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Applying Different Configurations for Thermal Management of a Lithium Titanate Oxide Battery Pack

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Abstract: This investigation's primary purpose was to illustrate the cooling mechanism within a lithium titanate oxide lithium-ion battery pack through experimental measurement of heat generation inside the lithium titanate oxide batteries. Dielectric water/glycol (50/50), air, and dielectric mineral oil were selected for the lithium titanate oxide battery pack's cooling purpose. Different flow configurations were considered to study their thermal effects. Within the lithium-ion battery cells in the lithium titanate oxide battery pack, a time dependent amount of heat generation, which operates as a volumetric heat source, was employed. It was assumed that the lithium-ion batteries within the battery pack have the identical initial temperature condition in all the simulations. The lithium-ion battery pack was simulated by ANSYS to determine the temperature gradient of the cooling system and lithium-ion batteries. Simulation outcomes demonstrated that the lithium-ion battery pack's temperature distributions could be remarkably influenced by the flow arrangement and fluid coolant type.

Keywords: Lithium titanate oxide lithium-ion battery; battery pack thermal management

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1. Introduction

Lithium-ion batteries were appointed as an alternative for e-mobility utilizations attributable to their excellent performances. Furthermore, there is a continuing demand to advance lithium-ion battery characteristics to lengthen the period in which they can be utilized. Lifetime, power output, and energy storage capacity are principal performance characteristics for renewable energy storage utilization.

Different researchers [1-4] studied the thermal management of lithium-ion batteries. Several consequences were utilized to parameterize the recommended thermal model of the lithium-ion batteries. Different cooling strategies have been studied for lithium-ion batteries, with dissimilar coolants, including phase change material, mineral oil, and air, water, and heat pipes. Water-based cooling arrangements have brought about much consideration between the different cooling coolants and procedures because water has good thermal properties as a coolant [5].

Mineral oil, attributable to its dielectric behavior, might be employed for direct liquid cooling with superior efficiency; nevertheless, feasibility for the application requires to be examined [6]. Air-based cooling arrangements benefit from a simplified configuration and low maintenance cost; nevertheless, they suffer from restrictions in the most significant heat dissipation capacity. Moreover, the noise problem attributable to the immense fan speed makes it unacceptable [7]. Combining phase change material into the cooling arrangement has presented the benefit of temperature distribution homogeneity; nevertheless, the small cooling efficiency problem requires to be resolved [8].

Different cooling methods were studied. Water-based cooling approaches offer adequate cooling and have the benefit of fewer volume demand attributable to compactness.

A numerical and experimental investigation of prismatic lithium-ion battery cells' thermal behavior was accomplished by employing a mini-channel cold plate. Computational fluid dynamics simulations were used in the optimization and configuration of lithium-ion battery cooling systems. It should be noted that important automotive manufacturing companies, including General Motors, Hyundai, Tesla, are employing water-based cooling procedures for thermal management of the lithium-ion batteries in electric vehicles [9].

Heat generations coming out of experimental measurements were compared to heat generations specified from the thermal model. The heat generation was calculated using reversible and irreversible heat supplies in a lithium-ion battery cell. Experimental heat generation was quantified employing an isothermal battery calorimeter. The lithium-ion battery's heat loss throughout operating was approximated through the accumulating of two essential sources, which are the reversible and irreversible heat [10].

Lithium-ion batteries should work at optimum temperatures in an extensive range of environmental temperature and working conditions to achieve maximum utilization of lithium-ion batteries in electric vehicles [11, 12]. The aforementioned is essential, especially at fast charging and discharging cycles. Factors affecting the temperature of lithium-ion batteries battery is illustrated in Figure 1.

Lithium-ion battery thermal management is indispensable in attaining functioning and lengthening lithium-ion batteries' life in electric vehicles. One of the critical issues of employing lithium-ion batteries in electric and hybrid vehicles is appropriate thermal management. Proper thermal management is essential with the intention of controlling degradation at a satisfactory rate. Besides, it is crucial to decrease the risk of thermal runaway. Figure 2 demonstrates a comparison between direct liquid cooling and air-cooling.

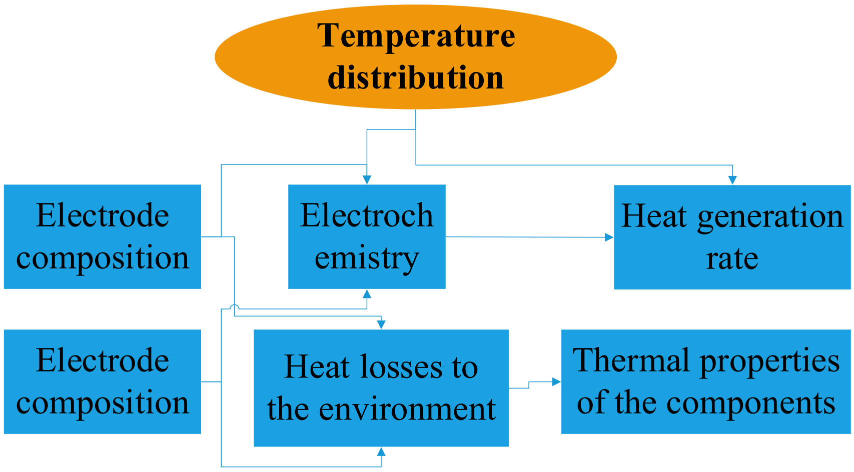


Figure 1. Factors affecting the temperature of the battery [13].

