



Research Paper

Comparative investigation of different liquid-cooled battery thermal management systems (LC-BTMS) designs for battery module of electric vehicle

Ashutosh Sharma^{a,b}, Sheshadri Sreedhara^b, Mehdi Khatamifar^a, Wenxian Lin^{a,*}

^a College of Science and Engineering, James Cook University, Townsville, QLD, 4811, Australia

^b Mechanical Engineering Department, Indian Institute of Technology Bombay, Mumbai, Maharashtra 400076, India

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ABSTRACT

Efficient thermal management of lithium-ion batteries is crucial to ensuring the safety, reliability, and longevity of electric vehicles, particularly in hot climates. In this study, seven different liquid-cooled battery thermal management systems (LC-BTMS) designs for cylindrical lithium-ion battery (LIB) modules are comparatively investigated. The considered configurations include cold-plate-based, rigid-channel-based, flexible-channel-based, and block-based cooling concepts. A three-dimensional computational fluid dynamics (CFD) model is developed to analyse the thermo-hydraulic behavior of each design under 1C and 3C discharge conditions at an ambient temperature of 30 °C. The performance of the LC-BTMS designs is evaluated using four key indicators: maximum battery temperature (T_{max}), temperature non-uniformity (ΔT), pressure drop (ΔP), and HTF outlet temperature ($T_{HTF,outlet}$). The results indicate that the block-based design provides the best thermal performance, achieving the lowest T_{max} of 298.62 K at 1C and 304.25 K at 3C and the smallest ΔT of 2.08 K at 1C and 3.16 K at 3C due to enhanced heat spreading and effective convection. Flexible channel-based designs offer reasonable thermal control but impose higher hydraulic penalties, with ΔP reaching 173.71 Pa. To include practical considerations, a survey involving experts from industry and academia was conducted. The combined thermo-hydraulic and practical criteria are integrated using the VIKOR multi-criteria decision-making method, which identifies the flexible straight-channel design as the best overall compromise. The findings offer valuable guidance for selecting LC-BTMS designs for electric vehicles operating in hot climate environments.

1. Introduction

Global energy demand is increasing faster than in previous years, rising by 2.2% in 2024, which is significantly higher than the decade's average of 1.3%. This trend is primarily due to rapid population growth and improving living standards in developing regions [1]. At present, this demand is met mainly by fossil fuels, which are finite and cause significant environmental pollution. One of the major contributors to fossil fuel consumption and environmental degradation is the transportation sector. As a result, the pursuit of clean, sustainable transportation alternatives has attracted significant attention from researchers and entrepreneurs worldwide [2]. Electric vehicles (EVs) have emerged as a promising alternative to traditional internal combustion engine (ICE) vehicles. The battery is arguably the most critical component of an EV, as it directly affects both charging rate and driving

range [3]. Lithium-ion Batteries (LIB) are particularly favoured in EV applications due to their high energy density, storage capacity, and relatively low weight [4]. Despite their advantages, LIBs are constrained by a narrow optimal operating temperature range (15 °C to 40 °C). Exceeding these thermal limits can lead to a host of issues, including reduced capacity, thermal runaway, and in extreme cases, explosions [5]. Thus, developing an efficient Battery Thermal Management System (BTMS) has become a critical engineering challenge.

Various BTMS configurations have been explored to maintain batteries within the optimal temperature range. Active cooling systems that circulate heat transfer fluids (HTFs) offer fast, effective cooling, albeit at higher complexity and operational costs [6]. In contrast, passive systems are simpler and less expensive to operate but generally offer limited cooling capacity and thermal regulation [7]. Hybrid BTMSs can deliver improved cooling performance compared to either approach alone, but often suffer from increased design complexity and cost constraints [8].

* Corresponding author.

E-mail address: wenxian.lin@jcu.edu.au (W. Lin).

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Nomenclature

Cap	Capacity of battery (Ah)
C_p	Specific heat (J/kg.K)
dU_{OC}/dT	Thermal entropy coefficient of battery (V/K)
I	Current (A)
k	Thermal conductivity (W/m.K)
Q_{gen}	Total heat generated (W/m ³)
$\dot{Q}_{HTF}$	Flow rate of HTF (kg/s)
R_{int}	Internal resistance (Ω)
T	Temperature (K)
T_{max}	Maximum battery module temperature (K)
$T_{HTF, outlet}$	Outlet temperature of the heat transfer fluid (K)
ΔT	Temperature difference (K)
U	Terminal voltage (V)
U_{oc}	Open circuit voltage (V)
V_{bat}	Battery volume (m ³)
ρ	Density (kg/m ³)
μ	Viscosity (Pa.s)
u	Velocity component in the x direction
v	Velocity component in the y direction
w	Velocity component in the z direction
$\vec{V}$	Velocity vector
P	Pressure

Abbreviations

AC-BTMS Air Cooling Battery Thermal Management System

BTMS	Battery Thermal Management System
EV	Electric Vehicle
HTF	Heat Transfer Fluid
IC	Internal Combustion
LC-BTMS	Liquid Cooling Battery Thermal Management System
LCP	Liquid Cooling Plate
LIB	Lithium-Ion Battery
MCDM	Multi-Criteria Decision Making
PCM	Phase Change Material
SoC	State of Charge
SoD	State of Discharge
TCS	Thermal Conductive Structure
VIKOR	Vise Kriterijumska Optimizacija Kompromisno Resenje

Subscripts

amb	Ambient
HTF	Heat transfer fluid
bat	Battery
irr	Irreversible
max	Maximum
min	Minimum
nom	Nominal
r, bat	Radial direction in the battery
rev	Reversible
$t = 0$	Initial time
z, bat	Axial direction in the battery

Considering these factors, active BTMSs are currently the most widely adopted solution in EVs. Among active methods, liquid-cooled (LC) systems are preferred over air-cooled (AC) systems due to the superior heat transfer properties and fluid dynamics of liquids [9]. Fig. 1 illustrates that LC-BTMS designs can be classified into direct (immersion) and indirect types. In direct or immersion LC-BTMS designs, the LIB is in direct contact with the HTF. Although direct LC-BTMS designs offer

superior thermal performance, their high cost, temperature non-uniformity, and leakage risks are the main factors limiting their implementation in commercial EVs [10]. The other LC-BTMS configuration widely adopted in commercial EVs is the indirect LC-BTMS [11,12]. Indirect LC-BTMS designs can be further categorized into three main types: cooling-plate-based, channel-based, and block-based designs. This study exclusively investigates indirect LC-BTMS designs.

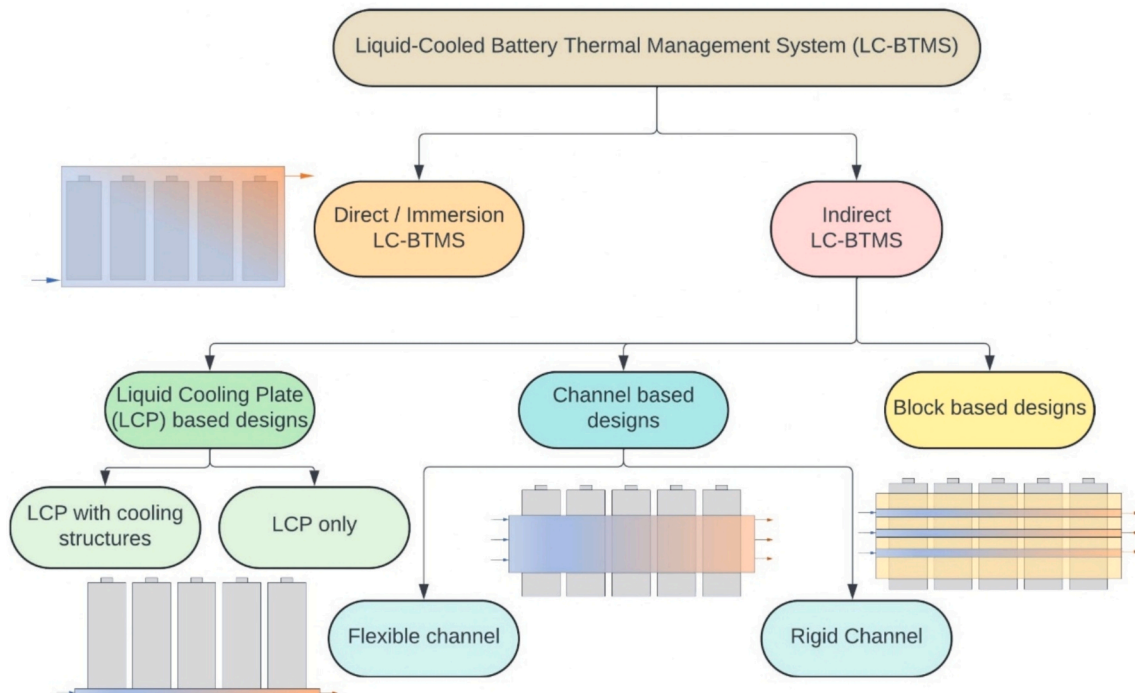


Fig. 1. Classification of different LC-BTMS designs.

Numerous studies have been reported on different indirect LC-BTMS designs. In LCP-based designs, either only LCP or LCP with other cooling structures have been studied. Huang et al. [13] investigated an LCP-only LC-BTMS design and found that the module temperature decreased sharply with increasing flow rate initially, but beyond a flow rate of 0.02 kg/s, little to no variation was observed. Another well-investigated design type in the LCP-based LC-BTMS design category is the LCP with different cooling structures. Zhao et al. [14] numerically investigated the LCP-based design with hollow HTF jackets around each LIB as a cooling structure. The system successfully maintained the battery module's temperature below 40 °C. Dong et al. [15] numerically analyzed an LC-BTMS using a cylindrical jacket with a helical cooling channel around the cells. They optimized the geometrical parameters of the BTMS design, achieving a maximum temperature (T_{max}) of 32.36 °C and a temperature difference (ΔT) of 6.98 °C. Similarly, Lai et al. [16] studied a lightweight LC-BTMS with LCP and thermal conductive structures (TCS) at a 5C discharge rate. The impact of HTF flow rate was investigated, and it was found that a flow rate above 1×10^{-4} kg/s keeps T_{max} below 40 °C.

