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Experimental and Numerical Investigation on the Effect of Inlet and Outlet Position on the Thermal Performance of an Immersion-Cooled Battery Module

Lithium-ion batteries (LiBs) are extensively used in stationary and transportation energy storage applications because of their high energy and power densities. However, their performance is strongly temperature dependent, presenting challenges related to thermal management and thermal runaway risks. Direct liquid or immersion cooling provides a high heat transfer rate by allowing direct contact with the LiBs. In contrast, single-phase dielectric immersion fluids improve cooling and safety, reducing parasitic power consumption and space requirements. This work combines experimental and numerical analyses to assess the thermal performance of an immersion-cooled 4S4P battery module, focusing on the effects of the position of the fluid inlet and outlet, the fluid flowrate and the type of immersion fluid on maximum temperature, temperature rise, and temperature uniformity. Although the inlet and outlet positions of the fluid had a minimal impact on the temperature rise, a more substantial temperature increase was observed when fluid inlet was positioned at the top compared to the center of the module. Among the fluids tested, the highest temperature rise of 9.28 °C was observed with mineral oil, while NOVEC 7000 showed the lowest temperature rise of 6.24 °C. As the immersion fluid flowrate increased from 0.003 kg/s to 0.010 kg/s, the temperature rise of the battery module decreased by 4.02 °C and the temperature nonuniformity dropped by 3.41 °C. Higher power is needed to move the fluids through the battery module at higher pressure drops. In general, NOVEC 7000 demonstrated superior thermal performance among the fluids tested. [DOI: 10.1115/1.4069005]

Keywords: lithium-ion battery, thermal management, immersion cooling, electric vehicle, thermal performance, electronic cooling, energy systems, forced convection, heat transfer enhancement

Introduction

Electric vehicles (EVs) are seeing widespread use, influenced by higher fossil fuel costs and government incentives. Lithium-ion batteries (LiBs) are often selected for EVs because they offer a high energy density, considerable specific power, extended cycle life, and minimal self-discharge. However, higher temperatures can hinder their thermal efficiency, leading to increased degradation over time. Operating at elevated temperatures during charging or discharging causes lithium ions to intercalate in a way that cannot be reversed, diminishing the active material in the electrodes [1]. Furthermore, continuous cycling at these high temperatures accelerates capacity decline as it accelerates electrode deterioration [2]. In

lithium ion batteries (LiBs), heat production arises from charge transfer processes and exothermic reactions, which can be reversible or irreversible. Entropic or reversible heat originates from changes in entropy during electrochemical reactions [3,4], while irreversible heat results from polarization and shifts in enthalpy [5]. The standard operating temperature range for LiBs is between 15 °C and 60 °C, with nonuniformity of temperature kept below 5 °C in battery packs [6]. However, optimal thermal performance is achieved in a still narrower temperature range of 15 °C–35 °C, with nonuniformity in temperature below 3 °C [7]. Therefore, an efficient battery thermal management system (BTMS) design is crucial to maintain the temperature of the LiB module within these optimal limits for extended battery life and enhanced safety.

BTMS strategies in the literature based on parasitic power consumption can be categorized into three main types: active, passive, and hybrid BTMS [8]. Active BTMS requires parasitic power to operate the cooling auxiliary systems and includes

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Manuscript received November 3, 2024; final manuscript received June 14, 2025; published online July 17, 2025. Assoc. Editor: Vinod Narayanan.

methods such as forced air cooling, fluid cooling, thermoelectric cooling, and immersion cooling. In contrast, passive BTMS primarily utilizes phase-change materials and heat pipes. Hybrid battery thermal management systems combine active and passive cooling strategies. Given the limitations of air cooling systems, liquid cooling presents a promising alternative for large-scale EVs [9,10]. Based on the interaction between LiBs and cooling fluids, cooling systems can be categorized as indirect or direct (immersion) cooling. Due to the superior thermophysical properties of liquids and their ability to maintain temperature uniformity, indirect cooling is commonly used in electric vehicles for battery module cooling [11,12]. Water and ethylene glycol mixtures are frequently used as coolant options. Despite the advantages of indirect liquid cooling, several challenges may limit its application. The complexity of the system increases significantly due to the incorporation of chillers, radiators, and cooling plates. Furthermore, the presence of liquid cooling tubes or plates can increase thermal resistance and reduce thermal contact between lithium ion battery (LiB) cells and the coolant [13]. In contrast, immersion cooling allows for direct contact between LiB cells and the cooling fluid, resulting in significantly enhanced heat transfer rates [14]. Moreover, some immersion fluids can function as fire suppressants, minimizing risk and preventing potential thermal runaway incidents [14,15]. Consequently, researchers are increasingly exploring immersion-cooled BTMS strategies to evaluate thermal performance under direct LiB cooling conditions.

Immersion cooling strategies can be categorized on the basis of their physical states into single-phase and two-phase cooling. Single-phase immersion cooling fluids include hydrofluoroethers, hydrocarbons, silicone lubricants, and water/glycol mixtures. Due to their cost advantages, single-phase immersion cooling is often preferred over two-phase fluids and has garnered considerable attention from researchers recently. For example, Dubey et al. [16] compared the thermal performance of immersion cooling with plate-based indirect liquid cooling BTMS. Their results indicated that immersion cooling reduced the maximum cell temperature and minimized temperature nonuniformity, even at high discharge rates, owing to its higher thermal conductivity compared to cooling plates. In another study, Luo et al. [17] examined the performance of immersion water cooling for a cylindrical LiB module. A unique sealing structure was implemented to prevent direct contact between the water and the LiB, preventing potential short circuits. The results demonstrated that even at a discharge rate of 3C and a lower fluid flowrate the battery temperatures could be

maintained below 50°C, although the nonuniform temperature exceeded the limit of 5°C.

The use of hydrocarbon-based fluids in immersion-cooled battery thermal management systems (BTMS) is gaining traction because of their affordability, low toxicity, and broad operating temperature range. Examples of these fluids include mineral oils, poly-alpha-olefins, and other synthetic hydrocarbon oils. Patil et al. [18] examined the thermal performance of a mineral oil-cooled BTMS for prismatic lithium-ion batteries (LiBs) at various flowrates. Their results indicated that effective performance could be achieved even with lower flowrates of the cooling fluid. At higher flowrates, the maximum module temperature was maintained below 40°C, even at a discharge rate of 5C. Li et al. [19] studied the thermal performance of a mineral oil-based immersion-cooled single LiB cell during continuous discharge and charge cycles, finding that mineral oil-based BTMS efficiently kept the maximum temperature below 40°C, even at a discharge rate of 4C.

Furthermore, Satyanarayana et al. [20] experimentally investigated the thermal performance of immersion cooling using mineral and Therminol oils for a 5S4P battery module, comparing it with natural and forced air convection. Their findings showed that the immersion cooling method successfully limited the maximum temperature to below 40°C at a discharge rate of 2C. Han et al. [21] reported similar results for a 4S4P battery module utilizing thermal fluid (E5-TM410 fluid).

Al-Zareer et al. [22] conducted a numerical investigation of an ammonia-based BTMS using electrochemical-thermal modeling. Their analysis revealed that a pressure of 9.0 bar, covering 5% of the LiB cell, was sufficient to maintain battery temperatures below 40°C during the charging and discharge cycles at a rate of 7.5C. Park and Jung [23] numerically compared the thermal performance of immersion-cooled BTMS with air-cooled systems, concluding that air-cooled BTMS consumes significantly more power at high discharge rates and requires wider cell spacing, while immersion cooling allows for narrower spacing. Jithin and Rajesh [24] performed a numerical study on the thermal performance of a single-phase immersion-cooled BTMS, using three immersion fluids: oil, deionized water, and engineered fluid. Their results indicated that fluids with lower viscosity require 76.43% less pumping power than mineral oils. Le et al. [25] proposed a manifold immersion cooling design using deionized water and assessed the impact of the design parameters on thermal performance, finding that the length of the manifold channel and the spacing of the battery significantly affected the cooling efficiency, with maximum temperatures

Table 1 Summary of literature for immersion-cooled BTMS

Working fluid	LiB type	Module size	MC	ST	Inlet	Outlet	FFRM (kg/s)	CRM	$T_{\max}$ (°C)	ΔT (°C)
AC-100 [24]	18650	4S1P	2.6	Num	–	–	0.05	3C	37.93	7.2
AC-100 [28]	Prismatic	1	68	Exp	M	–	0.0068	C/2	22.5	–
Deionised water [24]	18650	4S1P	2.6	Num	–	–	0.05	3C	31.61	2.2
HFE-6120 [35]	18650	32P160S	102.4	Num	–	–	2.2	3C	36	2
HFE-7000 [32]	18490	1	1	Exp	–	–	–	5C	33	0.7
HFE-7000 [34]	18650	12S5P	16	Exp	T	T	0.3 m/s	5C	35.1	3.71
HFE-7500 [16]	21700	1	–	Num	B	T	0.17	3C	44	<2
HFO-SF33 [30]	18650	1	3	Exp	–	–	–	7C	34.5	0.8
Mineral oil [19]	18650	1	2.6	Exp	M	M	0.273	4C	30	2.4
Mineral oil [20]	18650	5S4P	10	Exp	B	T	0.02	3C	40.6	8.9
Mineral oil [26]	18650	4S1P	2.6	Exp	T	B	0.05	3C	<40	<1
Mineral oil [24]	18650	4S1P	2.6	Num	–	–	0.05	3C	39.5	8.6
Dimethyl silicone oil [30]	Pouch	5	24	Num	–	–	1.16	3C	38.9	–
Silicon oil [17]	18650	1	2.6	Exp	–	–	–	2C	36.84	2.75
Transformer oil [17]	18650	1	2.6	Exp	–	–	–	2C	32.81	1.75
Transformer oil [36]	Pouch	1S5P	50	Exp	T	T	1.4	2C	39.4	1.23
E5-TM410 [21]	18650	4S4P	14	Exp	M	M	0.013	4C	44.6	16.8
Therminol oil [20]	18650	5S4P	10	Exp	B	T	0.02	3C	42.66	10.65
Liquid ammonia [37]	18650	4S3P	–	Num	–	–	3 m/s	7.5C	31.4	<3.0
R1233ZD(E) [31]	18650	12S5P	13	Exp	T	T	43.44	3C	36.58	3.4

Note: M, mid position; T, top position; B, bottom position; ST, study type; MC, module capacity in Ah; FFRM, fluid flowrate maximum; CRM, C rate maximum.