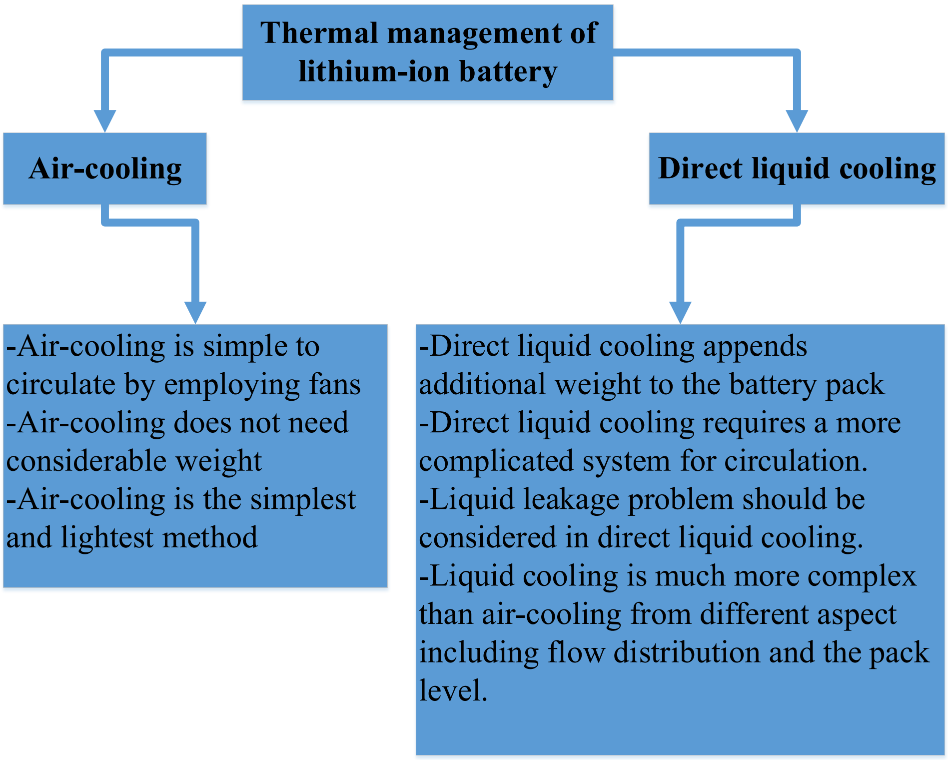


Figure 2. Comparison between direct liquid cooling and air-cooling [14].

The investigation regarding lithium-ion batteries has increased enormously across the world, and different researchers studied different aspects of thermal management of lithium-ion batteries. However, thermal management of lithium titanate oxide lithium-ion batteries have been studied less than the other features. The heat generation model of lithium-ion batteries was simplified. Nevertheless, without much research heretofore, the dynamic heat generation model has not been developed using experimental data from isothermal battery calorimeter 284. Consequently, this research objective is to introduce and help analyze a thermal management system through the precise determination of heat generation of lithium titanate oxide batteries.

2. Methodology

It is crucial to understand the lithium-ion batteries' heat generation behavior, notably during rapid discharging and charging conditions for different applications, specifically electric vehicles. The aforementioned is necessary to construct a thermal management system for lithium-ion batteries. The present investigation studied the thermal management of a lithium-ion battery pack. A full discharge cycle was applied to the lithium titanate oxide battery, as shown in Figure 3. The corresponding heat generation of the lithium titanate oxide battery for different discharge rates is demonstrated in Figure 4.

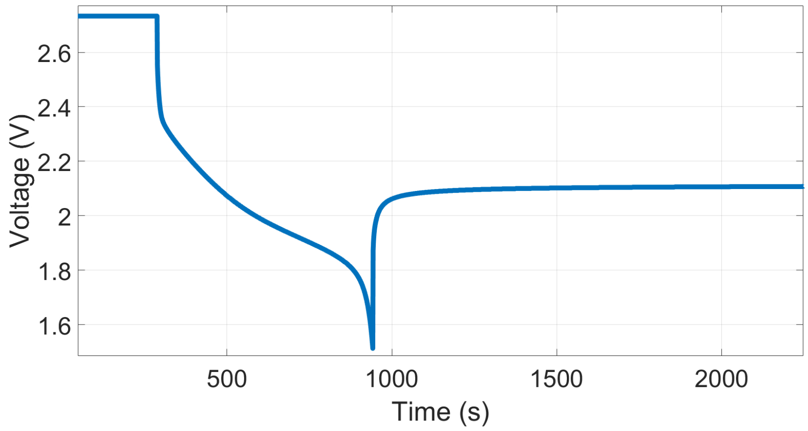
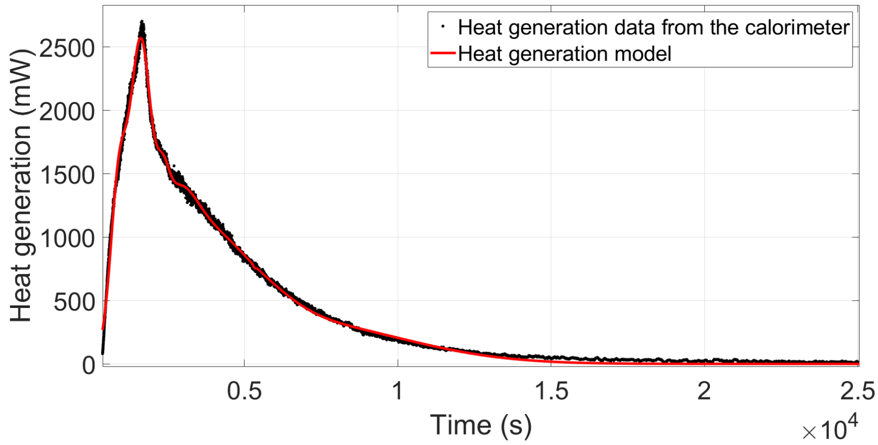


