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A comparative study of novel designs of liquid-cooled battery thermal management systems

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Abstract

The Li-ion battery has emerged as the heart of electric vehicles. The efficient thermal management of these lithium-ion batteries is an important aspect of electric vehicles for their safety and improved performance. The present work proposes two innovative and efficient modular designs of battery cooling systems. Both configurations are modeled with 5S1P and 5S5P cell configurations, and their performance is evaluated using computational fluid dynamics for heat generation and maximum temperature rise. The effect of heat generation rate and coolant flow on the thermal behavior of the battery modules has been thoroughly studied under different discharge rates. The performance of the systems was estimated using theoretical analysis and compared with the CFD simulations. It has been found that the maximum temperature rise obtained in designs 1 & 2 is 25.89℃ and 27.84℃ respectively and the maximum temperature difference between adjacent batteries is below 5℃. The details of the innovative designs and the performance analysis have been discussed in this article.

Keywords: BTMS, Liquid Cooling, Cylindrical cells

1. Introduction

The automobile industry is transforming into a new era, with a focus on environmentally sustainable vehicles that emit zero emissions, minimal noise, and low power consumption. To accomplish this, the development of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has received much interest around the world. One of the challenges for EVs is the development of an effective battery thermal management system (BTMS) (Choudhari, 2020). Lithium-ion batteries (LIBs) have gained more attention in the electronics market owing to their high energy density, long cycle life, stable charge-discharge rates, and capacity (Hekmat et al., 2022; Keng et al., 2020; Liu et al.,

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2020; Tete et al., 2021). These work as promising energy storage devices for EVs and various electronic applications as well. Li-ion batteries generate a significant amount of heat while being charged and discharged, which raises the temperature of the battery pack collectively. Hence, a BTMS is designed to keep the battery safe and efficient while ensuring that the temperature stays within the safe operating range (Liu et al., 2020). The ideal temperature range for LIBs is 15–35°C (Hekmat et al., 2022; Keng et al., 2020; Liu et al., 2020; Tete et al., 2021) and there should be no more than a 5°C temperature variation between adjacent cells (Hekmat et al., 2022; Keng et al., 2020; Liu et al., 2020; Tete et al., 2021).

Khan et al. (2022) investigated a novel and improved U-shaped, light, liquid-cooled battery thermal management system for electric vehicles using a machine learning approach and conclude that the developed BTMS would significantly improve the thermal performance of the batteries than conventional ones by keeping the maximum temperature within the desired range. Gao et al. (2022) studied an innovative lithium-ion battery module design based on gradient channels that follow the flow orientation. The results conclude that the gradient channel design (GCD) significantly changes the basic characteristic of the monotonic increase in temperature along flow direction when compared to uniform channel designs. Yin et al. (2022) investigated the performance of a modified serpentine-shaped liquid-cooled-BTMS under a vibration environment. The study concludes that the novel structure outperforms the original one in terms of cooling efficiency when subjected to vibration. Vibration lowers the average channel wall temperature by 1.8℃ for novel structures with various design parameters and raises the wall-averaged Nusselt number to at least 17, which is twice the value for the original structure. The increase in pressure drop is negligible. Numerous researchers are working on the development of an efficient BTMS worldwide by considering the various parameters that may affect the performance and life cycle of LIBs. The development of an efficient and compact BTMS is one of the major areas of improvement in EVs, which eventually relates to its range, safety, economy, and reliability.

In the present work, two modular battery packs with rectangular duct (for 5S1P configuration) and square duct (for 5S5P configuration) comprised of 5 cells and 25 cells respectively were investigated numerically. These ducts are incorporated with the cylindrical casings into which the batteries are inserted to make a perfect fit. Also, the rectangular and square ducts are treated as a channel for the circulation of the coolant through them. An active liquid cooling technique is implemented in these battery modules with water as a coolant. Firstly, the thermal performance of the battery modules without any cooling techniques under natural convection is investigated numerically using the computational fluid dynamics (CFD) software package ANSYS Fluent 2021R1. Then, a series of CFD simulations have been performed for both battery modules using water as a coolant under different discharge rates. Finally, the simulation results are validated using mathematical models based on the empirical correlations of heat transfer. The detailed thermal investigation of these designs has already been studied by the authors (Tete et al., 2022). The primary objective of this article is to provide a comparative analysis of the thermal characteristics of these two designs under similar operating conditions.