Another widely studied category of LC-BTMS designs is channel-based configurations, which can be further classified into rigid and flexible channel-based systems. Wang et al. [17] studied a rigid channel-based LC-BTMS design both experimentally and numerically. The LC-BTMS maintained T_{max} and ΔT at 37.67 °C and 5.76 °C, respectively. Xie et al. [18] conducted a numerical study on a flexible channel-based LC-BTMS design, inspired by the battery pack of Tesla's Model S electric vehicle. The design effectively maintained the LIB temperature within

the optimal range. Another suitable LC-BTMS design is a block-based design in which a conductive metal block with bores is used for LIB placement [19–21]. These designs are highly effective in maintaining the LIB's T_{max} and ΔT within the optimum ranges.

The literature review indicates that LC-BTMS designs are generally effective in maintaining the temperature of EV battery packs within the desired range. A variety of LC-BTMS configurations have been explored; however, comparative investigations focusing on both performance metrics and practical considerations, such as manufacturing, maintenance, and safety, are largely absent from the literature. To address this gap, the primary objective of the present study is to conduct a comparative evaluation of various indirect LC-BTMS designs. A numerical investigation was carried out involving seven distinct designs, each representing a specific category within the broader indirect LC-BTMS classification. These designs were systematically developed and simulated under consistent boundary conditions to ensure a fair and reliable comparison. A validated numerical model was employed for all simulations. The comparative analysis primarily focused on key thermo-hydraulic performance indicators, i.e., T_{max} , ΔT , and pressure drop (ΔP). In addition, qualitative aspects – such as manufacturing complexity, ease of maintenance, and overall practicality – were assessed through expert consultations to provide a comprehensive evaluation of each design's applicability. An MCDM method was used to calculate performance indices and rank the different designs. The following sections outline the design selection process, the conceptual framework, the performance evaluation methodology, and the results and discussion.

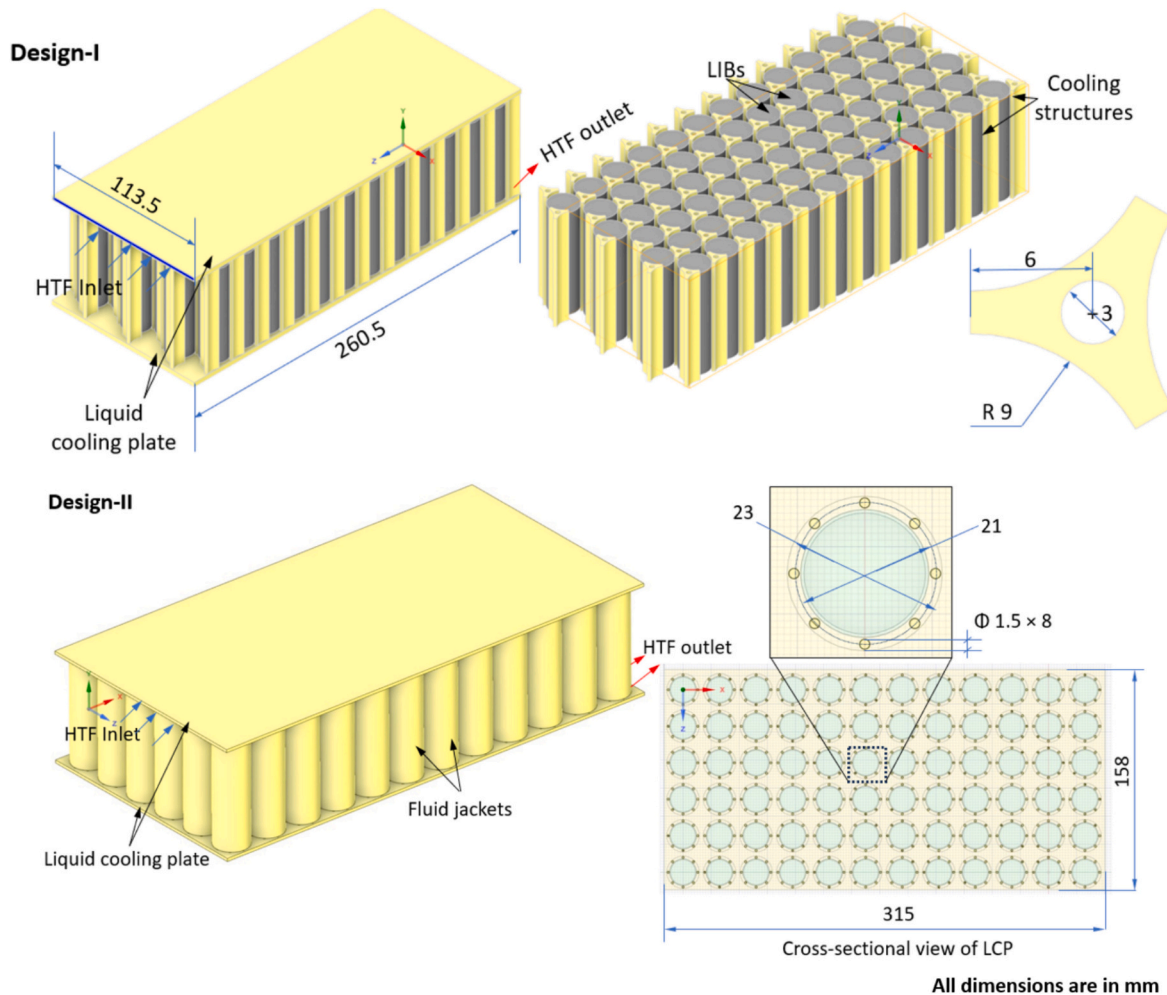


Fig. 2. Cooling plate-based LC-BTMS Design-I and Design-II.

2. LC-BTMS designs for comparison

The conceptualization of the various indirect LC-BTMS designs was carried out based on an extensive review of relevant literature. As reviewed above, the literature survey revealed that indirect LC-BTMS designs can be classified into three main categories: cooling plate-based, channel-based, and block-based (Fig. 1). For comparative analysis, a total of seven representative designs were selected – two from each of the cooling plate-based ([14,15]), rigid channel-based ([17,22]), and flexible channel-based categories ([18]), and one from the block-based category ([21]). Detailed schematic representations of the seven selected LC-BTMS configurations are shown in Figs. 2–5, illustrating the structural layout and cooling pathways for each design. These selections were made to ensure a comprehensive evaluation that captures the diversity of design approaches currently explored in the field.

To ensure a fair and consistent comparison, both the design and operational parameters were standardized across all configurations. The total number of battery cells in each system was fixed at 72 to maintain a consistent heat generation rate across all selected LC-BTMS designs. Similarly, the HTF flow rate, initial and inlet temperature were held constant for all simulations. The performance of each design was then evaluated using thermo-hydraulic metrics, including T_{max} , ΔT , and ΔP . Notably, the material for various solid structures in all the designs has

been selected as Aluminum to justify the comparison. Similarly, water has been used as the HTF. The thermophysical properties of Aluminum and water are given in Table 1.

3. Battery Heat Generation Model

The literature review reveals that a variety of battery heat generation models have been employed in the thermal analysis of LC-BTMS designs. Among these, the Bernardi heat generation model [23] is one of the most widely adopted in numerical studies due to its simplicity and effectiveness in capturing key thermal phenomena. According to the Bernardi model, the total heat generated (Q_{gen}) within a battery during discharging is the sum of two components: reversible (Q_{rev}) and irreversible heat generation (Q_{irr}). Mathematically [23],

$$Q_{gen} = Q_{irr} + Q_{rev} = \frac{I}{V_{bat.}} (U_{OC} - U) + \frac{I}{V_{bat.}} T \frac{dU_{OC}}{dT}$$

$$= \frac{I}{V_{bat.}} \left(IR_{int.} + T \frac{dU_{OC}}{dT} \right) \quad (1)$$

For numerical simulations using the Bernardi model, both $R_{int.}$ and dU_{OC}/dT are experimentally determined across different C-rates and states of charge (SoC). SoC itself is defined as a function of the battery's nominal capacity and the duration of charging or discharging.

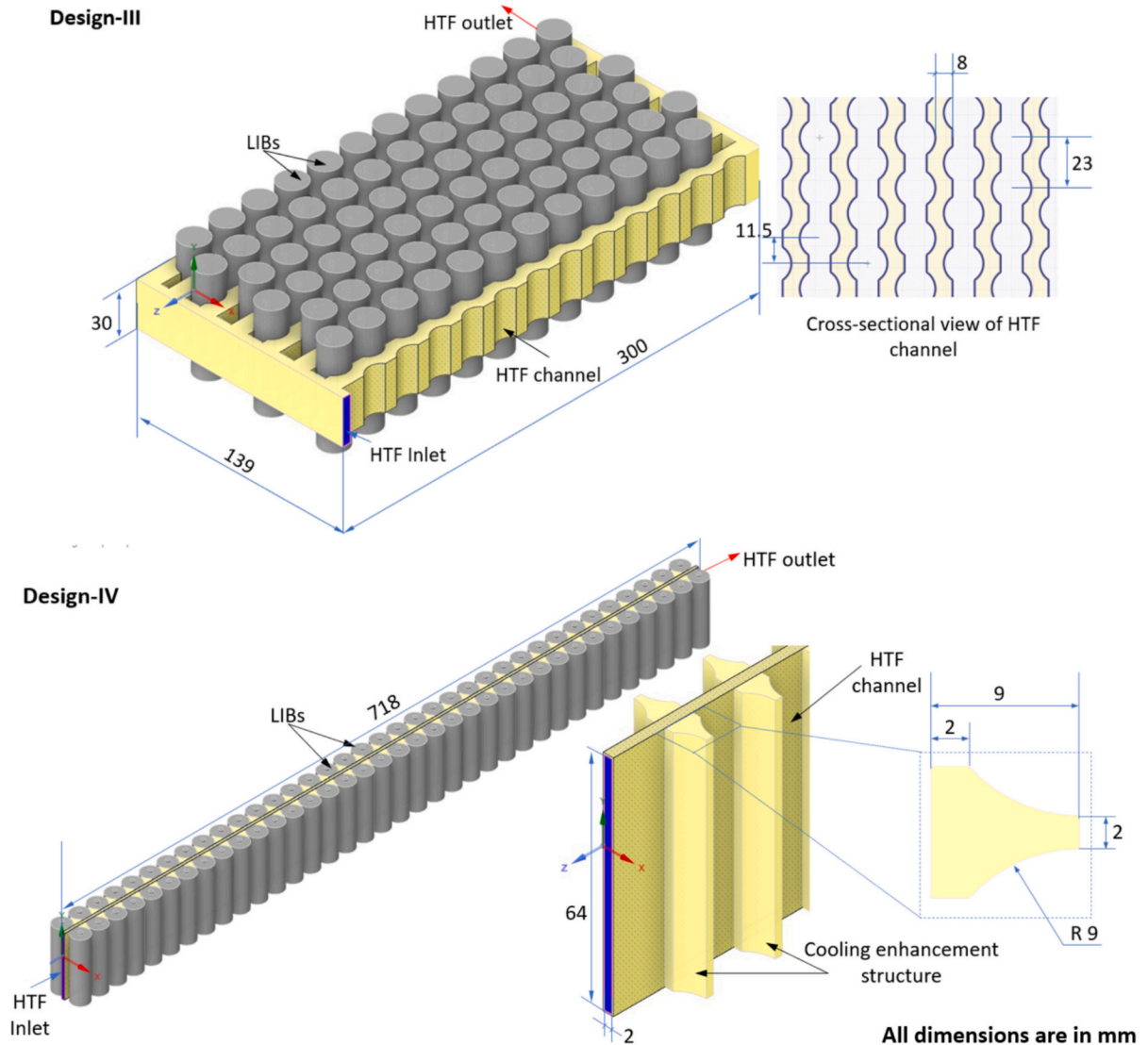


Fig. 3. Rigid channel-based LC-BTMS Design-III and Design-IV.