Figure 3. Voltage profile during discharge.



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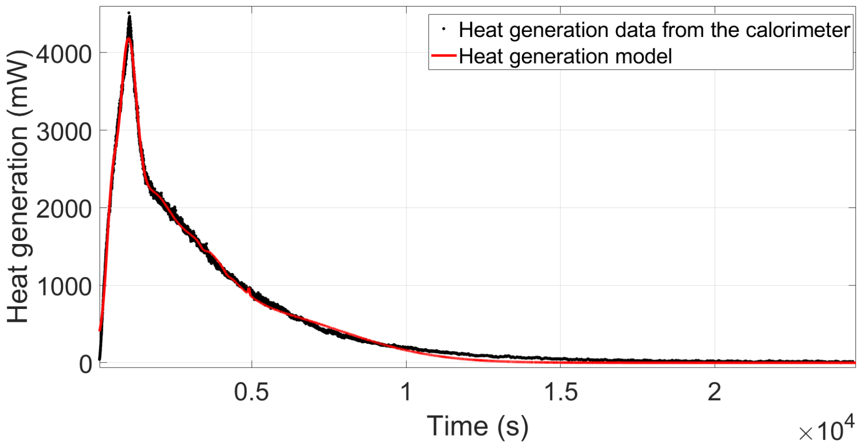

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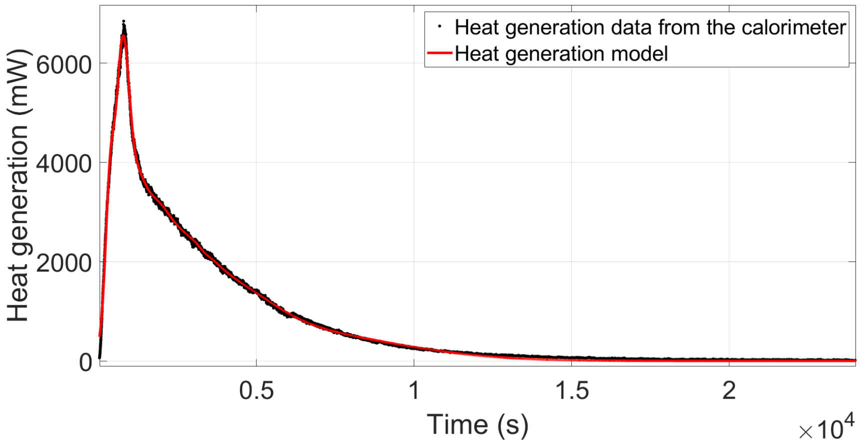


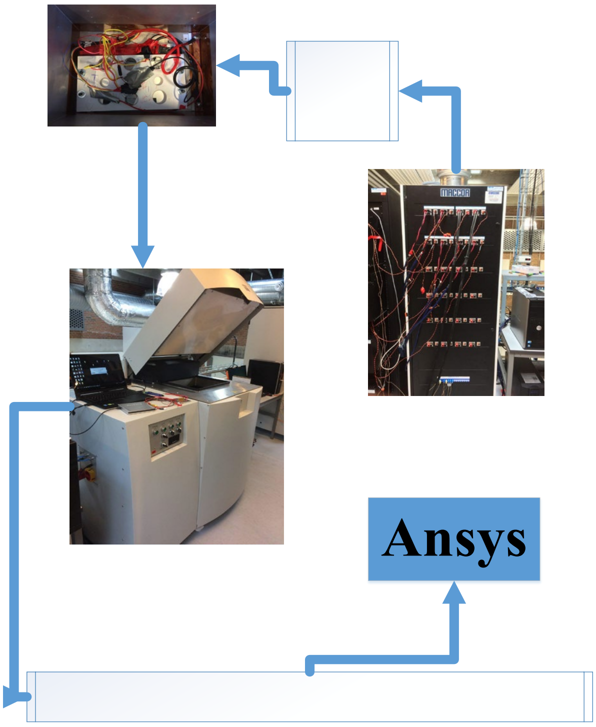
(c)

Figure 4. Hear generation of lithium titanate oxide battery during: (a) 39 A discharge (b) 52 A discharge (c) 65 A discharge.