Nomenclature

5S1P	Cell Configuration: 5 Series / 1 Parallel.
5S5P	Cell Configuration: 5 Series / 5 Parallel.
T_{max}	Maximum cell Temperature

2. Governing equations

The mass, momentum, and energy equations are the governing equations that were applied to solve three-dimensional flow problems in this study. In the process of discharging the batteries, the heat produced inside the cells is transferred to the aluminium casings via heat conduction and then expelled from the cell casings via convection into the coolant. Given constant velocity inlet and static pressure outlet boundary conditions, this is accomplished by using the finite volume method to solve the Navier-Stokes equations and energy equation.

The equation of conservation of mass for coolant in the rectangular/square duct can be expressed as follows:

$$\frac{\partial \rho_c}{\partial t} + \nabla.(\rho_c \vec{u}) = 0 \qquad (1)$$

where ρ_c represents the density of coolant, $\vec{u}$ is the velocity vector.

The conservation of momentum equation of coolant is expressed as:

$$\frac{\partial}{\partial t}(\rho_c\vec{u}) + \nabla.(\rho_c\vec{u}\,\vec{u}) = -\nabla P \quad (2)$$

where P is the static pressure of the coolant.

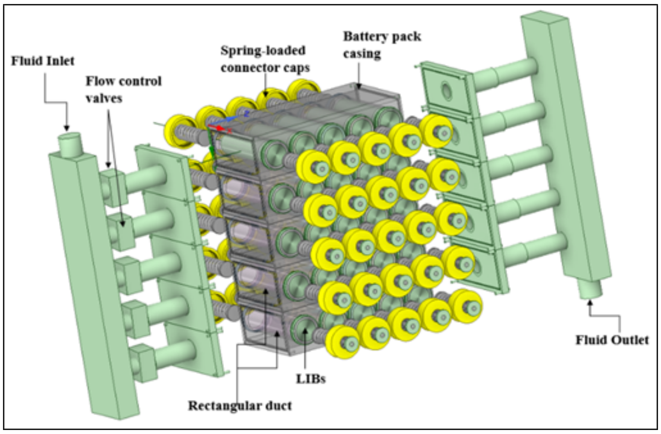
The equation of conservation of energy of coolant is expressed as:

$$\frac{\partial}{\partial t}(\rho_c C_{pc} T_c) + \nabla.(\rho_c C_{pc}\vec{u}\,T_c) = -\nabla.(K_{pc}\nabla T_c) \quad (3)$$

where C_{pc} is the specific heat capacity, T_c is the temperature and K_{pc} is the thermal conductivity of coolant material.

3. Modeling and simulation

This investigation focused on two innovative designs for battery modules: (a) a battery module with a rectangular duct (design 1), and (b) a battery module with a square duct (design 2). Both designs employ cylindrical cells enclosed in conductive casing material to prevent direct contact between the coolant and the cell surface. In design 1, the battery pack incorporates a rectangular duct with a cylindrical casing to accommodate the cells. In design 2, the battery pack consists of a square duct with a cylindrical casing for the cells. For this study, two battery modules were created with configurations of 5S1P and 5S5P. In design 1, five 18650 cylindrical lithium-ion batteries with a capacity of 3000 mAh were employed, while in design 2, twenty-five batteries were used for the same configuration. The coolant is introduced into both the rectangular and square ducts, effectively extracting heat from the cylindrical cells, as depicted in figures 1(a) and 1(b).