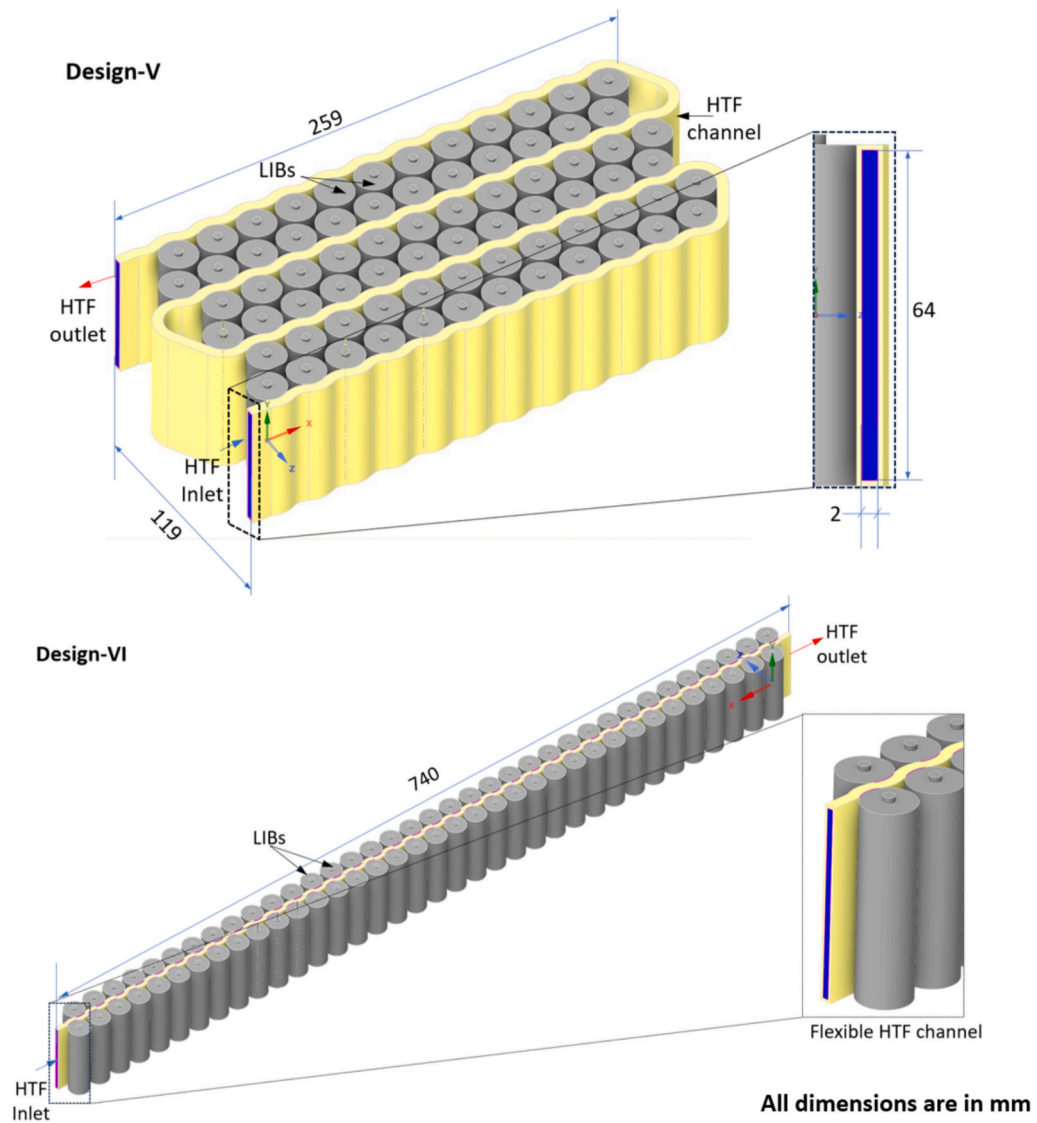


Fig. 4. Flexible channel-based LC-BTMS Design-V and Design-VI.

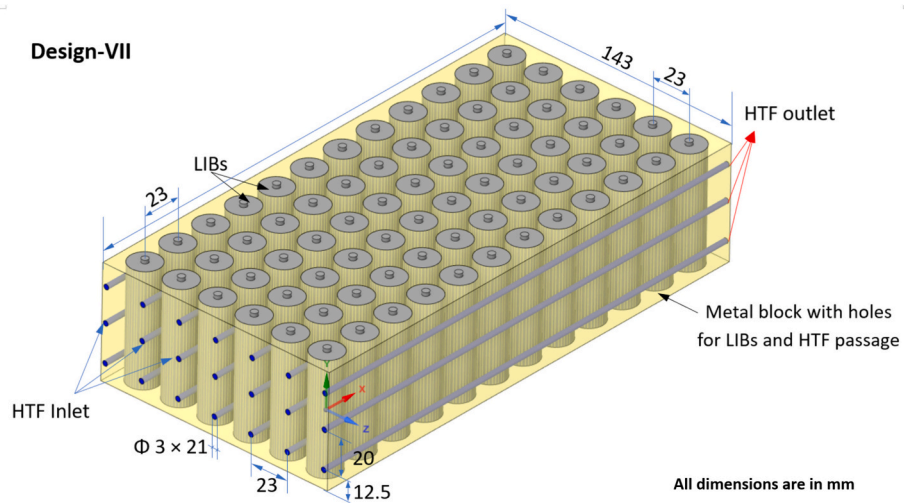


Fig. 5. Block-based LC-BTMS Design-VII.

Table 1

Thermo-physical properties of Aluminum and the HTF.

Material	Density (ρ) (kg/m ³)	Specific heat (C_p) (J/kg•K)	Thermal conductivity (k) (W/ m•K)	Viscosity (μ) (Pa•s)
Aluminum	2719	871	202.4	–
HTF (Water)	998.2	4182	0.6	1.003×10^{-3}

$$SoC = SoC_{t=0} - \frac{1}{Cap.} \int I(t).dt \quad (2)$$

The state of discharge (*SoD*) is complementary to *SoC* ($SoD = 1 - SoC$).

3.1. Experimental method

In the present study, the experiment was conducted to estimate $R_{int.}$ and dU_{OC}/dT of the cylindrical LIB for the battery heat generation modelling. An 18,650 cylindrical LIB (Sony, Model No. US18650VTC6) was used for study. The properties of the cylindrical LIB are given in Table 2. Notably, the experimentation facility at the EV powertrain lab at the Indian Institute of Technology Bombay, India, was used for this experimentation.

A schematic of the experimental setup is shown in Fig. 6. An Arbin charge/discharge system was used to perform the charging and discharging cycles of the LIBs, during which voltage, current, test duration, and internal resistance were continuously recorded and transferred to a connected PC. To monitor the thermal response, three K-type thermocouples were placed on the LIB surface. Fig. 7 illustrates the thermocouple locations. The thermocouples were connected to a data acquisition system (DAQ), which recorded temperature data in real time and transmitted it to the PC.

The initial temperature rise experiments were conducted on the LIB under controlled ambient conditions. The experiments were performed in a dedicated battery-testing room at the EV Powertrain Lab, IIT Bombay (approximately $8 \times 10 \times 11$ ft), equipped with two air conditioning units. The ambient temperature was carefully maintained at the desired level and monitored using several thermocouples. The battery was first subjected to a standard charging process; after which it was allowed to rest for two hours to ensure thermal equilibrium with the surrounding environment. Following this stabilization period, the LIB was discharged at a constant C-rate until it reached its cut-off voltage. Throughout the discharge process, temperature data were continuously recorded to evaluate the battery's thermal behavior under load. Notably, battery testing was conducted at two discharge rates: 1C and 3C.

$R_{int.}$ at different *SoCs* was measured for the 1C and 3C discharge rates. Afterward, the correlation for $R_{int.}$ was developed. The developed correlations for $R_{int.}$ are as follows,

$$R_{int.} = \begin{cases} 0.36609SoC^6 - 0.93466SoC^5 + 0.93259SoC^4 - 0.58598SoC^3 + 0.33608SoC^2 - 0.13458SoC + 0.0257, 1C \\ 0.06831SoC^6 - 0.17305SoC^5 + 0.18261SoC^4 - 0.13981SoC^3 + 0.09486SoC^2 - 0.03753SoC + 0.0201, 3C \end{cases} \quad (3)$$

Similarly, the correlation for the entropy thermal coefficient dU_{OC}/dT was also developed and is given as,

$$\frac{dU_{OC}}{dT} = -0.00665SoC^6 + 0.01733SoC^5 - 0.01668SoC^4 + 0.00908SoC^3 - 0.00381SoC^2 + 9.86331 \times 10^{-4}SoC - 3.4377 \times 10^{-5} \quad (4)$$

Table 2

Battery properties.

Parameter	Values
Dimensions	Diameter = 18 mm, Length = 65 mm
Density (ρ_{bat})	2523 kg/m ³
Specific Heat ($C_{p, bat}$)	1145 J/kg.K
Thermal conductivity (k_{bat})	$k_{r,bat} = 1.3$ W/m.K; $k_{z,bat} = 14.15$ W/m.K
Rated Capacity (C_{rid})	3000 mAh
Nominal Voltage (V_{nom})	3.6 V
Maximum Voltage (V_{max})	4.2 ± 0.05 V
Minimum Voltage (V_{min})	2.5 ± 0.05 V
Maximum discharging rate (C)	7C
Standard charging method	Constant Current-Constant Voltage (CC-CV)

3.2. Uncertainty and repeatability analysis

Temperature was measured using standard K-type thermocouples connected to a DAQ (Agilent 34970 A). Based on DAQ specifications (± 1.0 °C) and the standard K-type thermocouple tolerance (± 2.5 °C or $\pm 0.75\%$ of reading), the overall temperature measurement uncertainty is estimated in the range of ± 3.5 °C. LIB charging and discharging tests were performed using an Arbin battery cycler, for which the voltage and current measurement accuracies are $\pm 0.02\%$, introducing minimal uncertainty in the measurements.