In present research, all the experiments were accomplished employing an experimental setup (isothermal battery calorimeter and Maccor system) and recorded with time for all experiments.13 Ah pouch type commercial lithium titanate oxide lithium-ion battery cells were used in the present research. The experiential prearrangement is controlled by the graphical user interface of the LabVIEW front panel interface.

In this study combination of time-dependent heat generation model and computational fluid dynamics from ANSYS for transient thermal research of thermal management of lithium-ion battery packs was used. Integration of the heat generation model with ANSYS is illustrated in Figure 5. In the heat generation model, HG (t) is heat generation (mW) at the time(s) t. Heat generation parameters are demonstrated in Table 1.

The data obtained from isothermal battery calorimeter 284 allows distinguishing and characterizing the thermal aspect of lithium-ion batteries. In addition, it assists in developing appropriate arrangements for lithium-ion battery thermal management systems. Suitable modeling can be advantageous to predict the lithium-ion battery's thermal behavior and improve the heat management system's design. Modeling is the cheapest way to investigate the effect of various parameters such as the type of coolant, heat transfer mechanism, system geometry on thermal management system performance. A representation of the lithium titanate oxide battery pack's research methodology is demonstrated in Figure 6. The parameters of the thermal management system employed in this research displayed in Table 2. In addition, properties of air, dielectric water/glycol (50/50), and dielectric mineral oil are shown in the table [15].



$$HG(t) = A_1 e^{(-((t-B_1)/C_1)^2} + A_2 e^{(-((t-B_2)/C_2)^2} + A_3 e^{(-((t-B_3)/C_3)^2} + A_4 e^{(-((t-B_4)/C_4)^2} + A_5 e^{(-((t-B_5)/C_5)^2} + A_6 e^{(-((t-B_6)/C_6)^2} + A_7 e^{(-((t-B_7)/C_7)^2} + A_8 e^{(-((t-B_8)/C_8)^2}$$

Figure 5. Integration of the heat generation model with ANSYS.

Table 1. Heat generation parameters.

	39 A	**52 A**	**65 A**
A1	1972	2922	4519
B1	1590	967.1	724.7
C1	468.2	398.5	286.7
A2	1239	1116	1882
B2	900.2	1603	1066
C2	382.9	841.8	443.2
A3	316.2	1252	1657
B3	2334	454.6	1613
C3	286.6	234.3	723.5
A4	995.6	1035	2806
B4	2707	2818	341.8
C4	1147	1640	211.6
A5	142.2	-61.15	1218
B5	4275	3434	2509
C5	912.3	154.4	1152
A6	-18.58	-38.59	-44.68
B6	5325	4207	3343

C6	60.5	142.3	229.3
A7	327.1	674.7	1060
B7	6688	4821	3762
C7	4856	4333	2117
A8	493.8	91.83	616.7
B8	4579	4907	5739
C8	1999	30.81	4784