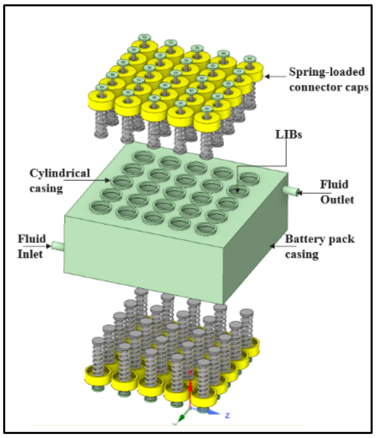


Figure 1: Novel design of the battery module with (a) rectangular duct (design 1) and (b) square duct (design 2)

The computational fluid dynamics (CFD) software package ANSYS FLUENT 2021R1 was employed in this study. The mass, momentum, and energy equations were evaluated using the finite volume method. The solver was configured to run the transient analysis for 720 seconds with a pressure-based, first-order implicit method. The rate of generated heat was the source term at different discharge rates. The initial battery pack temperature was set to be the same as the ambient temperature. Incompressible fluid and laminar flow were the assumptions used to carry out the numerical simulation. The battery module's outer casing is open to natural convection with an initial temperature of 25°C. All the electrical connections were neglected to reduce the simulation complexities, computational time, and cost. To check the accuracy of the simulations, a mesh independence study has been conducted by varying the mesh elements and the number of divisions parameter for edge sizing. A mesh element size of 453820 was considered for the rest of the simulations. The thermophysical properties of the materials, boundary conditions, heat generation model, and the technical specifications of the selected lithium-ion battery are referred from the literature (Tete et al., 2022).

4. Results and discussion

Both design configurations, namely (a) the rectangular duct (design 1) and (b) the square duct, were simulated and analyzed using a simulation tool, as detailed in Section 3. The simulation aimed to explore the impact of varying inlet coolant velocities and ambient temperatures on the thermal behaviour of the battery pack. The performance was compared with the battery pack operating without any cooling arrangement. The findings from the simulation were then compared with analytical solutions derived from mathematical models. The outcomes of both simulation and mathematical modelling are elaborated in the following sections.

4.1 Thermal response without cooling

The battery module with rectangular and square duct flow channels was developed and investigated numerically using the ANSYS Fluent 2021R2 CFD software package. Both designs were tested under similar operating conditions. A wide range of discharge rates from 0.5C to 5C was applied while running the simulation. Initially, the battery modules were simulated at the natural cooling conditions where no external cooling arrangements have been made for the cooling of batteries. All the simulations were run at different times based on their C-rates. For 0.5C-7200s, 1C-3600s, 2C-1800s, 3C-1200s, 4C-900s, and 5C-720s, but it has been observed that, after a while, for no cooling conditions, the temperature were increasing exponentially. Therefore, all the results were then limited to the value of 720s.

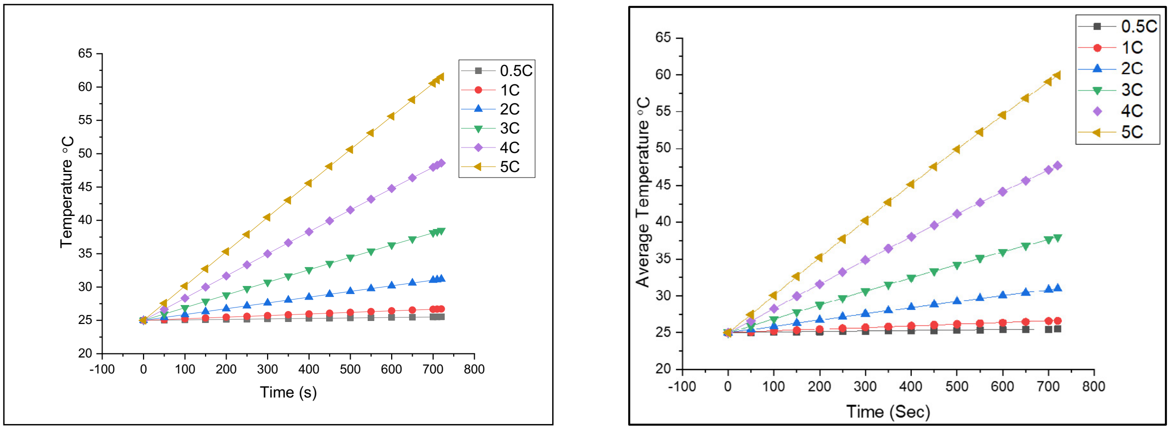


Figure 2: Thermal performance under natural cooling conditions (a) design 1 and (b) design 2