The battery heat generation rate was calculated using fitted electro-thermal parameters (I , T , $R_{int.}$ and dU_{OC}/dT). The uncertainty in the estimated heat-generation rate arises primarily from experimental scatter in these parameters, polynomial-fitting residuals, and temperature-measurement uncertainty. A conservative propagation of these effects indicates that the overall uncertainty in the estimated heat-generation rate is on the order of $\pm 10\%$ (see supplementary material). Since the present study focuses on a comparative evaluation under identical boundary conditions and modelling assumptions, the relative performance trends are not expected to be significantly affected.

To evaluate experimental repeatability, each discharge test was repeated three times under identical operating conditions. The measured temperature histories showed good repeatability, with the maximum deviation in peak temperature among the three repetitions remaining within ± 1 °C.

4. Numerical methodology

4.1. Numerical modelling and boundary conditions

A three-dimensional transient conjugate heat transfer model was developed to investigate the thermal and hydraulic performance of different BTMS designs. The following modelling assumptions were adopted in the numerical simulations,

1. The HTF was considered as an incompressible, single-phase liquid.

2. Thermo-physical properties of the HTF, LIBs, and cooling structures/channel were assumed to be constant at the mean operating temperature.
3. To maintain a consistent comparative framework across all LC-BTMS designs, thermal contact resistance (TCR) at solid-solid interfaces was neglected by assuming perfect thermal contact.
4. For all LC-BTMS designs, the Reynolds number (Re) was evaluated using the hydraulic diameter and the local HTF velocity in the

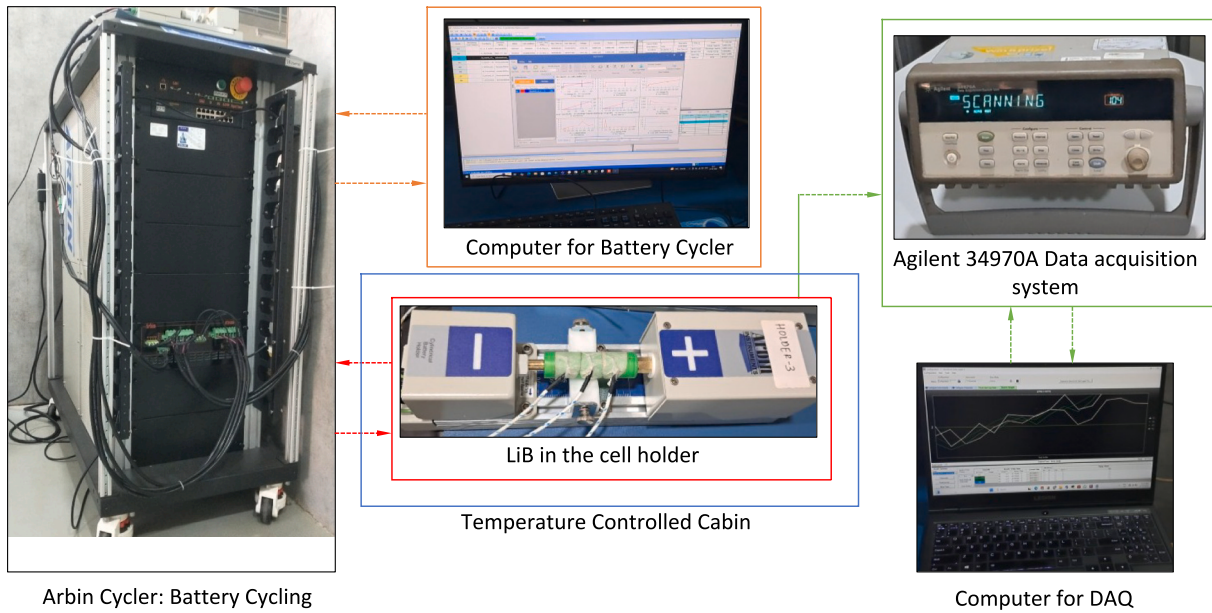


Fig. 6. Schematic picture of the experimental setup.

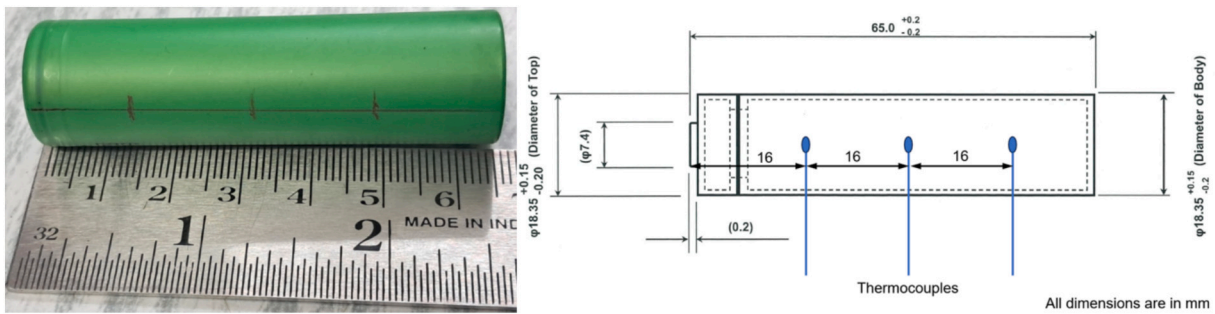


Fig. 7. Positions of thermocouples on the LIB.

smallest flow passages. Under the considered operating conditions, the Re for all designs remained below the laminar–transition threshold (see supplementary material). Therefore, a laminar flow model was adopted in this study.

5. All LIB surfaces not in contact with the cooling channel and cooling structure/channel surfaces not in contact with LIBs were treated as thermally insulated, representing the presence of fire-retardant materials used for safety purposes.
6. Radiative heat transfer effects were neglected.

For the HTF domain, the mass, momentum, and energy conservation equations were solved:

$$\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz} = \nabla \cdot \vec{V} = 0 \quad (5)$$

$$\frac{\partial \rho_{HTF} \vec{V}}{\partial t} + \nabla \cdot (\rho_{HTF} \vec{V}) = -\nabla P + \nabla \cdot (\mu_{HTF} \nabla \vec{V}) \quad (6)$$

$$\rho_{HTF} C_{p,HTF} \left(\frac{\partial T_{HTF}}{\partial t} + \vec{V} \cdot \nabla T_{HTF} \right) = \nabla \cdot (k_{HTF} \nabla T_{HTF}) \quad (7)$$

The energy equation in the solid domain solved was,

$$(\rho_{bat} C_{p,bat}) \frac{\partial T_{bat}}{\partial t} = \nabla \cdot (k_{bat} \nabla T_{bat}) + Q_{gen} \quad (8)$$

For all the studied LC-BTMS designs, the HTF modelled to enter

through the mass-flow inlet at a flow rate of 0.008 kg/s. The inlet temperature of the HTF was modelled as 298 K. The present study aims to investigate the cooling performance of the LC-BTMS under hot climatic conditions. Therefore, the ambient and initial temperatures of both the solid and fluid domains were set to 303 K. A pressure outlet boundary condition was applied at the outlet. No-slip boundary conditions were imposed at all solid-fluid interfaces. The cooling performance of the considered LC-BTMS designs was analyzed at 1C and 3C discharge rates, representing moderate and high-load operating conditions.

The numerical simulations were performed using the commercial CFD program ANSYS Fluent 2023 R2. The governing equations were discretized using the finite-volume method. Pressure-velocity coupling was handled using the SIMPLE algorithm, and second-order discretization schemes were used for pressure, momentum, and energy equations. The equations for battery heat generation were implemented using user-defined functions. The maximum iteration step was set to 100 per time step to ensure convergence accuracy in the transient simulation. The convergence residues for the energy equation and other equations were set to 10^{-6} and 10^{-3} , respectively.

4.2. Grid size and time step independence test

Grid- and time-step-independence tests were performed to ensure that the numerical results are independent of spatial and temporal discretization. Notably, for these tests, R_{int} and dU_{OC}/dT computed by Lai et al. [16] has been utilized ($T_{HTF,inlet} = 25^\circ C$, $T_{amb} = 30^\circ C$, $5C$, $Q_{HTF} =$

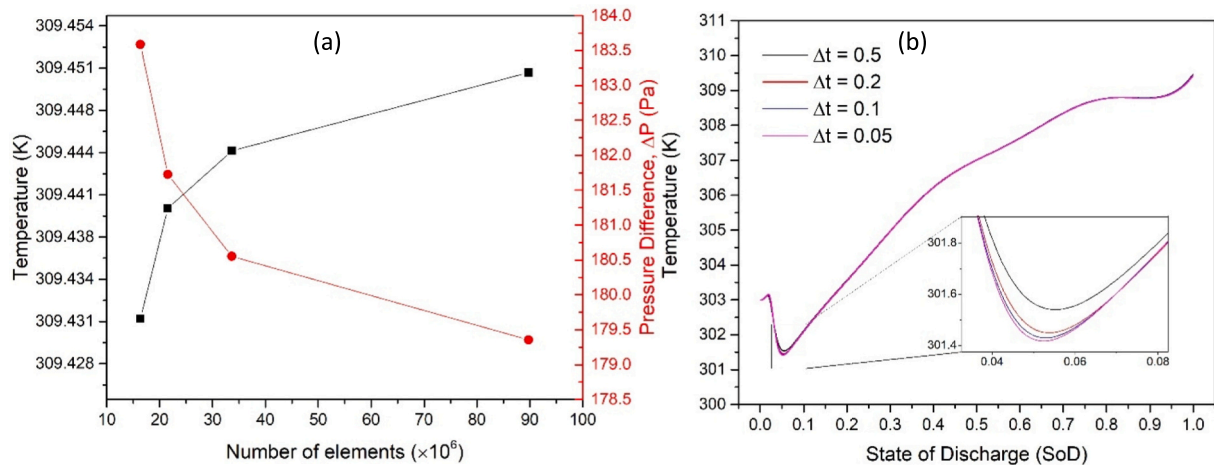


Fig. 8. (a) Grid size and (b) time step size independence test results.