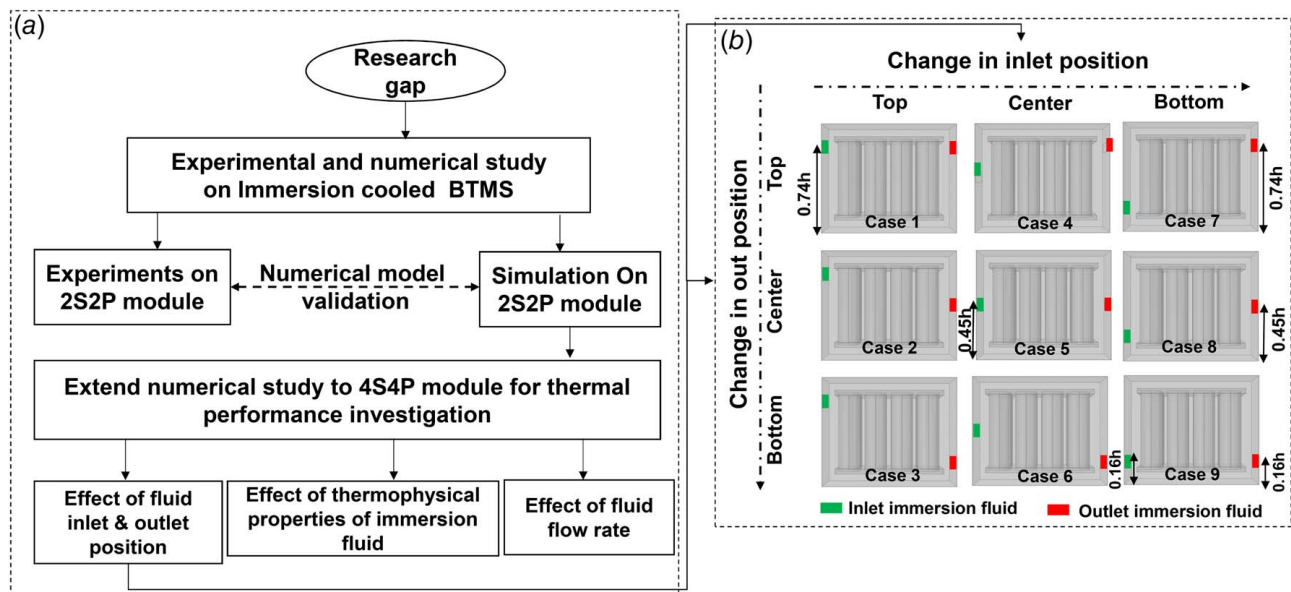


Fig. 1 Schematic of methodology adapted: (a) flowchart of the process and (b) inlet and outlet positions for immersion fluid

below 36.06 °C and temperature nonuniformity below 6.66 °C. Trimbake et al. [26] experimentally investigated a mineral oil-based immersion-cooled BTMS, considering both direct jet and two-jet cooling methods for high discharge rates. Their results demonstrated a temperature nonuniformity of less than 1 °C within the module, with jet applications that improve cooling performance under high discharge conditions. Karimi and Li [27] numerically evaluated forced air cooling along with silicone oil in immersion-cooled BTMS, concluding that distributed forced cooling is an effective and cost-efficient thermal solution.

Furthermore, the application of engineered fluids in immersion cooling was explored by Sundin and Sponholtz [28]. Li et al. [29] investigated immersion cooling based on the fluorinated liquid (SF33) for a single LiB, reporting a temperature rise reduction of 9.09 °C under a 4C discharge rate compared to forced air convection. Furthermore, dimethyl silicone oil was identified to have promising potential for immersion cooling applications [30]. Two-phase immersion cooling was explored experimentally by Wang et al. [31], and the thermal performance of a staggered LiB module cooled using ethanol-mixed refrigerant (R1233ZD(E)) was investigated. The result showed that the refrigerant was mixed with ethanol at a low boiling point, the transfer of heat from the wall boiling increased significantly, and the uniformity of the temperature increased 57%. Forced convection heat transfer of the liquid phase substantially assisted in decreasing the temperature rise of the LiB module, and its influence increased as the refrigerant inlet flowrate increased. Recently, immersion-cooled BTMS that uses hydrofluoroether (Novec 7000, manufactured by 3M) has been explored by researchers, which possesses a wide range of thermal properties [32–35]. When the LiB temperature reaches the boiling point, the fluids boil, significantly improving the heat transfer capabilities. The added advantage of being non-flammable reduces safety concerns. The result showed that the temperature nonuniformity in the immersion-cooled battery module is restricted below 5 °C in most cases. In addition, the density of hydrofluoroether is approximately 40% lower compared to the water–glycol systems [15]. Van Gils et al. [32] experimented with cooling of a single LiB by immersion in Novec 7000 fluid. The result showed that two-phase immersion cooling performs well for different discharge rates. A detailed summary of immersion-cooled BTMS is summarized in Table 1.

Recently, Wahab et al. [38] presented advances in battery thermal management and safety within immersion cooling technologies for future electric vehicles. Immersion cooling has been increasingly

adopted in commercial lithium-ion battery (LiB) modules for various cooling applications, with notable examples including Kressel's use of shell thermal fluids, Xing Mobility's application of 3M Novec fluid, Rimac Automobili's utilization of Solvay Galden fluids, and TotalEnergies' incorporation of immersion technology for battery cooling solutions [15]. Despite this trend, the literature reveals a limited number of studies focusing on the thermal performance of single-phase immersion-cooled LiB modules, and the effects of fluid inlet and outlet positioning, as well as the thermophysical properties of immersion oils, on the thermal performance of battery modules have not been extensively explored. To address these gaps, the present study aims to experimentally and numerically investigate the thermal performance of an immersion-cooled LiB module, specifically using high-power and high-energy density nickel–cobalt–aluminum (NCA18650) LiBs, arranged in a 4S4P configuration. Through a comprehensive parametric sweep study, this research analyzes the impact of the immersion fluid's inlet and outlet positions, the thermophysical properties of the immersion fluid, and the flowrate of the immersion fluid on the overall thermal performance of the module. The thermal performance metrics for the proposed battery module are evaluated using key indicators, including the maximum temperature of the battery module ($T_{b,max}$), the average temperature rise ($T_{avg, rise}$), and the temperature nonuniformity (ΔT).

Methodology

A flowchart outlining the methodology used to investigate the thermal performance in this study is presented in Fig. 1(a). To assess the impact of the inlet and outlet positions of the immersion fluid, nine combinations were evaluated—comprising three different inlet positions and three outlet positions—as shown in Fig. 1(b). These positions are referenced in relation to the height (h) of the battery module enclosure. A three-dimensional model was created using COMSOL MULTIPHYSICS, incorporating the appropriate assumptions and boundary conditions. In-house experiments were conducted to validate the numerical model of the 2S2P battery module using mineral oil as immersion fluid at 1C discharge rate. The validated model was subsequently extended to the 4S4P module to further explore thermal performance. Specifically, three immersion fluids with varying thermophysical properties were examined: one mineral oil and two engineered fluids (Ampcool and Novec 7000), with their thermophysical properties listed in

Table 2 Thermophysical properties of immersion fluid used in the present study [26,34]

Properties	Unit	Mineral oil	AmpCool 100	Novec 7000
Density	kg/m ³	829	811	1472
Dynamic viscosity	kg/m s	0.05	0.008	0.00043
Thermal conductivity	W/m K	0.13	0.14	0.08
Specific heat capacity	J/kg K	1900	2203	1223
Dielectric strength	kV	79	–	>25
Dielectric constant	–	–	7.4	

Table 2. The thermal performance of the battery module was analyzed using key performance parameters: $T_{b,max}$, $T_{avg, rise}$, and ΔT_{max} at different inlet and outlet positions. In addition, the effects of the thermophysical properties and flowrates of the immersion fluid were investigated. Here, T_{max} indicates the maximum temperature of the LiB in the module at the end of the discharge cycle, $T_{avg, rise}$ reflects the increase in the average temperature of the battery module from its initial temperature, and ΔT represents the difference in temperature between the LiB cells in the module. The mathematical expressions for these performance parameters are provided in Eqs. (1)–(6).

$$T_{b,max} = \max(T_{i,ribs}) \quad (1)$$

where $T_{i,ribs}$ is the temperature rise of the i th battery in the module and $T_{i,ib}$ and $T_{i,fb}$, are the initial and final temperature, respectively, expressed as Eq. (2):

$$T_{i,ribs} = T_{i,fb} - T_{i,ib} \quad (2)$$

where the initial cell surface temperature of the i th battery measured at the anode and cathode is represented by $T_{i,iba}$ and $T_{i,ibc}$, respectively. Similarly, the final battery cell surface temperature given by $T_{i,fba}$ and $T_{i,fbc}$, expressed in Eqs. (3) and (4), respectively. The

location of temperature sensors on the battery cell surface is shown in Fig. 2(c).

$$T_{i,ib} = \frac{(T_{i,ibc} + T_{i,iba})}{2} \quad (3)$$

$$T_{i,fb} = \frac{(T_{i,fbc} + T_{i,fba})}{2} \quad (4)$$

$$T_{avg, rise} = \frac{\sum_{i=1}^n T_{i,ribs}}{n} \quad (5)$$

where $T_{avg, rise}$ is the average temperature increase of the LiB module.

$$\Delta T = \max(T_{i,ribs}) - \min(T_{i,ribs}) \quad (6)$$

where $\max(T_{i,ribs})$ maximum and $\min(T_{i,ribs})$ minimum temperature rise among all LiB cells in the module.