For design 1, it was observed that the maximum temperature (T_{max}) rises from 26.70°C at a 1C discharge rate to 61.52°C at a 5C discharge rate, which was beyond the safe operating temperature limit of LIBs. Similarly, for design 2, the highest temperature rise of 62.63°C at a 5C discharge rate has been observed in a cell centrally located inside the battery pack. The maximum average temperature achieved by designs 1 and 2 at different discharge rates are represented in figures 2 (a) and (b) respectively.

4.2 Thermal response with liquid cooling

The rise in the average temperature of battery modules under various discharge rates is significantly different. The temperature rise increases under the discharge rate, which ultimately decreases the LIBs' ability to function efficiently. Through the battery pack's inlet and outlet, a liquid was pumped around the LIBs to improve the operating conditions of the battery system. Water was utilized in this situation as a liquid coolant. Figure 2 shows the temperature distribution in the battery pack at different discharge rates for 720 seconds.

Using water-cooled BTMS, a minimal rise of 0.05°C and 0.13°C was obtained at a 0.5C discharge rate from the initial battery temperature of 25°C for designs 1 and 2 respectively. At the 5C discharge rate, the maximum temperature was observed as 25.89°C and 27.84°C respectively and the maximum temperature difference between adjacent batteries is below 5°C.

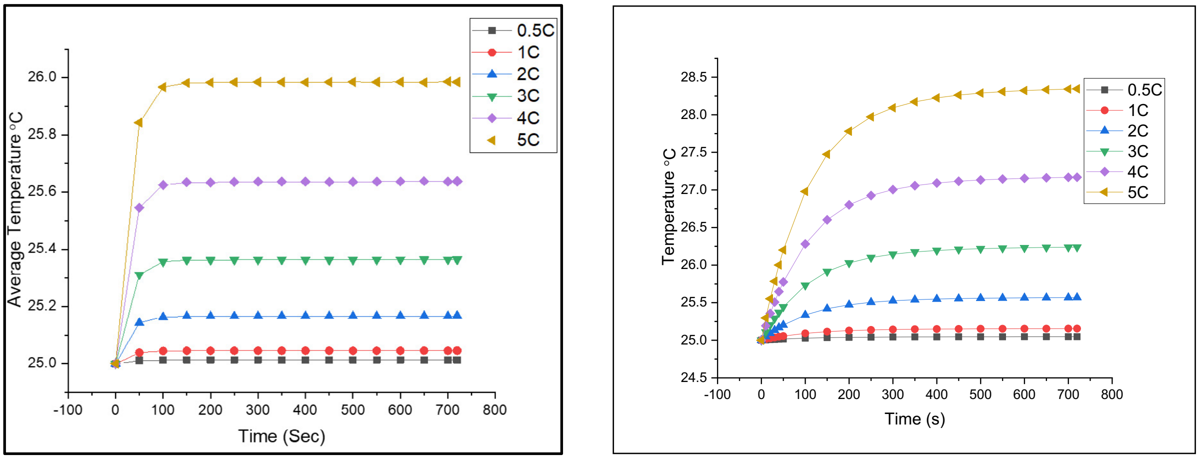


Figure 3: Average temperature of the battery modules using water cooling (a) design 1 and (b) design 2

4.3 Thermal response using liquid cooling at varying inlet velocity

The thermal performance of the battery module has been investigated numerically under a 5C discharge rate by varying inlet velocities from 0.01 m/s to 0.1 m/s.