0.005 kg/sec). Four grid sizes ranging from 16.3×10^6 to 89.7×10^6 elements were examined. Although the HTF flow is laminar, a relatively fine mesh is required to capture the complex 3D geometry, narrow flow passages, and conjugate heat-transfer interfaces. Local mesh refinement was therefore applied near solid-fluid interfaces. As shown in Fig. 8 (a), variations in T_{max} and ΔP become negligible beyond 30.3×10^6 elements, which was selected as a compromise between accuracy and computational cost. The chosen mesh used a minimum cell size of 0.3 mm near the solid-fluid interface and a maximum cell size of 3 mm in the bulk region. Local mesh refinement was applied near all solid-fluid interfaces and narrow flow passages.

Time-step independence was evaluated over four-time steps ranging from 0.5 s to 0.05 s, as shown in Fig. 8(b). A Courant-Friedrichs-Lewy (CFL) based estimate was used to guide time-step selection. Since a pressure-based implicit solver was employed, the CFL number serves as an accuracy indicator rather than a strict stability limit; however, high CFL values may reduce temporal accuracy [24]. Therefore, CFL values were maintained within an order-of-magnitude range of 1–100 (see supplementary material). The results show negligible differences between the tested time steps, and the temperature history obtained with $\Delta t = 0.2$ s closely matches that of $\Delta t = 0.05$ s. Hence, $\Delta t = 0.2$ s was adopted for the simulations.

4.3. Validation

The experimental results were compared with the numerical results

to validate the numerical model. During the experimental study, the temperature of the LIB's outer shell was measured by averaging the readings from the three thermocouples. The same procedure was repeated for both the 1C and 3C discharging processes. The results of the temperature comparison for 1C and 3C discharge rates are shown in Fig. 9. The comparison clearly shows that the numerical results for the LIB temperature at different discharging times agree well with the experimental results. This trend suggests that the thermal model employed in this study was suitable and practical.

To validate the conjugate heat transfer and fluid flow model, the numerical results were compared with the data reported by Saleh and Jaffar [25]. In their study, the authors performed experimental and numerical investigations on a multi-channel cold plate. The Nusselt number (Nu) and ΔP obtained from the present model were compared with the corresponding results from Ref. [25], as shown in Fig. 10. The figure shows good agreement between the results, with only minor differences observed. Therefore, the present numerical model can be confidently applied to the analysis of LC-BTMS designs.

5. Results and discussion

The present study conducted a comparative investigation of various LC-BTMS designs. As detailed above, seven distinct indirect LC-BTMS configurations (Design I-VII) were analyzed in this study. The comparison was conducted in three stages. In the first stage, the thermo-hydraulic performance of each design was evaluated through

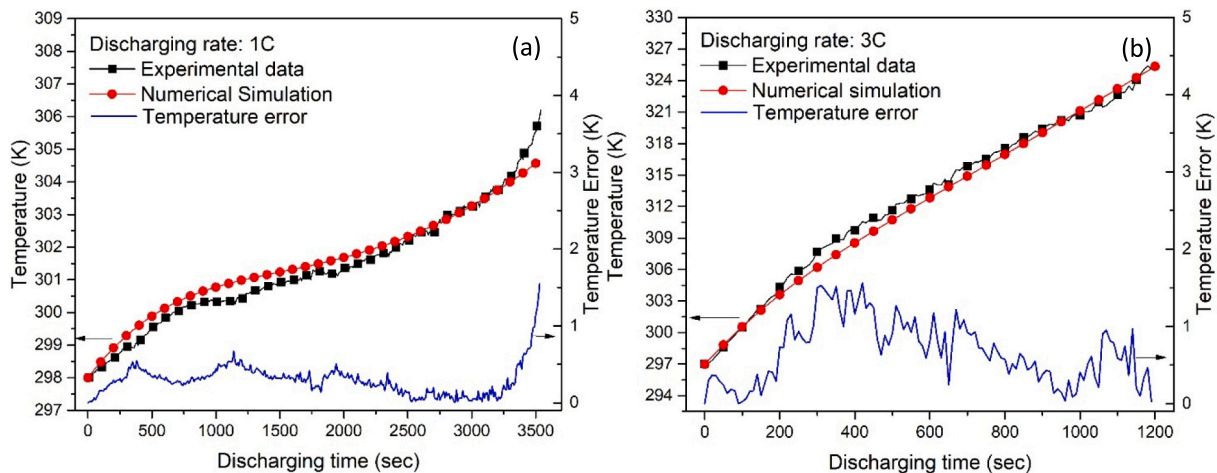


Fig. 9. Validation of the numerical model against the experimentation for (a) 1C and (b) 3C discharge rate.

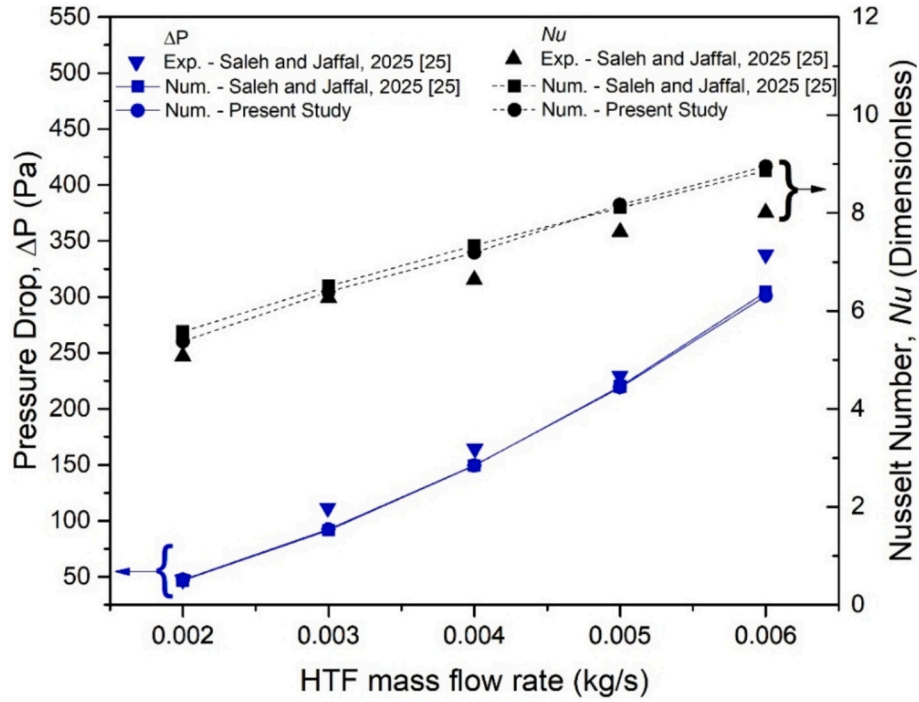


Fig. 10. Validation of the present numerical model by comparison of ΔP and Nu with the experimental and numerical data of Saleh and Jaffal [25].

numerical analysis. In the second stage, aspects related to manufacturing, maintenance, and safety were assessed based on expert reviews. Finally, multiple performance parameters were evaluated using the VIKOR MCDM technique, and the designs were ranked accordingly.

5.1. Comparison of thermo-hydraulic performance parameters

The thermo-hydraulic performance of various LC-BTMS designs was evaluated using a numerical model. Thermal performance was assessed based on the outlet temperature of the heat transfer fluid ($T_{HTF, outlet}$), T_{max} , and ΔT . Hydraulic performance was analyzed by comparing the ΔP across the different LC-BTMS designs. The thermohydraulic performance of the LC-BTMS designs was evaluated at 1C and 3C discharge rates to represent the moderate and high load conditions typically encountered in EV applications.

Fig. 11 illustrates the transient variation of ΔT with time for different LC-BTMS designs during discharging. Maintaining a low ΔT (typically below 5°C) is crucial for ensuring safety, consistent performance, and long-term reliability of the battery system. As shown in the figure, ΔT increases initially with discharge for all designs, reaching values of $2\text{--}5^\circ\text{C}$ within the $0.1\text{--}0.2$ SoD for both 1C and 3C cases. Following this phase, the trends in both 1C and 3C cases change drastically. The ΔT for all the LC-BTMS designs decreased rapidly for the 1C case, while only a slight variation in ΔT is observed over time for the 3C case. This difference is due to a higher heat generation rate in the 3C case than in the 1C case. For the 3C case, ΔT gradually decreases up to approximately $0.5\text{--}0.6$ SoD, with a very shallow slope, and then begins to rise again towards the end of the discharging process. For most LC-BTMS designs, the ΔT among the battery cells remained below the recommended threshold of 5°C , indicating acceptable thermal uniformity during

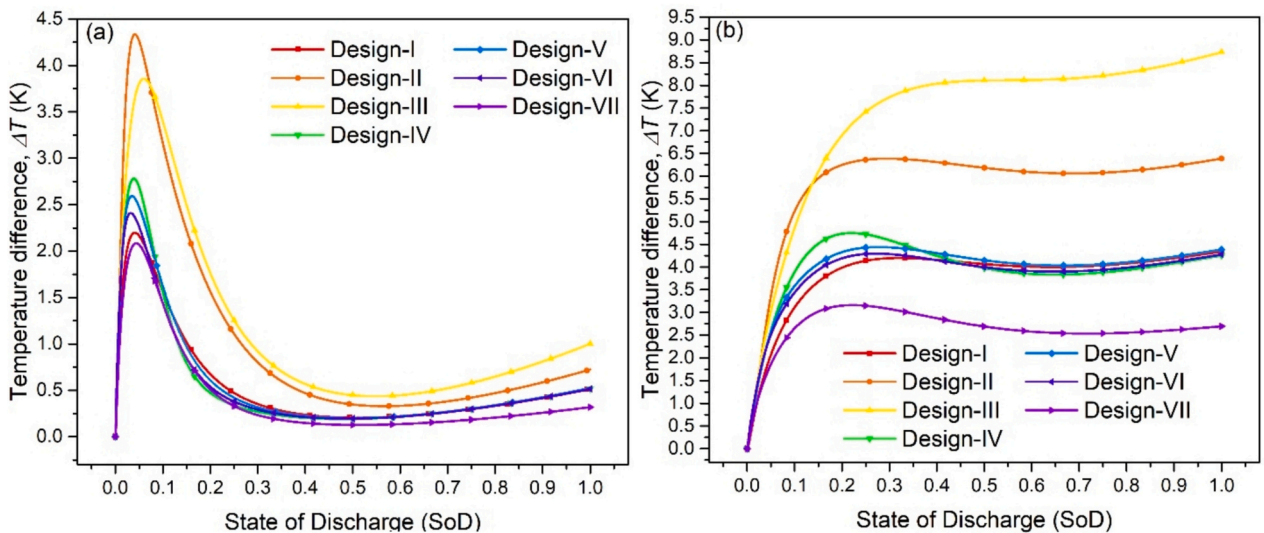


Fig. 11. Transient variation of ΔT with SoD for (a) 1C and (b) 3C discharge rates.

discharge. Among all configurations and for both 1C and 3C cases, Design VII exhibits the lowest ΔT (2.08 K for 1C and 3.16 K for 3C), indicating the most uniform temperature distribution within the battery module. This behavior is mainly attributed to the conductive block surrounding the cells, which enhances lateral heat spreading and suppresses local hot spots. ΔT values for Designs-I, IV, V, and VI are found in almost the same range, with Design-VI exhibiting the second lowest ΔT among all the designs. In contrast, Design-II exhibited the highest ΔT up to $SoD = 0.1$, and later Design-III showed the highest ΔT (3.85 K at 1C and 8.73 K at 3C), indicating strong temperature gradients resulting from non-uniform HTF coverage and limited contact between the HTF and the cell surface. Notably, the relative performance trend and ranking among the LC-BTMS designs remain consistent across the 1C and 3C cases, indicating that temperature uniformity is primarily governed by flow distribution and thermal contact rather than discharge rate.