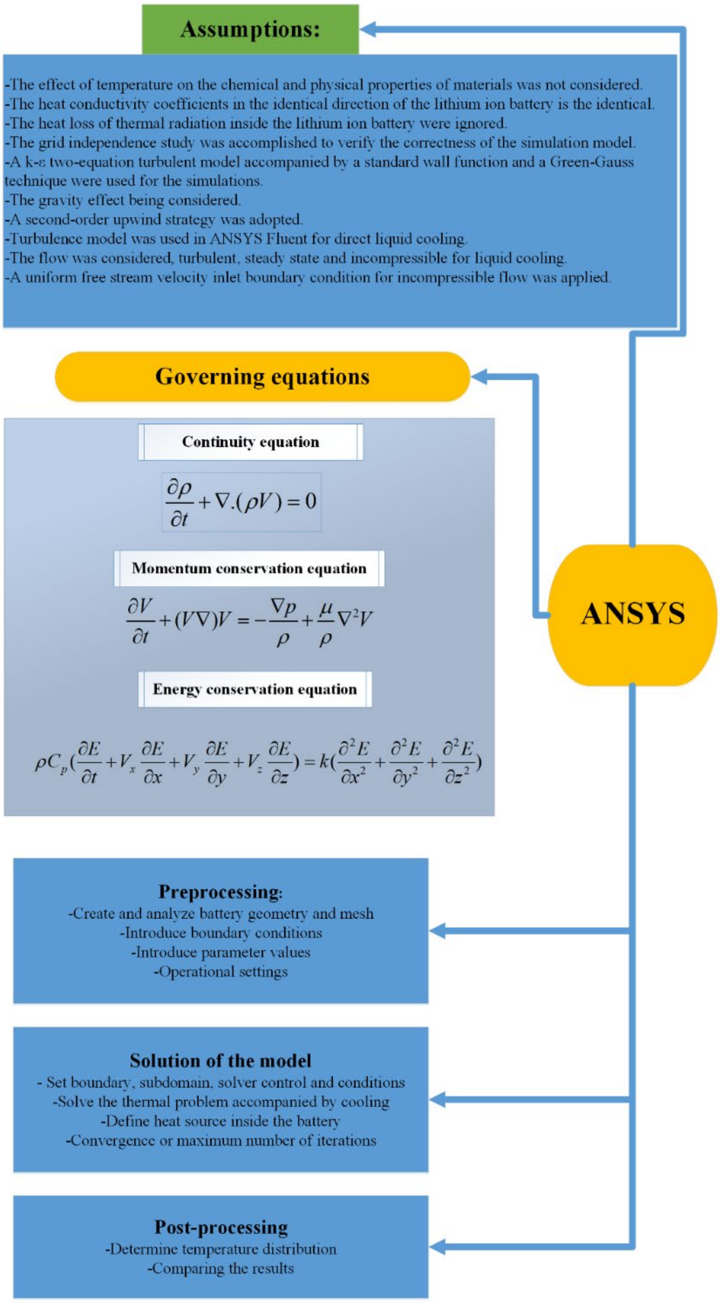


Figure 6. Representation of the research methodology of the battery pack.

Table 2. Parameters of thermal management system.

The nominal voltage of the lithium titanate oxide battery	**2.26 V**
Number of lithium titanate oxide batteries in the pack	20

Lithium titanate oxide battery cell surface area	26316 mm^2
The capacity of each lithium titanate oxide battery	13 Ah
Initial pack temperature	30 °C
The total thickness of the lithium titanate oxide battery cell	9 mm
The vertical distance between lithium titanate oxide batteries	4.5 mm
The horizontal distance between lithium titanate oxide batteries and boundaries	12 mm
Ambient temperature °C	30 °C, 20 °C
The inlet temperature of cooling media	30 °C, , 20 °C
Inlet air velocity	20 m/s
Inlet Water/glycol (50/50) velocity	0.08 m/s
Inlet dielectric mineral oil velocity	0.08 m/s
Heat transfer coefficient for the cooling media	25-250 W/m^{2}k
Density of air	1.225 Kg/m^3
Specific heat capacity of the air	1006 J/kg/k
Thermal conductivity of air	0.0242 W/m/k
Kinematic viscosity of air	1.46e-5m^2/s
The density of dielectric mineral oil	924.1 Kg/m^3
Specific heat capacity of dielectric mineral oil	1900 J/kg/k
Thermal conductivity of dielectric mineral oil	0.13 W/m/k
Kinematic viscosity of dielectric mineral oil	5.6e-5 m^2/s
Density dielectric water/glycol (50/50)	1069 Kg/m^3
Specific heat capacity dielectric water/glycol (50/50)	3323 J/kg/k
Thermal conductivity dielectric water/glycol (50/50)	0.3892 W/m/k
Kinematic viscosity dielectric water/glycol (50/50)	2.58e-6 m^2/s

3. Result and discussion

An electric vehicle lithium-ion battery pack is contained within lithium-ion battery cells stacked side-by-side without chilling facades, excluding the pack exterior surface. The inner lithium-ion battery cells in the pack are more prone to the accident of overheating. A thermal management system is crucial because lithium-ion batteries should work at an optimal working temperature range. Without an appropriate thermal management system, there is a risk of thermal runaway.

In the present research, the thermal analysis of commercial-sized lithium-ion batteries under various functioning circumstances was studied experimentally and mathematically. The present research's principal purpose is to evaluate if and how the lithium-ion battery thermal management system can be used to assure lithium-ion battery pack safety and increase lithium-ion batteries' lifetime.

The present research investigates different configurations for the cooling system of a lithium-ion battery pack. The heat dissipation of the lithium-ion battery was achieved from an isothermal battery calorimeter. Different configurations with dissimilar lithium titanate oxide battery arrangements were studied. Besides, various quantities of outlets and inlets and locations of the air cooling system's entrance and exit were compared.

Three different cooling fluids, including air, dielectric water/glycol (50/50), and dielectric mineral oil, were used, and different flow arrangements were proposed. The fluid inlet velocity was considered 20 m/s, 0.08 m/s 0.08 m/s for air, dielectric mineral oil, and dielectric water/glycol (50/50), correspondingly. The lithium-ion battery assembly's modeling results, including the temperature distribution inside the assembly for different coolant arrangements during 52 A discharge, are shown in Figure 7.

The black arrows inside each figure show the direction of movement of the cooling fluid flow inside the lithium-ion battery set. As could be seen, the fluid enters the collection from a corner and exits the collection from another corner on the same or different side. As could be seen in some parts, the lithium-ion batteries' heat is not well managed. This may be due to the low flow and high temperature of the coolant around them. This causes a high-temperature difference between the lithium-ion batteries.

In comparison with the airflow arrangement, the maximum temperature is reduced for other cooling liquids. However, a more uniform temperature distribution is not obtained. Some of the lithium-ion batteries in the arrangement experience higher temperatures. The aforementioned could be due to receiving less flow of cooling coolant compared to other lithium-ion batteries.