Experimental Study. The experimental setup used in this study is shown in Figs. 2(a) and 2(b). The test section, constructed of acrylic plastic, is designed for the 2S2P LiB module. This section is a rectangular box measuring 90 mm × 65 mm × 65 mm and 10 mm in thickness. A battery spacer (holder), made of acrylonitrile butadiene styrene, has dimensions of 4 mm (thickness), 45 mm (width), and 45 mm (depth) was used, creating a cell spacing of 4 mm between the LiB cells in the module. In addition, two circular pipes with a 6 mm inner diameter are connected to the test section to function as coolant inlets and outlets. The forced oil flow within the battery module is driven by a peristaltic pump. The test section is filled with mineral oil (Electrol IS335 Type-II), Table 2 has detailed thermophysical properties of various immersion oils. The immersion fluid exiting the battery module is collected at a high temperature in a reservoir, while an aluminum 12 W radiator system disperses heat from the incoming immersion fluid.

In the present study, fresh NCA ($\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$) 18650 (Panasonic) LiB cells are used for the experiments; the detailed parameters are shown in the previous work of the author [39].

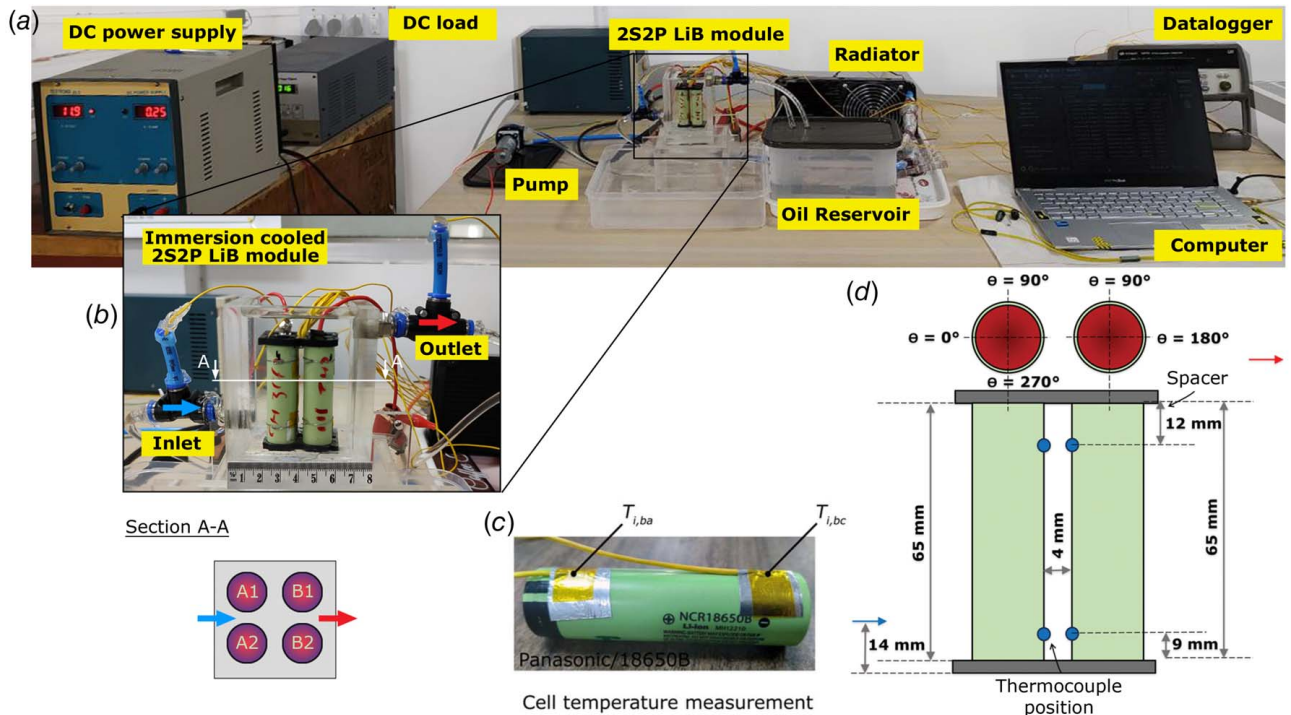


Fig. 2 Experimental setup and instruments used in the present study

Table 3 Specification of the LiB battery module

Module parameters (units)	Value
Battery arrangement	2P2S, aligned
Capacity (Ah)	6.5
Capacity (Wh)	46.8
Nominal voltage (V)	7.2
Lower cutoff voltage (V)	5
Upper cutoff voltage (V)	8.4

The batteries were fresh and preconditioned using the battery cyclers (CADEX C8000) (voltage precision 0.1% and current 0.25% in FS (full scale)) between the upper (4.2 V) and lower (2.5 V) cutoff voltages for five cycles according to Indian standards (IS 17855:2022) [40] for preconditioning of LiB. The preconditioning process reduces the impact of the formation of the solid electrolyte interface (SEI) on the thermal performance of the lithium ion battery. The battery module with 46.8 Wh (6.5 Ah, 7.2 V) capacity was used and consisted of four LiB cells, which were electrically connected in a 2S2P configuration in an aligned arrangement. Table 3 displays the specifications of the LiB module used in this investigation. Nickel strips 0.3 mm thick and 8 mm wide were spot welded to create series and parallel connections of LiB cells. In addition, the copper wire at the positive and negative terminals of the battery module connects the module to the DC power source and the DC electronic load. Table 3 gives the specifications of the LiB module used in this study.

The module was charged using a DC power supply (PSD3210, DC voltage 0–32 V, current 0–10 A) and a DC electronic load (KP184, 400 W) was used for discharging. The battery module was charged in this investigation using a multistage constant current charging methodology [41]. Throughout the charging procedure, the ambient temperature was monitored to ensure that the value was at $26 \pm 2^\circ\text{C}$ to ensure the same battery capacity for each cycle. Figure 3(a) shows the characteristics of the LiB module charging cycle. For module charging, the lower cutoff current was set at 0.65 A and the upper cutoff voltage limit was set at 8.4 V. K-type thermocouples were used for all temperature readings and calibrated using a Fluke-1586A temperature sensor calibrator in a range of 0–125 °C. The highest possible error in temperature measurement was $\pm 0.35^\circ\text{C}$. Each LiB anode and cathode in the module had their surface temperature measured; the average of these readings served as the representative surface temperature. A data acquisition unit consisting of a data logger (Keysight-

DAQ973A), multiplexers (Keysight-DAQM901A), and a laptop computer was used for data recording. During the discharging cycle, the current was kept constant, while the module voltage varied due to the IR drop, activation, ohmic, and concentration overpotentials. This IR drop caused the discharge cycle to complete before the ideal completion time ($t = 3600$ s), as shown in Fig. 3(b). A rest period of 2 h was provided between the charging and discharging cycles to allow for stable Li-ion intercalation or deintercalation. Validation experiments were carried out at a LiB cell spacing of 4 mm, with an immersion fluid flowrate of 0.003 kg/s, at an ambient temperature of 27°C and a discharge rate of 1C. For analysis, average values from three measurements were used.

Numerical Study

Computational Domain. The geometry and dimensions of the 2S2P test section used for the validation of the numerical model in the present investigation are shown in Fig. 4(a). A test section of $65\text{ mm} \times 65\text{ mm} \times 90\text{ mm}$ is used. The transverse and longitudinal spacing between LiB cells (center-to-center distance) was fixed at 22 mm, and the cell-to-wall spacing was 10 mm. Due to the adiabatic boundary, only the fluid domain and batteries are simulated in the numerical model, whereas the acrylic sheet is ignored. Furthermore, Fig. 4(b) shows the domain and dimensions of the scaled version of the battery module from 2S2P to 4S4P. The 4S4P model has dimensions of 110 mm in length, 110 mm in width, and a height of 90 mm.

Governing Equations, Boundary Conditions, and Assumptions. The three-dimensional numerical study of the 4S4P LiB module was performed using COMSOL MULTIPHYSICS. A steady and incompressible flow of immersion fluid is considered to simulate the fluid flow through the aligned arrangement of 18650 cells in the test section. The governing equations for the conservation of mass and momentum are given in Eqs. (7) and (8), respectively, [24]; these equations are solved by the finite element method.

$$\nabla \cdot u = 0 \quad (7)$$

$$\rho(u \cdot \nabla)u = -\nabla p + \mu \nabla^2 u \quad (8)$$

where u is the velocity of fluid flow, ρ is the fluid density, μ is the fluid dynamic viscosity, and p is the pressure.