Another parameter used to compare the thermal performance of different LC-BTMS designs is T_{max} . Fig. 12 shows the variation of T_{max} with time for the different LC-BTMS designs. The maximum T_{max} value for the various designs was below the safe limit of 40 °C. The figure shows that the trends in T_{max} over time for the different designs are very similar to those of ΔT . Initially, T_{max} rises for all designs, then decreases, reaching a peak around 0.1 SoD . Following this phase, T_{max} drastically reduced for all configurations in the 1C case, while in the 3C case it decreased by 1–2 °C until about 0.5–0.6 SoD , then started increasing afterwards. Design-VII achieves the lowest T_{max} (298.62 K for 1C case and 304.25 K for 3C case) towards the end of the discharging period, confirming that the block-based cooling concept provides superior thermal control. Designs I, II, IV, V, and VI exhibit comparable T_{max} , indicating acceptable thermal performance. However, Design-III reaches a significantly higher T_{max} (299.43 K for 1C and 310.27 K for 3C) towards the end of discharge, which is undesirable from a safety perspective, especially for high C-rate operation under hot ambient conditions. Notably, the relative differences among the designs remain unchanged for both 1C and 3C cases, confirming the robustness of the observed trends across moderate and high EV operating loads.

Fig. 13 illustrates the variation in $T_{HTF,outlet}$ with SoD . This parameter reflects the amount of heat absorbed by the HTF as it passes through the LC-BTMS. Higher values of $T_{HTF,outlet}$ indicate better heat extraction capability and thus superior thermal performance. For both 1C and 3C cases, a sharp jump was observed at the beginning of discharge ($SoD \approx 0.05$). This trend is associated with a startup effect driven by initial conditions and HTF residence time. At the start of the simulation, the entire domain, including the solid and HTF, is initialized at ambient temperature (303K), while the inlet temperature is set at 298 K.

Therefore, the outlet temperature initially reflects the flushing of the warmer initial HTF, while heat generation in the LIBs begins simultaneously. Once the colder inlet HTF reached the outlet, $T_{HTF,outlet}$ decreased sharply for both 1C and 3C cases. The HTF flow rate was kept constant throughout the simulations, which confirms that this behavior is physical rather than a numerical instability.

After this phase, for the 1C case, $T_{HTF,outlet}$ decreased for all the LC-BTMS designs until $SoD = 0.3$, up to approximately 298.3 K, and afterward increased slightly identically across all configurations. For the 3C case, $T_{HTF,outlet}$ decreased sharply after $SoD \approx 0.05$, by about 1 °C to 1.5 °C for the majority of designs. Once thermal equilibrium was reached, $T_{HTF,outlet}$ stabilized for most designs. After approximately $SoD = 0.15$, $T_{HTF,outlet}$ began to decrease again for all designs, though at a slower rate, due to the gradual increase in heat generation as discharging progressed. Around 0.5–0.6 SoD , it began to rise again across all designs, driven by the high heat generation rate during the later stages of discharge. Among all configurations, Design-VII consistently showed the highest $T_{HTF,outlet}$ values, indicating superior heat transfer performance.

In contrast, Designs I, II, and III recorded lower $T_{HTF,outlet}$ values. This behavior is likely due to the non-uniform flow pattern in the cooling channels, which reduces heat transfer. Notably, for the 1C case, $T_{HTF,outlet}$ follows the same trend as the 3C case, but with a smaller temperature rise owing to the lower heat generation rate. This trend indicates that the relative heat extraction performance of the LC-BTMS designs is maintained across moderate and high EV operating loads.

Hydraulic performance is evaluated by measuring the pressure drop across the cooling channels (Fig. 14). Notably, the pressure drop remains the same for both the 1C and 3C discharge cases, since the HTF mass flow rate and fluid properties are the same across all simulations. Designs V and VI exhibit the highest ΔP values (173.71 Pa and 150.46 Pa, respectively). This is mainly due to their longer flow paths and multiple bends, which increase frictional and minor losses. Although these designs provide good thermal performance, the high pressure drop implies a higher pumping power requirement. Design-III exhibits the lowest ΔP (7.61 Pa) due to its relatively short and straightforward flow path. However, this hydraulic advantage is achieved at the cost of poor thermal performance. Design-VII presents a moderate ΔP (56.28 Pa), which can be considered acceptable given its substantial thermal benefits.

The electrical pumping power (P_{elec}) was also calculated using correlation $P_{elec} = \Delta P \cdot \dot{Q} / \eta$ with a pump efficiency of 0.6. Design-V exhibits the highest pumping power (2.3 mW), whereas Design-III shows the lowest, around 0.102 mW.

To better understand the above trends, Table 3 and Fig. 15 present

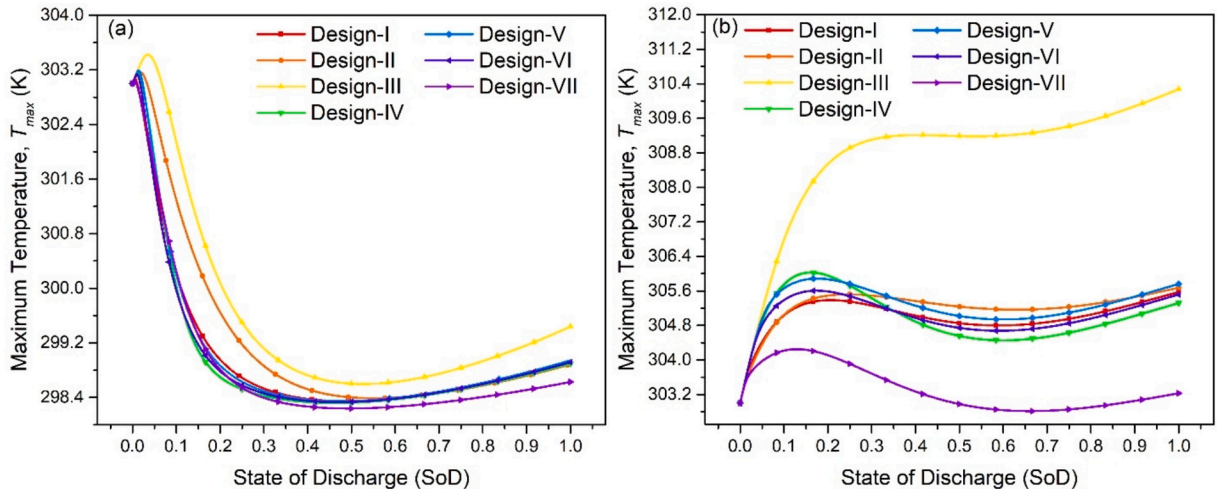


Fig. 12. Variation of T_{max} with SoD for (a) 1C and (b) 3C discharge rates.

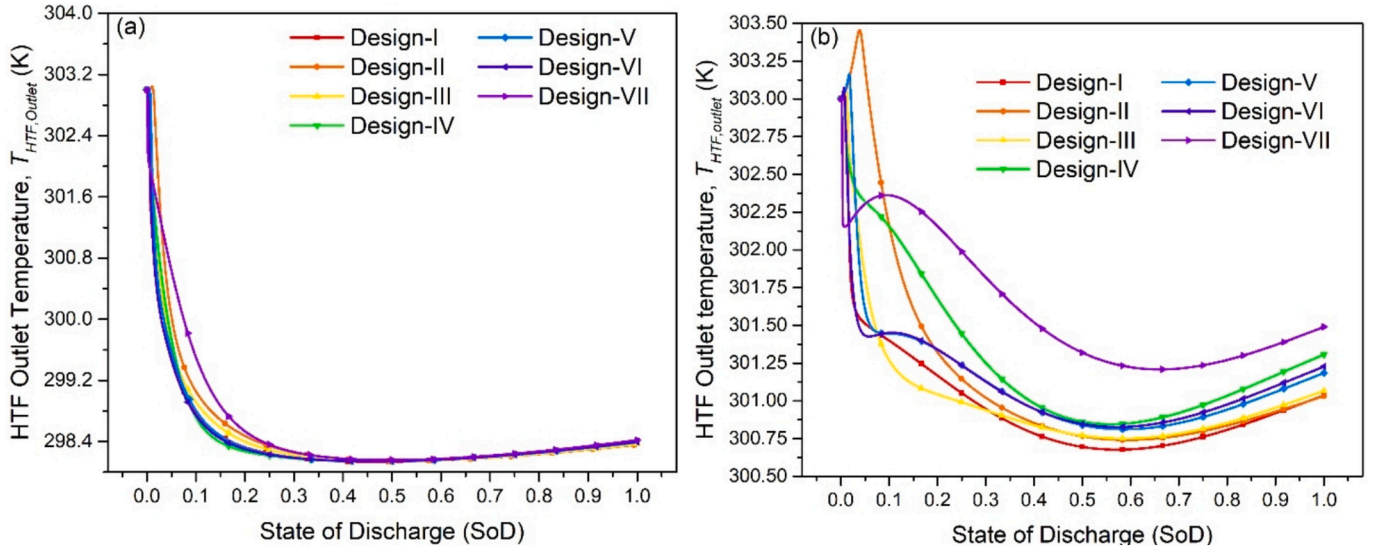


Fig. 13. Variation of $T_{HTF,outlet}$ with SoD for (a) 1C and (b) 3C discharge rates.