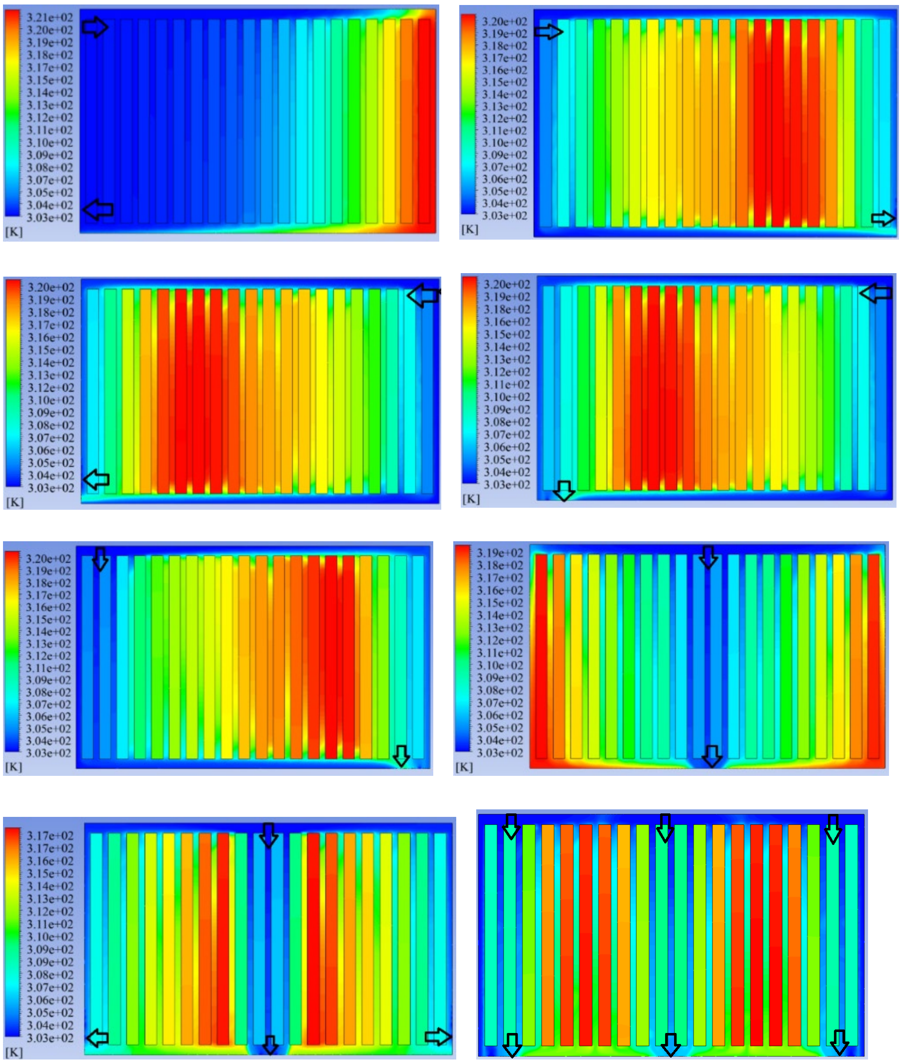
As can be seen, the lithium-ion batteries near the inlet duct have dissipated their generated heat well. The aforementioned could be due to their proximity to the inlet duct and higher flow rate, and lower adjacent fluid temperature. Notwithstanding the side lithium-ion batteries have not dissipated heat well even with a fluid such as dielectric mineral oil and dielectric water/glycol (50/50). The cooling fluid around these lithium-ion batteries has a lower flow rate, and it has a higher temperature due to heat exchange with other lithium-ion batteries.

Dielectric water/glycol (50/50), due to higher density, produce a higher pressure drop. High values of pressure drop and temperature variation can be justified by high kinematic viscosity and low thermal conductivity of dielectric mineral oil. Due to the bigger specific heat capacity and thermal conductivity of dielectric water/glycol (50/50), the maximum temperature was decreased more in comparison with air and dielectric mineral oil. In all flow arrangements and for all fluids, lithium-ion batteries' temperature is more near the fluid outlet. This may be due to the increase in coolant temperature in these areas. This leads to a non-uniform temperature distribution inside the assembly.

Air produces less pressure drop because of the lower viscosity, even for higher flow rates. Therefore, the fan cost decreases compared to pumping costs of dielectric water/glycol (50/50) and dielectric mineral oil. Nevertheless, due to air's low heat capacity, the results will not be satisfied even with high flow rates. The maximum temperature for all flow configurations was much higher than other cooling fluids. In general, it seems that the use of dielectric water/glycol (50/50) and dielectric mineral oil can be a better choice for heat management of the lithium-ion battery assembly at high discharge rates.

Dielectric mineral oil offers more acceptable results compared to air cooling in terms of maximum temperature due to its higher heat capacity than air, even at much lower flow rates. Although the costs associated with pressure drop and power consumption are much higher than air, the temperature uniformity is still unacceptable. There is still the problem of increasing the fluid temperature in some areas, even using dielectric water/glycol (50/50) as a coolant. This could be due to the decrease of flow fluid around lithium-ion batteries compared to other arrangements.

