%. The CR value for all pairwise matrices was below 10%, indicating that the AHP was consistent and the decision to choose the water was reliable.

The current study assumed the operating environment for the BTMS was perfect, which did not consider the risk of leakage of the system and the lifespan of the coolant. In terms of the geometry for the cells, inlet, and outlet, the current study only used a simplified shape in the simulation. It is recommended that future studies consider the safety and the lifespan of the coolant in the AHP to acquire more practical results in decision-making analysis. In terms of geometry, future studies shall apply more detailed geometry for the components to acquire more accurate results. The current study is also limited to a steady environment, where the SoC of the battery is at a constant level and produces constant heat output into the coolant. The assumption is not able to totally cover the operating conditions of the battery under different loads and SoC. Thus, future studies shall also consider the behavior of a battery pack under different operating conditions to obtain more precise result.

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Conflict of Interest

The authors declare no conflicts of interest.

CRedit Author Contribution Statement

The authors confirm their contribution to the paper as follows:

N. G. Ping, I. A. Ishak, M. A. R. Azahar, M. Arafat, M. A. S. A. Aziz (data study conception and design)

N. G. Ping (data collection)

N. G. Ping, M. A. S. A. Aziz, N. E. Othman, Z. M. Salleh (analysis and interpretation of results)

N. G. Ping, F. M. Sakri (draft manuscript preparation)

All authors reviewed the results and approved the final version of the manuscript.

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