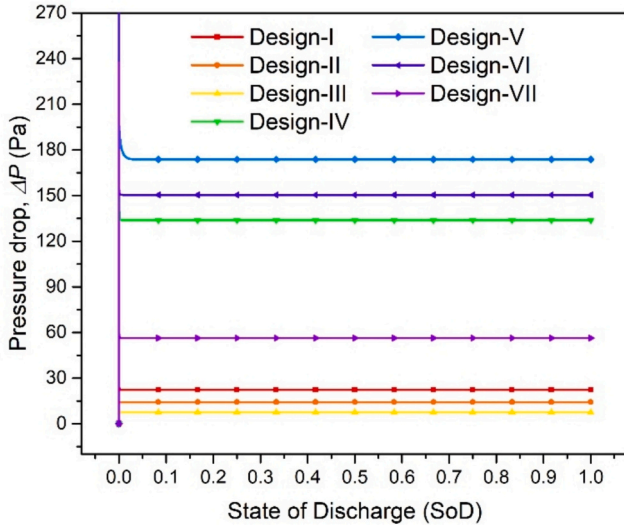


Fig. 14. Transient variation of ΔP with SoD in different LC-BTMS designs.

the HTF streamlines and LIB temperature contours (only the 3C case) for the different indirect LC-BTMS designs. These visual results provide important insight into how flow distribution and surface contact affect heat removal. For Designs I and II (LCP-based designs), the streamlines indicate that the HTF distribution inside the cold plate is not perfectly uniform. Some regions experience relatively lower velocities, which leads to weaker convective heat transfer. As a result, the temperature contours reveal warmer zones near the battery module's central region, leading to higher ΔT values than in the best-performing designs.

In Design-III, the streamlines reveal that the HTF does not uniformly sweep the entire curved surface of the cylindrical LIBs. Large portions of the LIB surface remain weakly cooled, leading to pronounced hot spots in the temperature contours. This clarification explains why Design-III exhibits the highest T_{max} and ΔT among all configurations. Design-IV shows improved flow coverage compared to Design-III, as indicated by more evenly distributed streamlines. Consequently, the temperature contours are more uniform, and both T_{max} and ΔT are reduced. However, the more complex channel routing and smaller passages increase the hydraulic resistance, which explains the higher pressure drop observed for this design.

For Designs V and VI (flexible channel-based designs), the

streamlines indicate that the HTF flows closely to the battery surface over a larger area, thereby enhancing convective heat transfer. This results in relatively low T_{max} and moderate ΔT values. Nevertheless, the long flow path and multiple bends increase the pressure drop, particularly for Design-V. In Design-VII, the streamlines demonstrate a well-directed HTF flow through the block's internal channels, while the block itself facilitates intense conductive heat spreading around each cell. This combined convection–conduction mechanism leads to the lowest T_{max} and ΔT with a moderate ΔP , explaining the superior overall thermo-hydraulic performance of this design.

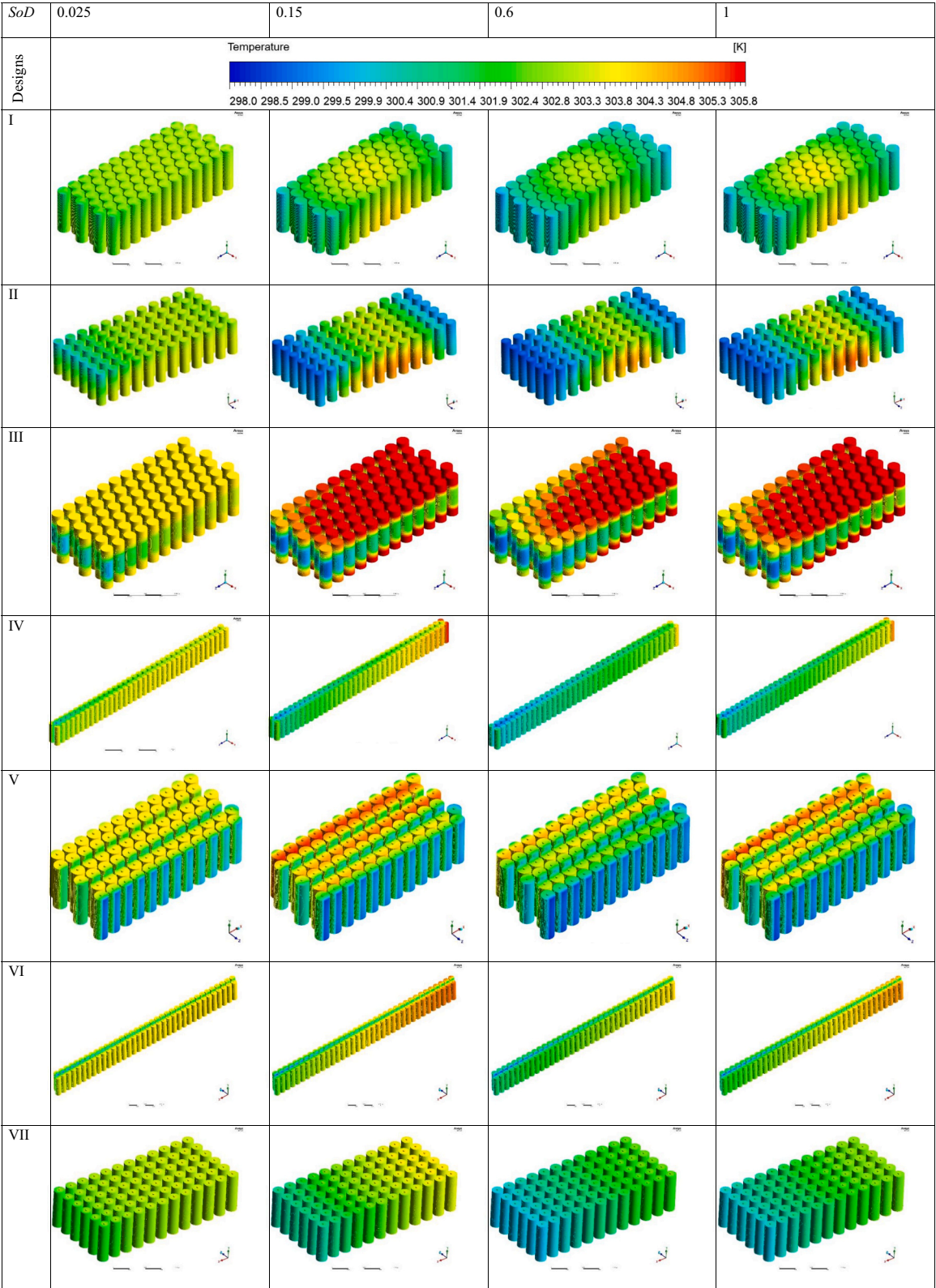
5.2. Comparison of manufacturing, maintenance, and safety parameters

The evaluation of manufacturing, maintenance, and safety parameters is critical to the practical implementation and success of any LC-BTMS design. These parameters cannot be assessed through experimental or numerical methods alone and instead require insights from experienced design engineers. A structured questionnaire was developed to facilitate this evaluation. Table 4 presents the layout of the designed questionnaire. For each LC-BTMS design, ten questions were included. Questions Q-1 to Q-9 were rated on a scale of 1 to 5, where 1 represents the lowest score and 5 the highest. Q-10 was included to capture general comments on the design. Questions Q-1 to Q-3 pertain to manufacturing aspects (A_{mfg}), Q-4 to Q-7 address maintenance considerations (A_{mnt}), and Q-8 and Q-9 focus on safety-related factors (A_{sfty}). Responses were collected from experienced design engineers working in various automotive industries, including AVL, Mahindra & Mahindra, and others. As these experts are actively involved in the design and development of LC-BTMS systems, their feedback was considered highly valuable for this study.

The survey results are presented in Table 5. A total of five responses were recorded. Similar MCDM and engineering design research has utilized small expert panels including 3–7 domain specialists [26–28]. Given that all responders were seasoned specialists in EV/thermal engineering, a sample size of five experts aligns with established practices in the literature. Question 10 was excluded from the analysis due to insufficient responses.

According to the survey results, Designs V and VI received higher scores for A_{mfg} and A_{mnt} . The flexible channel layouts reduce machining complexity, simplify assembly, and allow easier inspection and servicing. In contrast, LCP-based designs (I and II) received lower scores because plate bonding, sealing, and potential leakage at interfaces are practical concerns, especially over long-term operation. From a safety

Table 3
Temperature contours of LIBs in different LC-BTMS designs at various SoD.