The mass flowrates considered in the present study were in the range of 0.003 kg/s–0.01 kg/s, and the laminar flow was modeled,

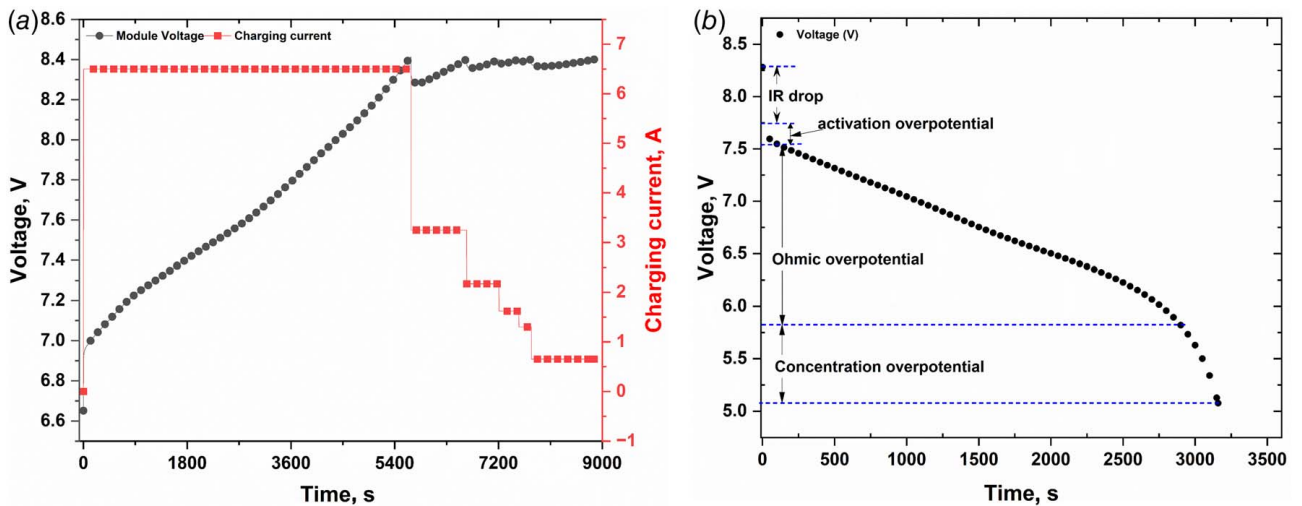


Fig. 3 Voltage characteristics of LiB module during (a) charging and (b) discharging for the experiments used for numerical model validation

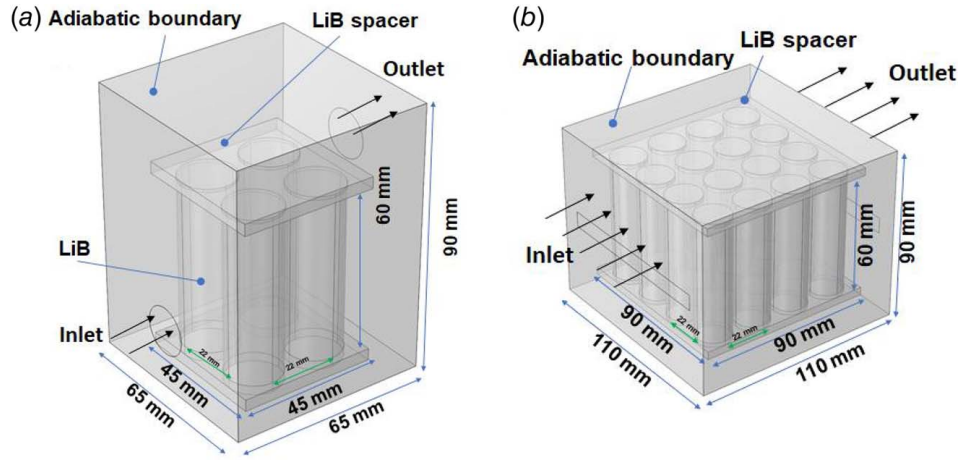


Fig. 4 Model geometry: (a) 2S2P module and (b) 4S4P module

and the Reynold number is calculated based on Eq. (9):

$$Re = \frac{\rho V D}{\mu} \quad (9)$$

where V is the velocity of fluid flow between the cells, ρ is the density of the fluid, μ is the dynamic viscosity of the fluid, and D is the diameter of the LiB battery cells. Reynolds number for mineral oil at fluid flowrates of 0.003 kg/s, 0.008 kg/s, and 0.01 kg/s, calculated as 12.73, 33.95, and 42.44, respectively. At the inlet boundary of the test section, a constant mass flowrate was specified and a pressure outlet boundary was assigned. A no-slip condition was assumed at the wall–fluid interfaces. The heat loss through the casing (acrylic) of the test section was neglected, as the boundaries are considered adiabatic. Figure 4(a) shows the boundary conditions of the inlet, outlet, and side wall (adiabatic). The thermophysical properties of immersion fluid are considered constant and were defined for the average inlet and outlet temperatures. A nonisothermal multiphysics node was subsequently utilized to couple the fluid flow solution with the heat transfer models for the battery discharge cycle.

The detailed layered structure of a LiB cell has a negligible impact on its thermal behavior, allowing a simplified approach when diffusion predominantly controls charging and discharging on electrodes [42,43]. This simplification is generally valid in a lumped battery model in which the state of charge (SOC) is treated as a dependent variable [44]. The voltage estimation in this model accounts for losses due to the charge, ohmic, and activation overpotential, with temperature-dependent properties derived using the Arrhenius equation [45]. The thermal performance of this lumped model aligns closely with that of a more detailed layered electrochemical model at discharge rates up to 2C [46]. In this study, we used a galvanostatic mode to set the load current [42], as previous studies indicate that a lumped model reasonably represents cylindrical LiBs due to their small mass and moderate thermal conductivity [47]. To capture the heat generation in a single-cell battery alongside heat transfer in solids, we used

electrochemical coupling, applying certain assumptions for LiB cell modeling.

- (1) The materials of each layer of the anode and cathode of the battery have constant physical properties except for the thermal conductivity of the LiB. The thermophysical properties of LiB are shown in Table 4.
- (2) Heat generation within the cell is considered uniform.
- (3) The internal heat transfer inside the LiB is conduction dominant, ignoring convection and radiative heat transfer.

The conservation of energy is solved using Eq. (10):

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q - q_{\text{conv}} \quad (10)$$

where q_{conv} is given in Eq. (11) is the heat convection per unit volume through the LiB surface.

$$q_{\text{conv}} = \frac{4h}{d} (T - T_{\text{DF}}) \quad (11)$$

where q is the volumetric heat generation term given as (Q_{gen}/V) [49], and Q_{gen} is presented in Eq. (12):

$$Q_{\text{gen}} = \left(\eta_{\text{IR}} + \eta_{\text{act}} + T \frac{\partial E_{\text{OCV}}(\text{SOC}_{\text{X=1}}, T)}{\partial T} \right) I_{\text{cell}} + Q_{\text{mix}} \quad (12)$$

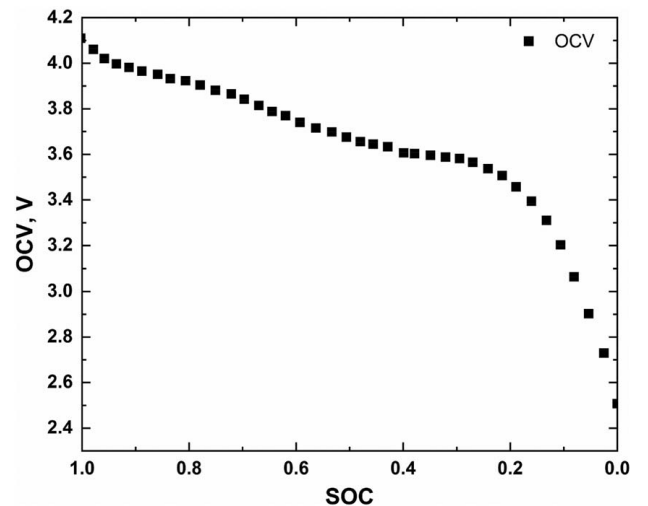


Fig. 5 Inputs for the lumped battery cell OCV–SOC mapping

Table 4 Thermophysical properties of LiB used in the present study [48]

Properties	Unit	LiB
Density	kg/m ³	2993
Specific heat capacity	kJ/kg K	834
Thermal conductivity, radial (cross-plane)	W/m K	1.1
Thermal conductivity, axial (in-plane)	W/m K	3.14

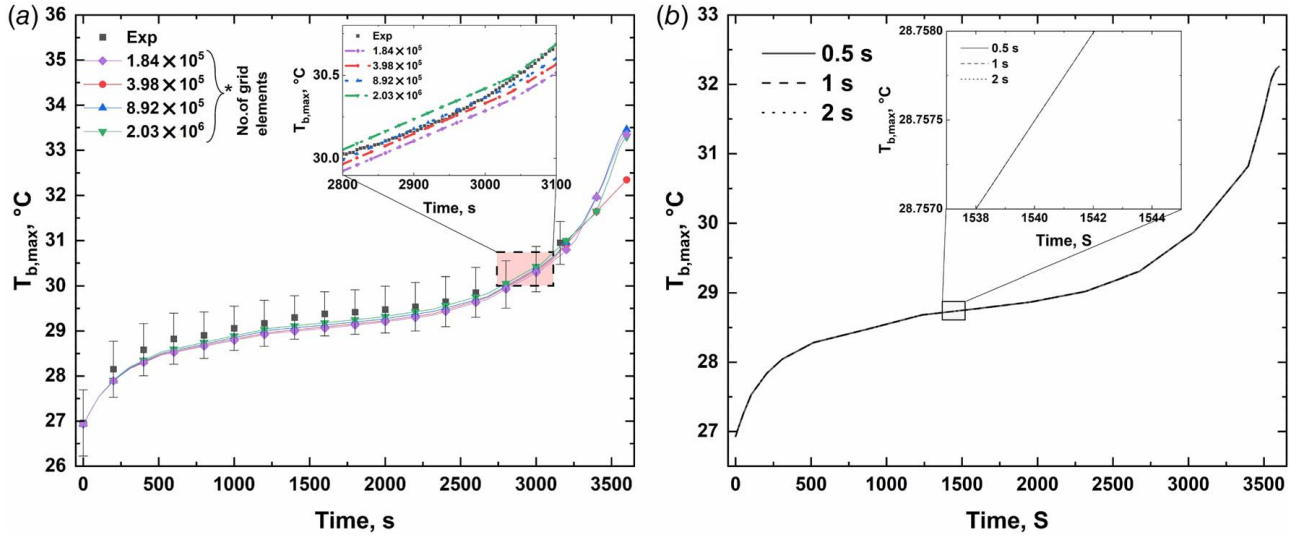


Fig. 6 Plots for (a) numerical model validation and grid independence study against in-house experimental results and (b) time-step independence study

The term Q_{mix} in Eq. (12) is given by

$$Q_{\text{mix}} = \frac{3Q_{\text{cell},0}}{\tau} \int_0^1 \frac{\partial E_{\text{OCV, therm}}}{\partial \text{SOC}} \frac{\partial \text{SOC}}{\partial X} \frac{\partial \text{SOC}}{\partial X} X^2 dX \quad (13)$$

where the thermoneutral voltage ($E_{\text{OCV, therm}}$) is represented by Eq. (14) [49]:

$$E_{\text{OCV, therm}} = E_{\text{OCV, ref}}(\text{SOC}) - T_{\text{ref}} \frac{\partial E_{\text{OCV}}(\text{SOC})}{\partial T} \quad (14)$$

Figure 5 displays the OCV–SOC data utilized for the lumped battery cell modeling. The Coulomb counting method and the pulse current test were used to carry out the OCV–SOC mapping. The present study assumed that the entropy coefficient ($\partial E_{\text{OCV}}/\partial T$) was a model-fitting parameter [49–51].