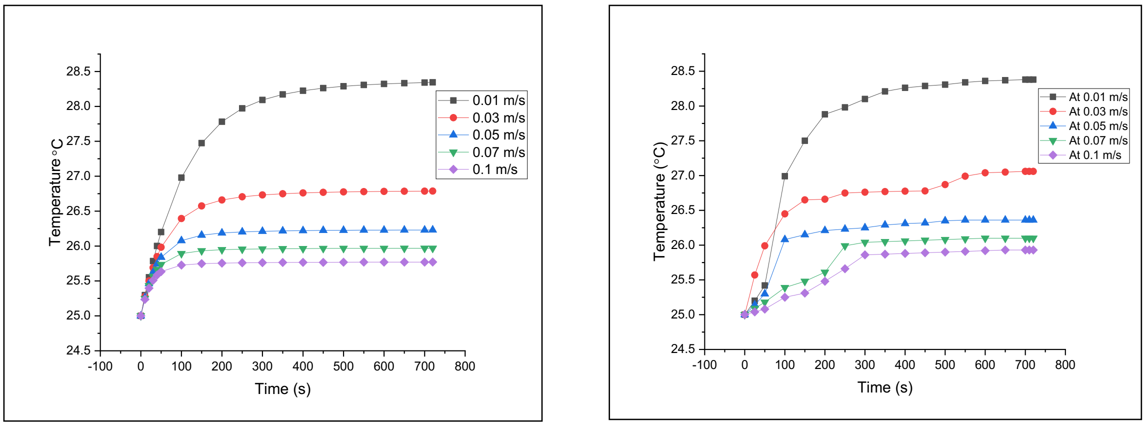


Figure 4: Thermal response using liquid cooling at varying inlet velocity (a) design 1 and (b) design 2

Figure 4 represents the maximum temperature of the battery module at various inlet velocities. The value of T_{max} obtained using water for designs 1 and 2 is 28.34°C and 28.51°C at 0.01 m/s and 25.77°C and 25.92°C at 0.1 m/s respectively. With the increase in the inlet flow rate, the maximum temperature of the batteries decreases and remains within the operating range of 15-40°C The T_{max} of the battery module has been reduced by 2.37°C at a 5C discharge rate when the inlet velocity varies from 0.01 m/s to 0.1 m/s.

4.4 Influence of ambient temperature

In commercial applications, batteries may have to perform at various ambient temperature conditions. The battery performance is affected in both the scenarios of low ambient temperature and high ambient temperature. At low temperatures, the battery's performance is noticeably degraded; the cell's power and energy are also significantly impacted. Moreover, it limits the battery's use in cold weather. Low temperature causes the electrolyte's viscosity to rise, which ultimately lowers its ionic conductivity and raises the internal resistance of the battery pack (Ma et al., 2018; Ouyang et al., 2019; Petzl et al., 2015). Overall, operating a battery at low temperatures leads to poor performance and an acceleration of the aging process. When batteries are exposed to extreme temperatures, the batteries self-discharge and their capacity begins to deteriorate over time (Wu et al., 2019). An excessive rise in the temperature of the battery pack may lead to thermal runaway (TR) causing the battery pack to catch fire and explode. To explore the impacts of ambient temperature on the thermal performance of the battery, the ambient temperature is varied from 15°C to 35°C with a 5°C interval in this work.