Figure 8 illustrates the lithium-ion battery pack's air cooling while the air velocity is 20 m/s during different full discharge cycles. Initial pack temperature, ambient temperature, and the inlet temperature of cooling media were assumed to be 20 °C. Three different values, including 39 A, 52 A, and 65 A, were considered for the discharge rate. As could be seen in the figures, the distance between the lithium titanate oxide batteries was increased. Although the temperature distribution is more homogenous compared to other cases, maximum temperature decreases. It should be noted that by increasing the current rate, more volume of cooling air is needed. Notwithstanding, the extra cooling capacity may be insignificant to provide a temperature homogeneity with coolant velocity enhancement.



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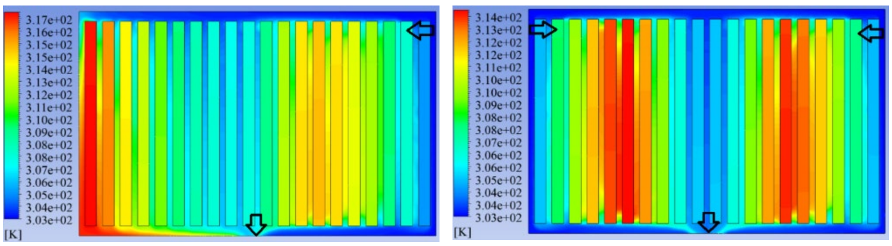