Equation (15) shows the LiB terminal voltage, SOC, and temperature-dependent OCV, and the various voltage losses during the discharge cycle.

$$E_{\text{cell}} = E_{\text{OCV}}(\text{SOC}, T) - (\eta_{\text{IR}} + \eta_{\text{act}} + \eta_{\text{conc}}) \quad (15)$$

The SOC and temperature dependency of E_{OCV} are shown in Eq. (16):

$$E_{\text{OCV}}(\text{SOC}, T) = E_{\text{OCV, ref}}(\text{SOC}) + (T - T_{\text{ref}}) \frac{\partial E_{\text{OCV}}(\text{SOC})}{\partial T} \quad (16)$$

In Eq. (15), η_{conc} is calculated using particle diffusion. Hence, the average value of SOC was considered for the loss estimation. The voltage losses from Joule heating in the electrodes are given in Eq. (17).

$$\eta_{\text{IR}} = \eta_{\text{IR, IC}} \frac{I_{\text{cell}}}{I_{\text{IC}}} \quad (17)$$

Table 5 Grid independence test results

No of grid elements	$T_{b, \text{avg}}, ^\circ\text{C}$		Error (%)
	Simulation	Experiment	
1.83×10^5	29.67	29.45	0.74
3.97×10^5	29.66		0.71
8.92×10^5	29.75		1.01
2.03×10^6	29.80		1.18

where the applied current (I_{cell}) is given by $Q_{\text{cell},0}/3600$, $\eta_{\text{IR, IC}}$ is ohmic overpotential for IC current, I_{IC} is IC current for battery, and the lumped voltage loss associated with the η_{act} on the electrode surfaces is considered as shown in Eq. (18) [42].

$$\eta_{\text{act}} = \frac{2RT}{F} a \sinh\left(\frac{I_{\text{cell}}}{2J_0 I_{\text{IC}}}\right) \quad (18)$$

Fick's law was used to describe the diffusion process due to the concentration gradient and Fick's diffusion equation was used to solve the dimensionless variable SOC expressed in Eq. (19) [42].

$$\tau \frac{\partial \text{SOC}}{\partial t} = -\nabla \cdot (-\nabla \text{SOC}) \quad (19)$$

The SOC gradient was calculated in the spherical coordinates due to the spherical particle consideration of the lumped LiB cell, and the boundary conditions at the center ($x=0$) and surface ($x=1$) of the particle are given in Eqs. (20) and (21), respectively.

$$\nabla \text{SOC}|_{x=0} = 0 \quad (20)$$

$$\nabla \text{SOC}|_{x=1} = \frac{\tau I_{\text{cell}}}{3Q_{\text{cell},0}} \quad (21)$$

The voltage losses due to the concentration difference of the spherical particles for the lumped battery are given by Eq. (22) [45].

$$\eta_{\text{conc}} = E_{\text{OCV}}(\text{SOC}_{x=1}, T) - E_{\text{OCV}}(\overline{\text{SOC}}, T) \quad (22)$$

Grid and Time-Step Independence Study. To determine the optimal number of mesh elements for an accurate estimate of the results, a grid independence test was performed using varying mesh sizes. A tetrahedral mesh was applied to construct the domain geometry, calibrated specifically for the modeling physics. Figure 6(a) displays the maximum temperature ($T_{b, \text{max}}$) of the module used in the grid independence validation. The study explored grid elements ranging from 1.84×10^5 to 2.03×10^6 , with Table 5 summarizing the results. The mesh elements numbered 8.92×10^5 yielded the results closest to the experimental data, showing an average error of 1.01%. This mesh size was therefore selected for further parametric analysis. The selected mesh was also used in a time-step independence study conducted at intervals of 0.5, 1, and 2 s. The results confirmed that the study was independent of the time-steps, as depicted in Fig. 6(b).

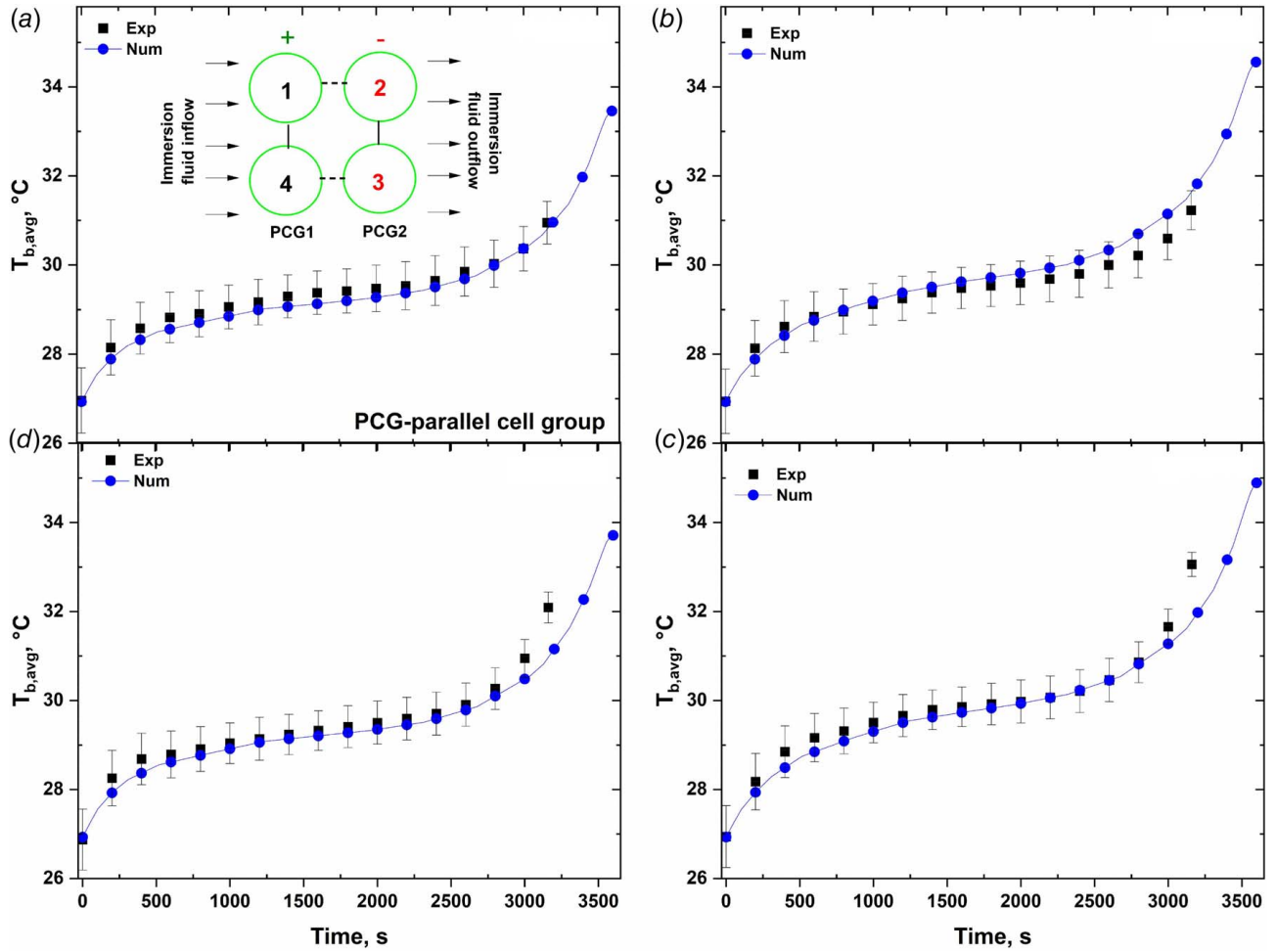


Fig. 7 Numerical model validation for LiB: (a) cell 1, (b) cell 2, (c) cell 3, and (d) cell 4, $T_{b,max}$ plots

Consequently, a time-step of 3 s was chosen to align with the data collection frequency in in-house experiments.

Model Validation. The numerical model was validated using the surface temperature of the individual LiB in the battery module against in-house experiments conducted at a 1C discharge rate. Figures 7(a)–7(d) compare the experimental and numerical result for the $T_{b,avg}$ for LiB in the battery module from LiB cell 1 to LiB cell 4, respectively. LiB cell 2 in Fig. 7(b) and LiB cell 3 in Fig. 7(c) show slightly higher temperatures at the end of the discharge cycle compared to LiB cell 1 and cell 4 shown in Figs. 7(a) and 7(d), respectively. The higher temperature for PCG 2 (LiB cells 2 and 3) can be explained by the direction of immersion fluid flow from PCG 1 to PCG 2 as shown in Fig. 7(a). The immersion fluid moving from the inlet to the outlet becomes hotter as a result of heat absorbed from LiB cells. Experiments revealed that the time required to discharge the battery was less than ideal ($t = 3600$ s) for simulations. The early termination of the discharge cycle can be attributed to the IR drop across the LiB terminals because of the resistance of the battery module discharging terminals. The higher the discharge rate, the more significant the IR drop caused by the high discharge current. Simulations were conducted with respect to the ideal discharge time of the respective C-rate. The difference between the experimental and simulated values of $T_{b,avg}$ was less than 3% at all times, except at the end of the discharge, where it reached 5%. Hence, the lumped battery parameter model fits well with the experiment results. The validated model was used for subsequent simulations and analyses.