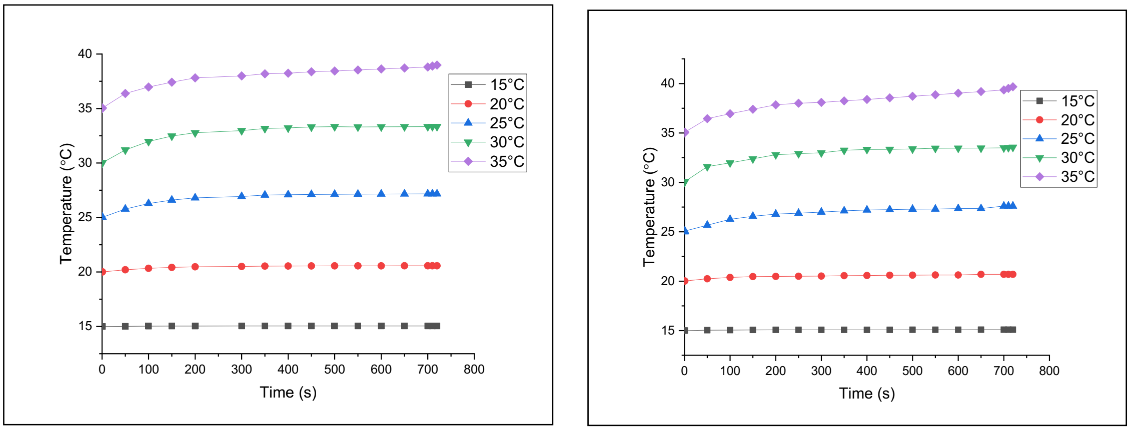


Figure 5: Temperature profile at different ambient conditions (a) water cooling (b) EG-water cooling

Figure 5 (a) and (b) illustrate how the battery's maximum temperature varies as a function of discharge time and ambient temperature using water-cooled BTMS with an inlet velocity of 0.01 m/s and at a 5C discharge rate respectively. The T_{max} obtained is 38.99°C and 39.67°C at a 5C discharge rate respectively. A small temperature difference of 0.68°C is noticed in the thermal performance of both designs. It is observed that at the initial stage of the discharge process, the temperature rises significantly and it remains constant after some time. This is attributed to the fact that battery heat is difficult to dissipate when the temperature rises in the surrounding area.

4.5 Mathematical modeling of the BTMS with rectangular duct

The laminar and turbulent flow in tube concepts is similar to the geometry model provided in the current work. As a result, the numerical simulation used in this study was validated using the empirical relations for heat transfer in the case of laminar flow in tubes. The mathematical formulation of the problem is stated as lithium-ion batteries are cooled by passing the water through a rectangular duct. The battery cells inserted in cell casings were arranged in an inline manner and treated as heated cells and the fluid was circulated across the cells. The cooling arrangement formulated using this concept is shown in Figure 6. All the correlations used for numerical validation are taken from the textbook by Cengel (2002).

Using the results of a FLUENT solver simulation, the area-weighted average temperature of the water at the inlet (Ti) and outlet (Te) of the battery pack was calculated. At the mean temperature ((Ti+Te)/2) of the inlet and outlet, all of the fluid's properties—in this case, the properties of water—were taken into account. At the average surface temperature of the battery cells, the value of Prs was measured. The value of the convective heat transfer coefficient h is calculated. The surface temperature of battery cells has been calculated by inputting the values of, As, Ti, Te, and water properties into equation $h * As * (Ts - Te) = m * Cp * (Te - Ti)$. The surface temperature of the battery pack was calculated, and it was 28.08°C, whereas the numerical result from the simulation was 25.89°C at a 5C discharge rate. The computational results for the current investigation are in good accord with the theoretical conclusions.

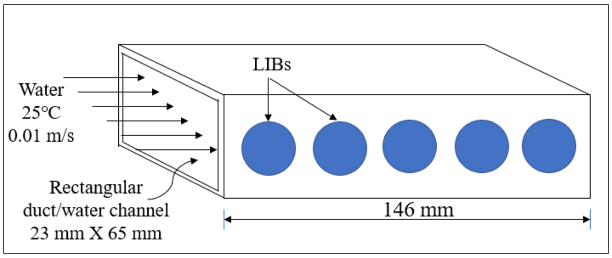


Figure 6: Depiction of the battery module as flow through a rectangular duct

4.6 Mathematical modeling of the BTMS with square duct

The geometry model put forward in this work is similar to the concept of tube bank flow. As a result, the numerical simulation used in this study was validated using the empirical relations for heat transfer in the case of flow over tube banks. The tubes in the tube bank are set up in an inline and spaced out according to the flow. The fluid flowed over the battery cells, which were lined up inside cell casings and treated like tubes. The arrangement of the tube bank is defined by the transverse pitch S_T and longitudinal pitch S_L, as shown in Figure 7. All the correlations used for numerical validation are taken from the textbook by Cengel (2002).