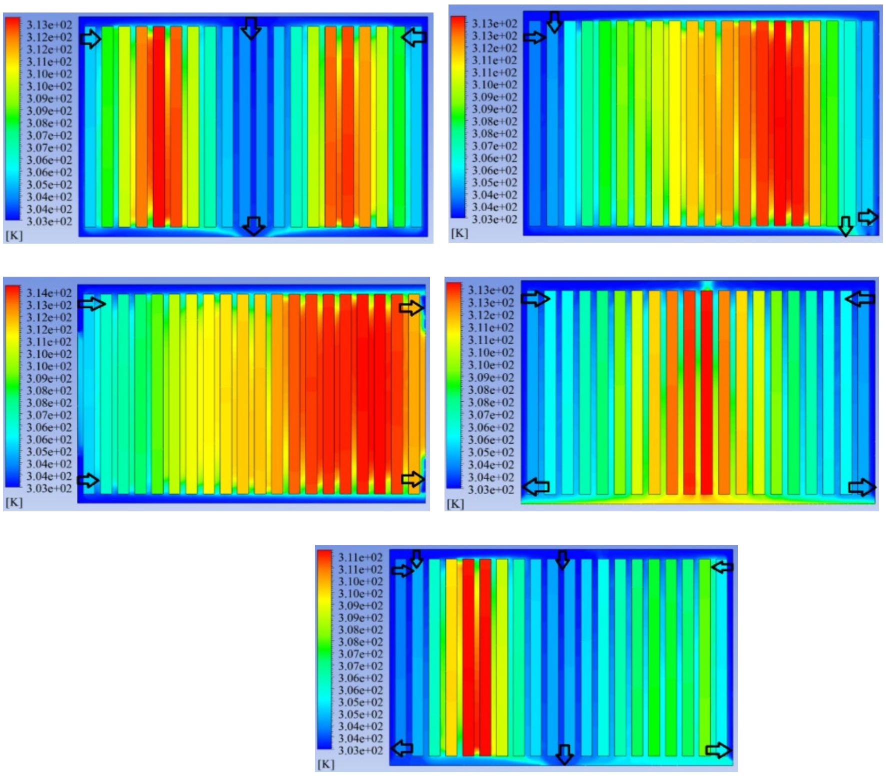

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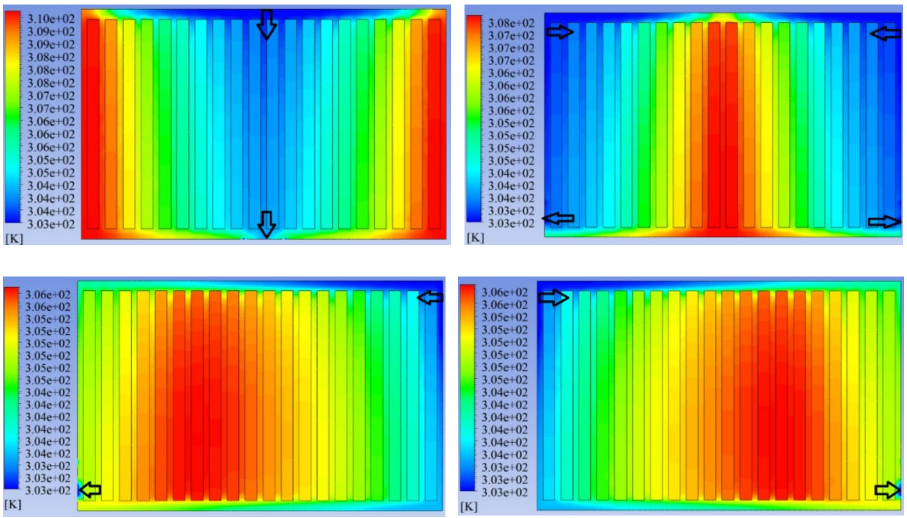
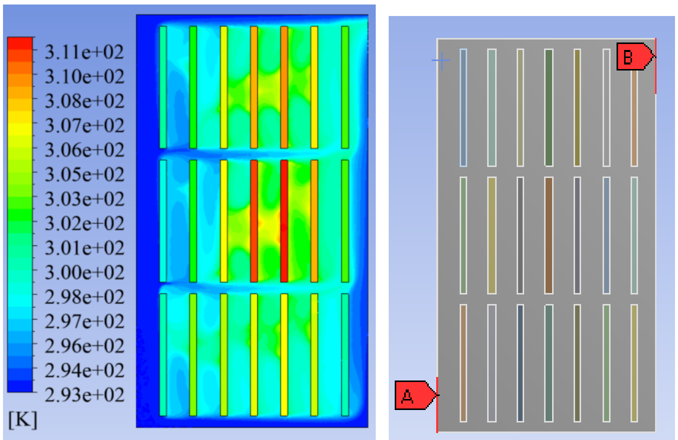
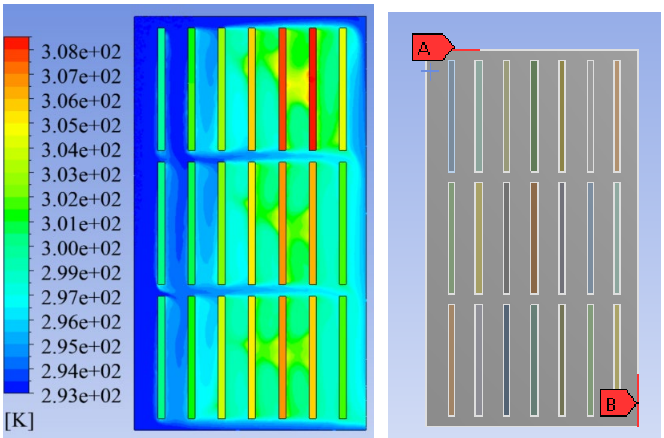


(c)

Figure 7. Thermal management of the lithium-ion battery pack by using (a) Air cooling, (b) Dielectric mineral oil cooling, and (c) Dielectric water/glycol (50/50) cooling.



(a)



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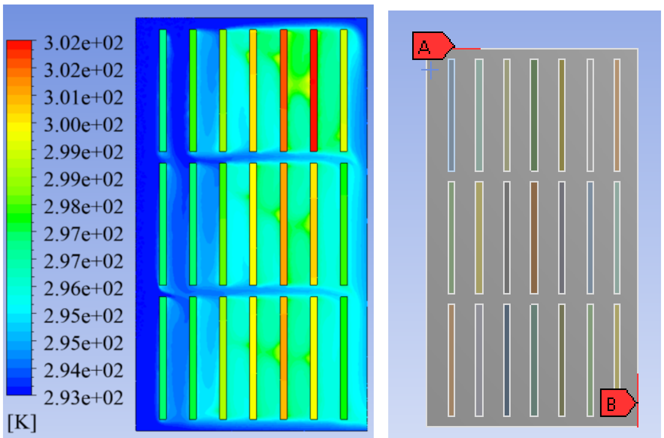

(c)

Figure 8. Air cooling of the lithium-ion battery pack V=20: (a) 65 A discharge, (b) 52 A discharge, (c) 39 A discharge.

4. Conclusion

This study's objective was to design and analyze an appropriate thermal management system for a lithium titanate oxide lithium-ion battery pack through heat dissipation measurement and thermal performance of the lithium titanate oxide batteries. The instrument, which was used in this investigation was an isothermal battery calorimeter. The lithium-ion battery cells employed in this investigation are 13 Ah high-power lithium titanate oxide lithium-ion battery cells. A comparison between different cooling methods was accomplished. Dielectric water/glycol (50/50), dielectric mineral oil, and air were considered cooling fluids in different flow configurations. It was shown that the combination of computational fluid dynamics and dynamic heat generation model could be an intuitionistic approach for transient thermal research of lithium-ion battery packs. Although the air does not require much power to move inside the arrangement, high flow rates will not be able to cool the lithium titanate oxide lithium-ion batteries and control their temperature during rapid discharging and high working temperature. Due to its high viscosity and pressure drop, Dielectric mineral oil does not seem appropriate, although decreasing the maximum temperature of lithium titanate oxide batteries works better than air. Between the investigated cooling fluids, the fluid produced more acceptable results, especially for high discharge rates, in terms of maximum temperature and temperature deviations was dielectric water/glycol (50/50). This is because of its high heat capacity, suitable viscosity, and distribution capability. It was shown how the flow arrangements would influence the temperature profile of the cooling system and lithium titanate oxide batteries. The results show that flow arrangements with more than one input or output could decrease the maximum temperature more than a single inlet and outlet. The results of this work can be used for the optimization of the lithium titanate oxide battery thermal management system. Since proper and optimal temperature control in lithium-ion batteries is very important, studying their control behavior from other aspects and using various criteria can be very important and influential in different design and construction stages and choosing between various designs.

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