Results and Discussion

The thermal characteristics of the LiB module are mainly influenced by the heat generated by individual battery cells and the cooling conditions. This study examines the impact of the position of the inlet and outlet, thermophysical properties, and the mass flowrate of the immersion fluid on the thermal performance, evaluated through parameters such as $T_{b,max}$, $T_{avg, rise}$, and ΔT . The results are discussed in the following subsections.

The parallel arrangement of the cells determines the discharge current capacity of any battery module. The 1C discharge current for a single LiB cell used in this study was 3.25 A, while the equivalent 1C discharge current for the designed module was 6.5 A. The corresponding upper and lower cutoff voltages were 8.4 V and 5.0 V, respectively. Heat generation in the battery module depends mainly on the current drawn, increasing quadratically as the current increases. Due to the ohmic resistance of the discharging terminals and battery cells, the module's terminal voltage drops significantly at the beginning of the discharge cycle and then decreases linearly during discharge. As shown in Fig. 3(b), the voltage sharply declines at the end of the cycle due to a rapid increase in overpotential resistance, driven by a higher concentration of lithium ions in the cathode [52]. Throughout the discharging cycle, the temperature rise remains relatively constant, but in the end, it becomes nonlinear due to a marked increase in overpotential and a high entropy coefficient, as shown in Fig. 3(b). Because the current is constant at a given C rate, irreversible heat generation remains nearly steady during discharge, reflecting the rate of local electrochemical reactions in LiBs.

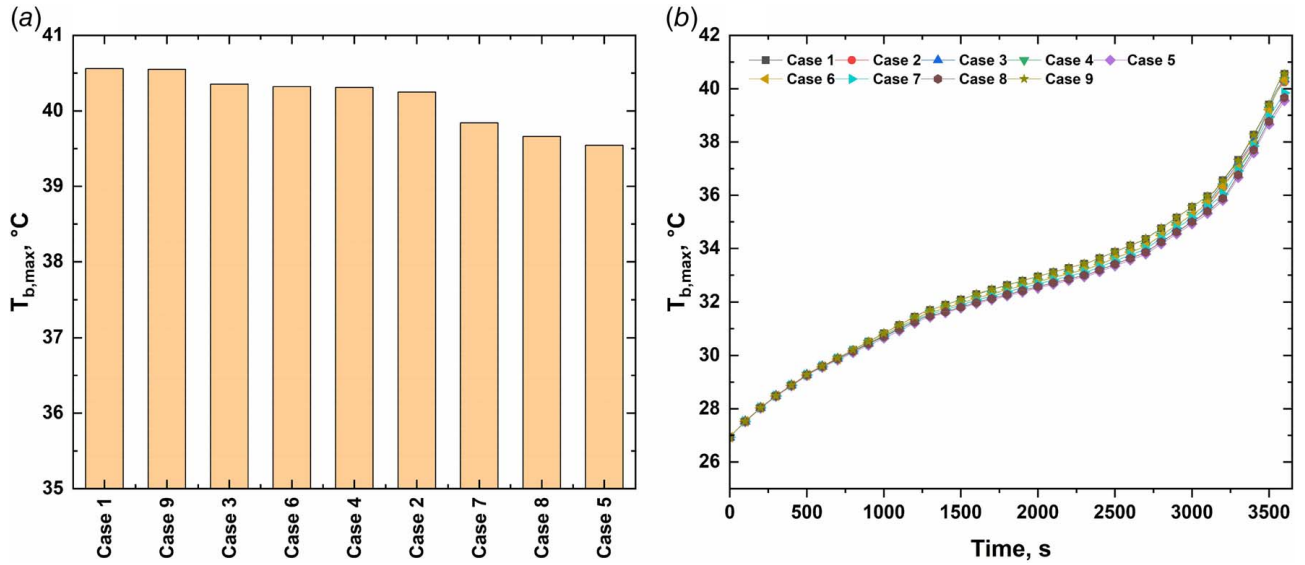


Fig. 8 Effect of inlet and outlet positions on the $T_{b,max}$: (a) end of the discharge cycle and (b) instantaneous

Effect of Position of Inlet and Outlet. The inflow and outflow positions of immersion fluids should be strategically placed to ensure adequate heat transfer from the cells to the immersion cooling fluid with a minimum pressure drop. Optimal positioning of the inlet and outlet facilitates homogeneous cooling, helping to prevent localized hot-spots or temperature differences between the LiB cells. Hence, to investigate the effect of the inlet and outlet positions on the thermal performance of the battery module, nine cases with different combinations of the inlet and outlet positions are considered, as shown in Fig. 1(b).

Figure 8(a) shows the $T_{b,max}$ for all the cases considered; the highest $T_{b,max}$ of 40.56°C was observed for case 1 among all the cases investigated and the second highest $T_{b,max}$ of 40.55°C reported for case 9, as both cases have an inlet and outlet at the top or bottom positions. A reduction of approximately 0.3°C is observed in $T_{b,max}$ compared to cases 1 and 9 when the inlet position changes to mid or above the middle and the outlet at mid or below the mid position (cases 3 and 6). Furthermore, $T_{b,max}$ is reduced by approximately 0.28°C when the inlet is moved to the mid or above the mid position, and the outlet is also at the mid or above the mid

position, but at a height different from that of the inlet (cases 4 and 2). The highest $T_{b,max}$ is observed when the inlet positioned is at any location and the outlet is at the bottom position, except in case 1. In addition, a reduction trend in $T_{b,max}$ is observed when the outlet position is fixed at the mid or top position and the inlet is changed from top to bottom. The lowest $T_{b,max}$ of 39.54°C observed for case 5. A maximum decrease in $T_{b,max}$ of 1.0°C from 40.55°C to 39.54°C was observed for case 5 (both inlet and outlet in the mid position) compared to case 1 (both inlet and outlet in the top position). No clear trend was observed for the outlet position, but keeping the outlet in the middle or top position provided a low temperature. The reason is attributed to the more cooled fluid flow from the inlet toward the outlet without any significant contact with the LiB. Furthermore, Fig. 8(b) shows the instantaneous $T_{b,max}$ for the battery module for all the cases of inlet and outlet positions. It can be observed throughout the discharge cycle that the minimum temperature is observed for case 5.

It has been observed that the inlet should be placed in the mid or below mid position and the outlet should be placed mid or above the mid position for better thermal performance. The optimal positioning

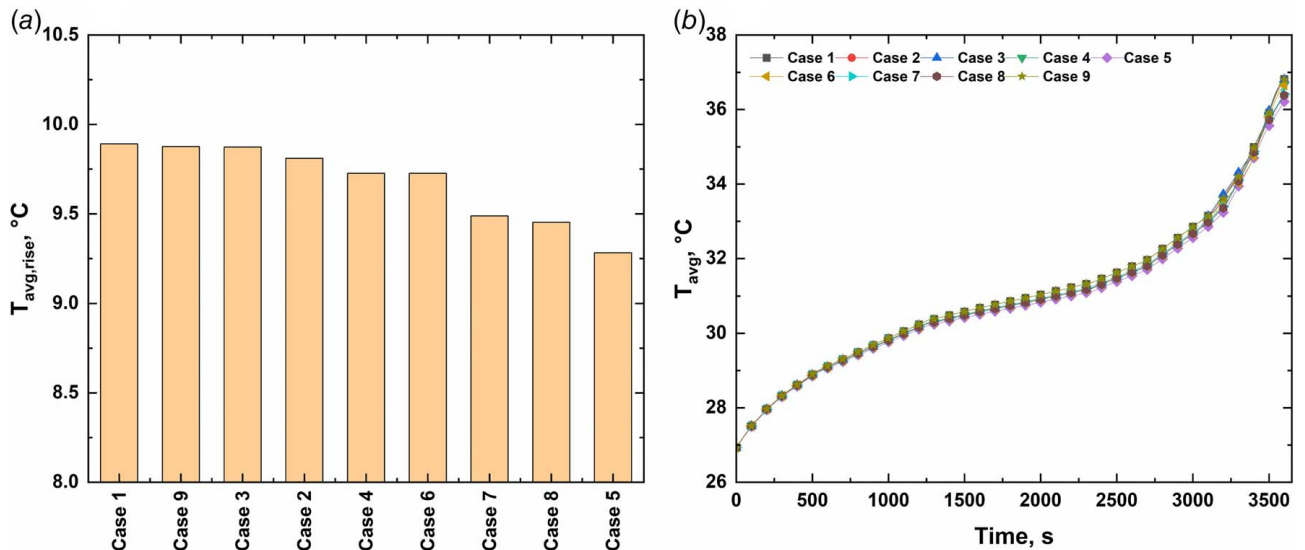


Fig. 9 Effect of inlet and outlet positions on the (a) $T_{avg,rise}$ and (b) instantaneous $T_{avg,rise}$