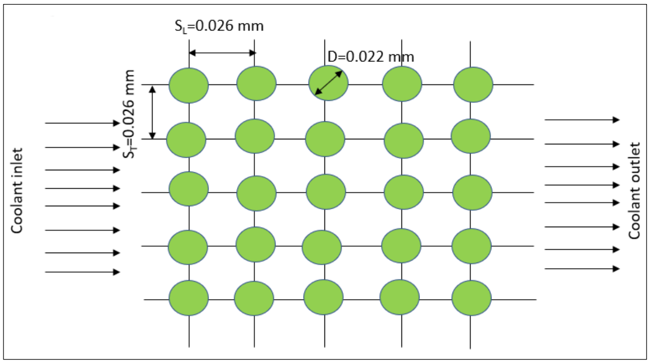


Figure 7: Depiction of the battery pack as tube banks

The values of the area-weighted-average temperature of water at the inlet (Ti) and outlet (Te) of the battery pack were determined using a FLUENT solver simulation results. All the properties of the fluid (in this case, water) were considered at the mean temperature ((Ti+Te)/2) of the inlet and outlet. The value of Prs was taken at the average surface temperature of the battery cells.

The value of h has been calculated using equation (5.23) and by putting the values of ṁ, As, Ti, Te, and properties of water in the equation $\dot{Q} = \dot{m} * Cp * (T_e - T_i) = hw * A_s * \Delta T_{ln}$, the value of the surface temperature of battery cells has been determined. From this equation, the value of the surface temperature of the battery pack obtained was 28°C, whereas the numerical value from the simulation was equal to 27.84°C at a 5C discharge rate. The theoretical results are in sound agreement with the computational results for the present study.

5. Conclusions and Recommendations

Two novel designs of a three-dimensional battery pack comprised of five and twenty-five 18650 lithium-ion batteries were developed to investigate the thermal performance of a liquid-cooled battery thermal management system. The literature reveals that the currently used indirect liquid cooling is the most promising solution for battery cooling, however, it restricts the effective performance of the battery pack due to the less heat transfer exposure area. In the present designs of BTMS, more emphasis was given to increasing the heat dissipation rate by enhancing the thermal interactions of the heat transfer surfaces. A series of numerical simulations using the finite volume method has been performed under different operating conditions for the cases of no cooling and with liquid cooling. The numerical model has been validated with the help of a mathematical solution using various empirical correlations of heat transfer and the results are in sound agreement with each other. The temperature contours and profiles under discharge rates of 0.5C, 1C, 2C, 3C, 4C, and 5C have been thoroughly examined. The significant findings of the study are concluded as follows:

1. The maximum temperature of the batteries is in the desired range of 15-40°C when the batteries are discharged at 0.5C and 1C rates, but the temperature rises beyond 60°C at a 5C discharge rate under natural cooling conditions for both the designs of BTMS. Therefore, a water-cooled BTMS has been implemented in both designs.
2. Using water-cooled BTMS, a negligible rise of 0.05°C was observed in design 1, whereas 0.13°C in design 2. At the 5C discharge rate, the maximum temperature was observed as 25.89°C and 27.84°C respectively and the maximum temperature difference between adjacent batteries is below 5°C.
3. The T_{max} of the battery module has been reduced by 2.37°C at a 5C discharge rate when the inlet velocity varies from 0.01 m/s to 0.1 m/s.
4. The numerical simulations and the mathematical results are in good agreement.
5. Both designs are performing effectively under higher discharge rates with a negligible deviation in their thermal performance. From the comparison point of view, based on the requirement of the commercial applications, its battery pack size, capacity, and coolant, the suitable BTMS design could be selected.

Certain limitations of the present work create the scope for further studies in the said domain. The present study has been conducted by considering the standard charge-discharge cycle; the effect of different charge-discharge cycles can be investigated. A rest period can be given in between the two cycles and their effect can be analyzed. One can explore the impact of staggered cell arrangement on the thermal behavior of the cooling system. The aging mechanism in LIBs could be studied for further studies.

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