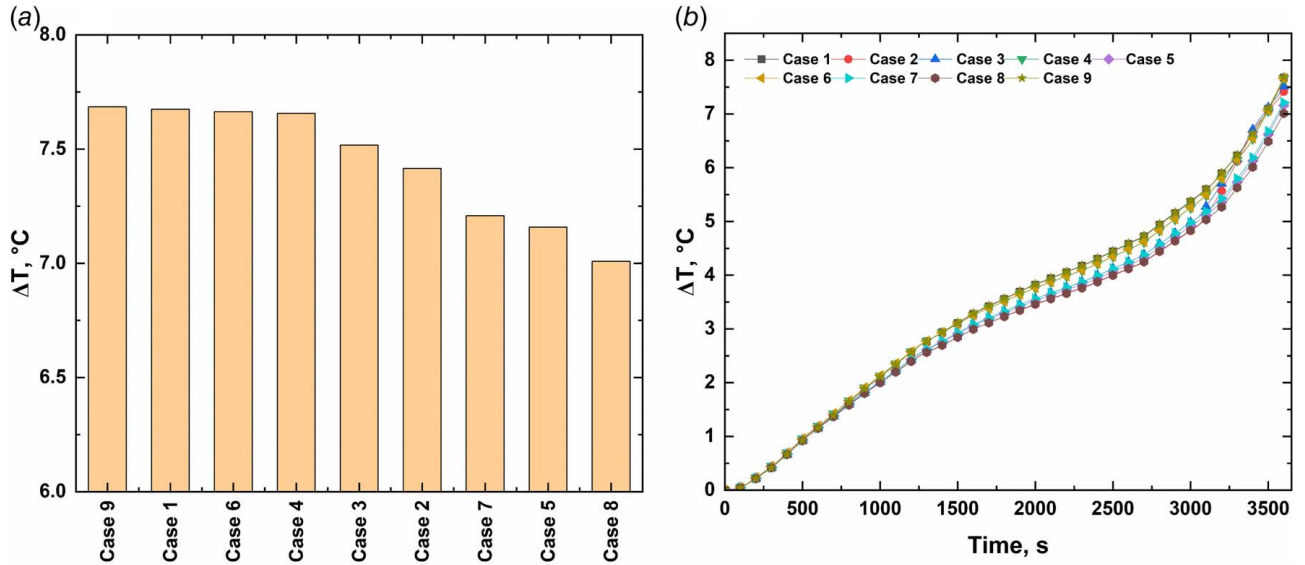


Fig. 10 Effect of inlet and outlet positions on the ΔT : (a) end of the discharge cycle and (b) instantaneous

of the inlet and outlet increases the convective heat transfer from the LiB cells to the immersion fluid. The flow of immersion fluid from the bottom to the top of the module also enhances natural convective heat transfer. The obstacle in the flow of the immersion fluid is also affected by the positioning of the inlet and outlet placement. Similarly, Figs. 9(a) and 9(b) show the $T_{\text{avg, rise}}$ and an instantaneous average temperature of the battery module, respectively. The $T_{\text{avg, rise}}$ of 9.89°C and 9.28°C observed for case 1 and case 5, respectively. A similar trend has been observed in the results for $T_{b, \text{max}}$ and $T_{\text{avg, rise}}$.

Figures 10(a) and 10(b) illustrate the temperature nonuniformity (ΔT) for the battery module, with Fig. 10(a) showing the maximum temperature nonuniformity and Fig. 10(b) displaying the instantaneous values. In all cases, in this study, temperature nonuniformity ranged from 7°C to 7.68°C . The highest nonuniformity was recorded for case 9 at 7.68°C , while the lowest, at 7°C , was observed for case 8. Furthermore, the second highest ΔT was observed in case 1, with the second lowest ΔT of 7°C occurring in case 5, closely aligning with the nonuniform temperature of

case 8. The maximum ΔT can be attributed to the nonuniform immersion fluid flow distribution.

A vital aspect of the BTMS is the drop in pressure of the cooling fluid, which influences the cooling power that the battery module must provide. Higher power is needed to move the fluids through the battery module at higher pressure drops. Figure 11 shows the pressure drop in the battery module for the various inlet and outlet positions. The maximum pressure drop is observed for the inlet and outlet placed diagonally opposite (cases 3 and 7). In these cases, the highest pressure drop can be attributed to the obstructions caused by the LiB cells as the longest fluid flow path due to diagonal positioning. Except for the mid position, the second largest pressure drop is recorded when the inflow and outflow positions are opposite walls at the same heights (case 1 and case 9). Due to the positioning of both the inlet and outlet near the LiB spacer, the pressure drop as a result of the LiB spacer also contributed significantly. A minimum pressure drop was observed in case 5 when both the inlet and the outlet were placed in the mid position. The low pressure drop is due to the low obstruction of LiB, a short path for immersion fluid flow. The highest pressure drop observed was reported for case 3 of 0.81 Pa and the lowest for case 5 of 0.72 Pa , respectively. Based on the discussion of $T_{b, \text{max}}$, ΔT , and pressure drop, In conclusion, positioning the inlet and outlet at the midpoint of the battery module yields the best thermal performance. Consequently, case 5 is identified as optimal among all cases considered in this study, as shown in Fig. 1(b). In addition, the impact of different immersion fluids and fluid flowrates for case 5 has been analyzed and discussed.

The observed temperature fluctuations are attributed to the uniformity, or lack thereof, in the distribution of the immersion fluid within the battery module. Previous studies, such as those by Siva et al. [53], have investigated the impact of the coolant's inlet and outlet configuration in heat sinks on thermal management. A uniform distribution of the immersion fluid ensures consistent cooling throughout the module, leading to a lower average temperature. This correlation is clearly demonstrated in Fig. 10, which shows a significant reduction in temperature variations. Furthermore, the pressure drop across the system, as illustrated in Fig. 11, further supports the flow characteristics and cooling efficiency. At higher flowrates, the thermal boundary layer on the surface becomes thinner, which enhances heat transfer up to a point. It is also observed that for AmpCool, with a mass flowrate of 0.008 kg/s and 0.01 kg/s , a similar thermal performance was observed. This performance can be attributed to a certain flowrate, the reduction in the thickness of the boundary layer reaches a limit,

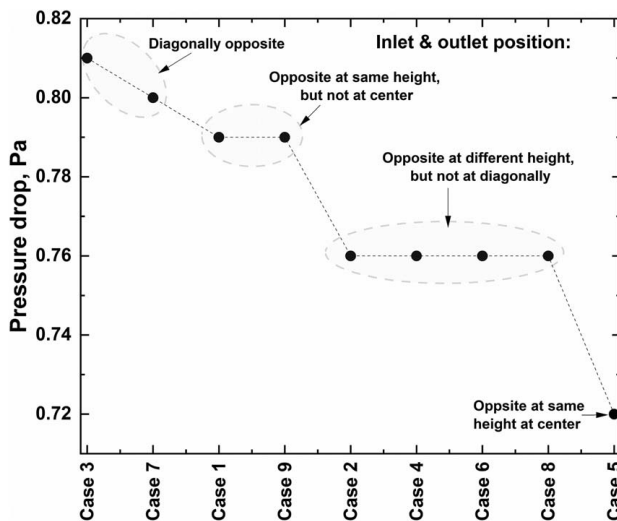


Fig. 11 Pressure drop for different cases for inlet and outlet positions

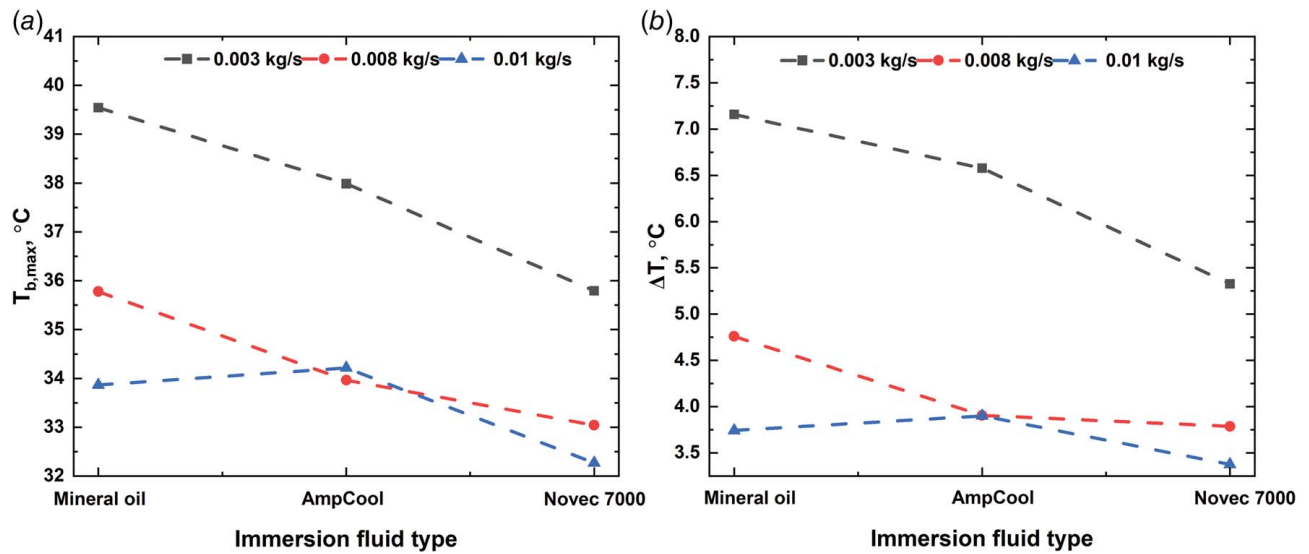


Fig. 12 Effect of immersion fluids and flowrate on the (a) $T_{b,max}$ and (b) instantaneous module average temperature

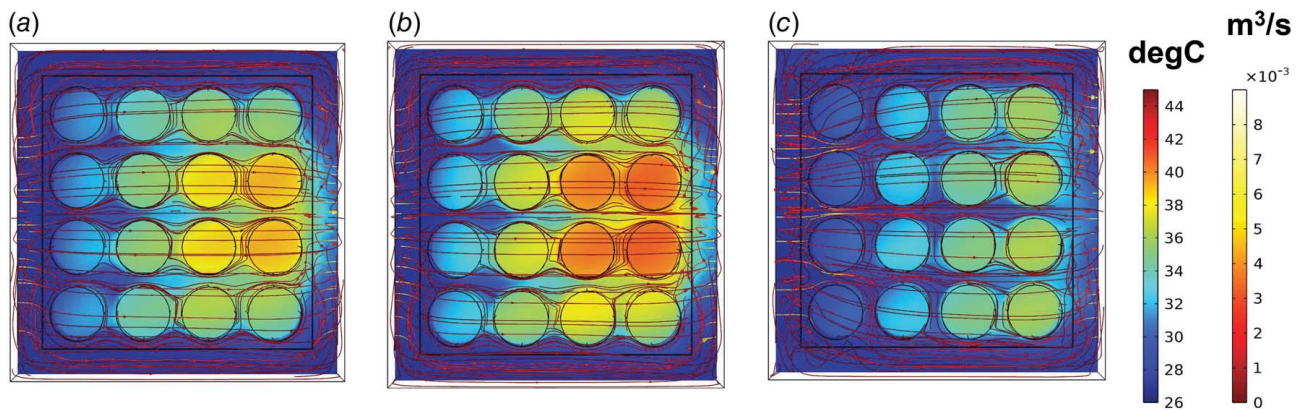


Fig. 13 Contour and streamline plots for different immersion fluids: (a) Ampcool, (b) Mineral oil, and (c) Novec 7000

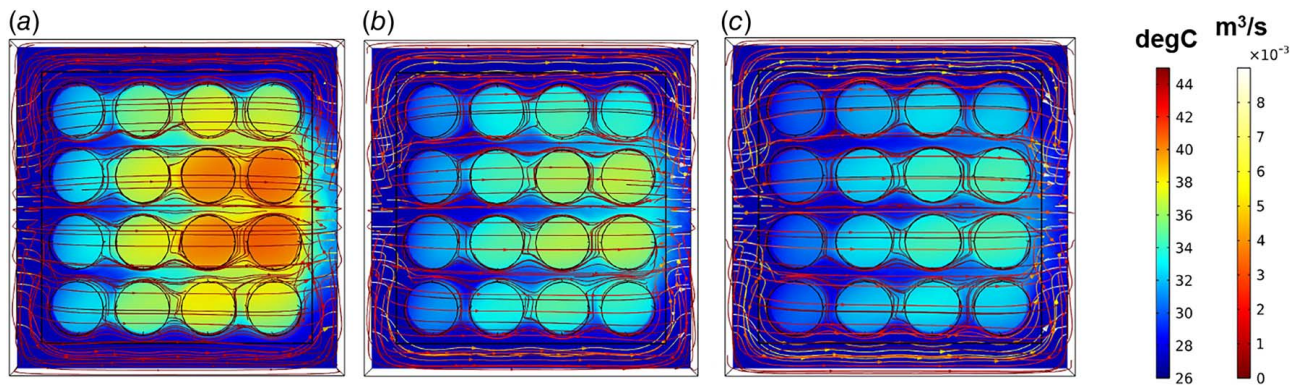


Fig. 14 Contour and streamline plots for different mass flowrates

and further increases in flow do not significantly enhance heat transfer.

Effect of Immersion Fluids and Flowrate. A review of the literature indicates that various immersion fluids are used in both research and commercial cooling applications [15]. The thermophysical properties of these immersion fluids significantly influence the thermal performance of battery modules [14]. This study examines

three distinct immersion fluids: one mineral oil (transformer oil) and two engineered fluids (AmpCool and Novec 7000). The thermophysical properties of these fluids are provided in Table 2.

The impact of immersion fluid flowrate on thermal performance was analyzed at three mass flowrates: 0.003 kg/s, 0.008 kg/s, and 0.01 kg/s. Figure 12(a) presents the $T_{b,max}$ values for different immersion fluids and flowrates. When transformer oil (mineral oil) is used as the cooling medium, it shows less capacity to limit temperature rise compared to engineered fluids. For transformer

oil, the highest $T_{b,max}$ of 39.54 °C was observed at a mass flowrate of 0.003 kg/s, while the lowest of 33.86 °C was observed at 0.01 kg/s.

A temperature decrease of 1.56 °C and 3.75 °C at a mass flowrate of 0.003 kg/s was observed for AmpCool and Novec 7000, respectively, compared to mineral oil, as shown in the contours in Fig. 13. At a flowrate of 0.01 kg/s, $T_{b,max}$ was reduced by 3.77 °C and 5.68 °C for flowrates of 0.003 kg/s and 0.008 kg/s, respectively, indicating that the maximum temperature in the battery module is significantly influenced by forced convective heat transfer. Figure 12(b) displays the nonuniform temperature (ΔT) in the battery module for transformer oil, AmpCool, and Novec 7000 at 0.003 kg/s, 0.008 kg/s, and 0.01 kg/s, respectively. The highest ΔT of 7.15 °C was observed at a flowrate of 0.003 kg/s for transformer oil due to its lower thermal conductivity.

When the flowrate of transformer oil increased from 0.003 kg/s to 0.01 kg/s, a decrease in ΔT was observed by 3.41 °C, as confirmed by the streamline plots in Fig. 14. At a flowrate of 0.003 kg/s, ΔT values of 7.15 °C, 6.41 °C, and 5.49 °C were recorded for transformer oil, AmpCool, and Novec 7000, respectively. Based on these findings, Novec 7000 demonstrates superior thermal performance compared to the other immersion cooling fluids studied here.

Conclusions

This study conducted a numerical and experimental investigation of the thermal performance of a 16-cylindrical Li-ion battery module with an aligned configuration under immersion cooling. Using $T_{avg,rise}$, ΔT , and T_{max} , the thermal performance was analyzed. The following is a summary of the key findings of the study.

- (1) As the current remains constant throughout the discharging cycle for the C rate, the irreversible heat generation is nearly constant during discharge.
- (2) The highest $T_{b,max}$ of 40.56 °C was observed for case 1 and the lowest of 39.54 °C for case 5. Positioning the inlet at or below the midpoint and the outlet at or above the midpoint was found to yield improved thermal performance.
- (3) The highest pressure drop observed was reported for case 3 of 0.81 Pa and the lowest for case 5 of 0.72 Pa, respectively. The inlet and outlet should be located at the midpoint of the battery module.
- (4) The highest $T_{b,max}$ of 39.54 °C and the lowest of 33.86 °C were observed at a mass flowrate of 0.003 kg/s and 0.10 kg/s, respectively, for transformer oil.

This study provides novel insights on where to position the immersion fluid inlet and outlet in an immersion-cooled battery module. Future scope of this study is to investigate active cooling techniques based on current thermal and electrical loading circumstances, such as variable flowrates or dynamic inlet and outlet alterations. To further improve cooling effectiveness, it is needed to explore into using different immersion fluids with different thermophysical characteristics, such as lower viscosity or higher thermal conductivity.

Acknowledgment

The authors sincerely thank the Science and Engineering Research Board of the Department of Science and Technology of India for the start-up research grant (SRG/2020/001171) awarded to AP, which supported experimental and computational studies at MNIT Jaipur. Furthermore, D. K. S. and H. L. wish to express their gratitude to the Ministry of Education, Government of India, for providing the Ph.D. and M.Tech research scholarships, respectively.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

d	= intercell spacing
h	= heat transfer coefficient, W/m ² /K
k	= thermal conductivity, W/m/k
n	= number of cells in module
u	= airflow rate, m/s
D	= diameter of the battery cell, m
E	= voltage, V
F	= Faraday's constant (96,486 C/mol)
I	= current, A
L	= height of battery cell, m
P	= pressure, N/m ²
Q	= heat generation, J
R	= universal gas constant (8.314 J/mol/K)
T	= battery cell temperature, °C
V	= LiB cell volume
u_r	= random uncertainties
u_s	= systematic uncertainties
A_s	= surface area of cells, m ²
C_p	= specific heat, J/kg/K
J_0	= dimensionless exchange current
$Q_{cell,0}$	= cell capacity at 100% SOC
S_L	= longitudinal pitch of battery cells, m
T_{amb}	= ambient temperature, °C
$T_{avg,rise}$	= average temperature rise of battery module, °C
$T_{b,safe}$	= safe temperature limit for individual cells, °C
$T_{f,in}$	= inlet temperature of air, °C
$T_{i,ib}$	= initial temperature of the i th battery cell, °C
$T_{i,iba}$	= initial anode temperature of the i th battery cell, °C
$T_{i,ibc}$	= initial cathode temperature of the i th battery cell, °C
$T_{i,fb}$	= final temperature of the i th battery cell, °C
$T_{i,fba}$	= final anode temperature of the i th battery cell, °C
$T_{i,fbc}$	= final cathode temperature of the i th battery cell, °C
T_{ref}	= reference temperature, °C
T_{riseb}	= temperature rise of the i th battery cell, °C
$T_{riseb,max}$	= maximum temperature rise of the i th battery cell, °C
$T_{riseb,min}$	= minimum temperature rise of the i th battery cell, °C
$\bar{T}_{cell}$	= average of surface temperature of cells, °C
$\bar{T}_f$	= volume average temperature of fluid, °C
$\bar{T}_{f,out}$	= average of outlet temperature of airflow, °C
Nu	= Nusselt number
Pr	= Prandtl number

Greek Symbols

ΔT	= temperature in battery module, °C
$\Delta T_{BMS,limit}$	= safe nonuniformity limit for battery module, °C
η_{IR}	= Ohmic overpotential for 1C-rate current, V
η	= overpotential, V
ρ	= air density, kg/m ³
τ	= diffusion time constant

Subscripts

1C	= 1C rate
act	= activation
con	= concentration
gen	= reactions
mix	= side reactions
ref	= value at reference condition
IR	= Ohmic
OCV	= open circuit voltage

Acronyms

BTMS = battery thermal management
 NCA = lithium nickel–cobalt–aluminum oxide
 NCA = solid electrolyte interface
 OCV = open circuit voltage
 SOC = state of charge

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