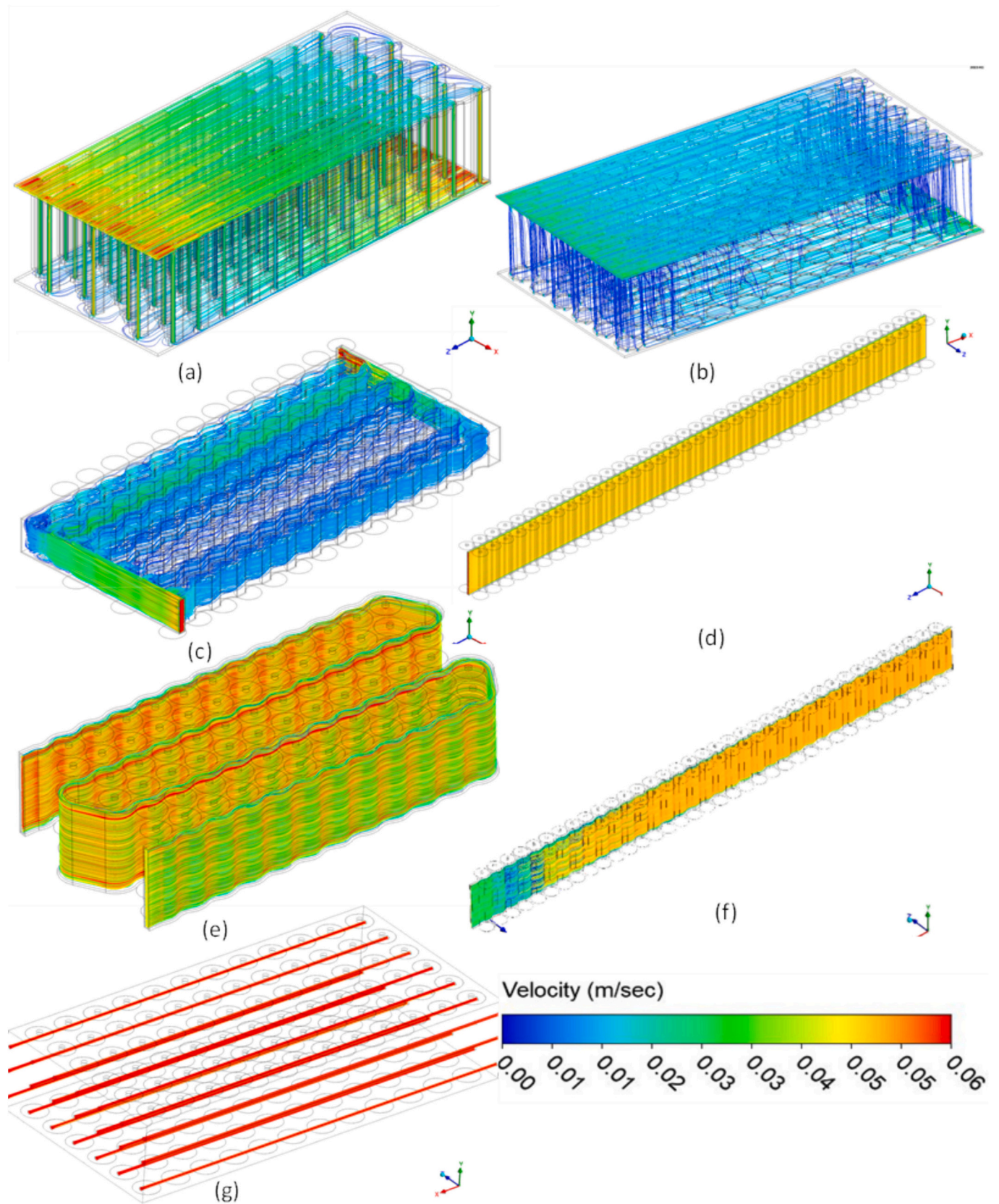


Fig. 15. Velocity streamlines for HTF flow in different LC-BTMS designs: (a) Design-I, (b) Design-II, (c) Design-III, (d) Design-IV, (e) Design-V, (f) Design-VI, and (g) Design-VII.

Table 4

Questionnaire for evaluating the manufacturing, maintenance, and safety aspects.

Que. No.	Question	Rating Scale
Q-1	Ease of Manufacturing	Poor
	How easily can the cooling system components be manufactured and assembled?	Excellent
Q-2	Manufacturing Cost Efficiency	Poor
	How cost-effective is the system for manufacturing at scale?	Excellent
Q-3	Complexity of Assembly	Poor
	How simple is the system to assemble into the battery pack?	Excellent
Q-4	Quality Assurance & Testing Feasibility	Poor
	How easily can the system be tested for defects or leaks during production?	Excellent
Q-5	Ease of Inspection	Poor
	How easy is it to inspect the cooling system during routine maintenance?	Excellent
Q-6	Ease of Repair	Poor
	How easily can components be accessed and replaced if needed?	Excellent
Q-7	Maintenance Cost Efficiency	Poor
	How cost-effective is the system to maintain over the EV's lifetime?	Excellent
Q-8	Coolant Handling Safety	Poor
	How safe and easy is it to drain, replace, or refill the coolant?	Excellent
Q-9	System Reliability	Poor
	How likely is the system to operate reliably over its whole expected service life?	Excellent
Q-10	Comments on Design (Optional)	

Table 5

Results of the survey.

Design	A_{mfg}	A_{mnt}	A_{sfty}
I	3.9	3.6	3.4
II	3.7	3.4	3.8
III	3.7	3.8	3.6
IV	3.8	3.9	4.1
V	4.4	4.4	4.4
VI	4.3	4.6	4.5
VII	3.9	3.9	3.9

perspective, Design-VII was generally viewed favourably due to its robust structure and fewer leakage-prone joints. However, experts also noted that the block-based design may increase system weight and promote heat propagation to neighboring cells in the event of any LIB failure, potentially limiting its large-scale adoption.

5.3. Ranking of designs using the MCDM technique

The numerical analysis results indicate that the different LC-BTMS designs exhibit varying performance characteristics. Similarly, the manufacturing, maintenance, and safety aspects of the various LC-BTMS designs differ. Some parameters should have higher values for better performance, such as A_{mfg} , A_{mnt} , and A_{sfty} . On the other hand, other parameters should be kept as low as possible, such as weight, T_{max} , ΔT , and ΔP . To compare the different LC-BTMS designs, an MCDM technique, namely VIKOR, was employed.

MCDM is employed when multiple, often conflicting, criteria influence the outcome of a system. MCDM focuses on evaluating, ranking, and selecting alternatives from best to worst based on decision-makers' preferences [29]. Key components of an MCDM method include: a set of alternatives; criteria against which these alternatives are evaluated; performance scores that indicate how well each alternative meets each criterion; and weights that reflect the relative importance of each criterion. The methodology of the VIKOR technique is discussed in the

Table 6

Decision matrix and best and worst values for different criteria.

Criteria →	Weight (kg)	ΔP (Pa)	ΔT (K)	T_{max} (K)	A_{mfg}	A_{mnt}	A_{sfty}
Alternative	C1	C2	C3	C4	C5	C6	C7
A1	1.0	22.3	4.3	305.6	3.9	3.6	3.4
A2	1.2	14.2	6.4	305.7	3.7	3.4	3.8
A3	0.2	7.6	8.7	310.3	3.7	3.8	3.6
A4	0.7	133.8	4.8	306.0	3.8	3.9	4.1
A5	0.4	173.7	4.4	305.9	4.4	4.4	4.4
A6	0.3	150.5	4.3	305.6	4.3	4.6	4.5
A7	3.7	56.3	3.2	304.3	3.9	3.9	3.9
Best (f^*)	0.2	7.6	3.2	304.3	4.4	4.6	4.5
Worst (f^{-1})	3.7	173.7	8.7	310.3	3.7	3.4	3.4

supplementary material. Notably, for the MCDM analysis, we chose thermo-hydraulic performance characteristics of the 3C case. This is because the 3C case is a high-load operating scenario in EVs where design trade-offs are most important. The 1C data are used to ensure trends are consistent, but they are not included in the VIKOR ranking because they would make the differences in performance under high thermal loading less clear.

In the first step, a decision matrix was constructed, as shown in Table 6. Seven designs have been denoted as alternatives (A1-A7), while different performance parameters, such as weight, ΔP , ΔT , T_{max} , A_{mfg} , A_{mnt} , and A_{sfty} , have been selected as the criteria (C1-C7). Next, the different criteria were divided into cost and benefit criteria. C1-C4 were selected as cost criteria, while C5-C7 were selected as benefit criteria. Based on the type of criteria, best (f^*) and worst (f^{-1}) values were identified for each criterion.

In the next step, equal weight was assigned to each criterion ($w_j = 1/7 = 0.1428$). Following this step, the normalized values (r_{ij}) for the alternatives and criteria were evaluated (see the supplementary material). After identifying r_{ij} and w_j , the utility measure (S_j), regret measure (R_j), and VIKOR index (Q_j) for the different alternatives were evaluated. Using the VIKOR index, the alternatives were ranked. Results are presented in Table 7. As per the ranking, A6 (i.e., Design-VI) has been selected as the best alternative. The thermo-hydraulic performance results showed that Design-VII performed comparatively better. However, the inclusion of additional parameters, such as weight, A_{mfg} , A_{mnt} , and A_{sfty} , changed the overall rankings. The ranking of the different designs in descending order is as follows: Design-VI > Design-IV > Design-V > Design-VII > Design-I > Design-II > Design-III.

To evaluate the robustness of the VIKOR ranking, a weight-sensitivity analysis was conducted by varying the relative weights of the thermal, hydraulic, and practical criteria. The results showed that Design-VI remained the best alternative for most weight-combination scenarios. In addition, a random-weight sensitivity analysis using the Monte Carlo method was conducted, and the results showed that, across all tested values of the Dirichlet distribution, Design-VI ranked as the best alternative. These findings further strengthen the reliability of the VIKOR ranking obtained. The detailed results of the weight sensitivity analysis are provided in the supplementary material.

Table 7

Utility measure (S_j), Regret measure (R_j), VIKOR index (Q_j), and ranking of different alternatives.

Alternatives	Utility measure (S_j)	Regret measure (R_j)	VIKOR index (Q_j)	Ranking
A1	0.47	0.14	0.81	5
A2	0.54	0.14	0.90	6
A3	0.63	0.14	1	7
A4	0.45	0.12	0.29	2
A5	0.25	0.14	0.56	3
A6	0.20	0.12	0.01	1
A7	0.44	0.14	0.77	4

6. Conclusions

The present study conducted a comparative investigation of different LC-BTMS designs for the battery module of an EV. Seven distinct indirect type LC-BTMS designs were selected from the various design categories for the comparison. A comparison of the thermo-hydraulic performance of the different designs was performed using a validated numerical model. The key parameters selected for the numerical study were ΔP , ΔT , T_{max} , T_{HTF} , and $T_{HTF,outlet}$. To consider the other parameters related to manufacturing, maintenance, and safety of the different designs, a survey was conducted with the assistance of design engineers from EV industries. Finally, the ranking of the selected designs was performed using the VIKOR MCDM method, considering various parameters. The broad conclusions from the study are,

1. The block-based LC-BTMS design (Design-VII) demonstrated the best thermal control, with the lowest T_{max} of 298.62 K at 1C and 304.25 K at 3C and the smallest ΔT of 2.08 K at 1C and 3.16 K at 3C, primarily due to vast heat spreading through the metal block and a more uniform HTF distribution. The rigid channel design with partial surface coverage (Design-III) exhibited the weakest thermal performance, with $T_{max} = 299.43$ K (1C) and 310.27 K (3C) and $\Delta T = 3.85$ K (1C) and 8.73 K (3C), despite providing the lowest ΔP (7.61 Pa) among all designs. Flexible channel designs (Design-V and VI) provided reasonable thermal control but incurred relatively high hydraulic penalties. The cold-plate designs (Design-I and II) delivered moderate cooling performance but exhibited uneven flow distribution.
2. The expert survey indicated that flexible channel designs (Design-V and VI) are preferred for manufacturability and maintenance, due to more straightforward assembly and reduced sealing complexity, while block-based designs (Design-VII) offer easier maintenance but may increase system weight and promote heat propagation to neighboring cells in the event of a LIB failure.
3. The VIKOR MCDM technique was used to compare the performance of different designs, considering the following parameters: weight, ΔP , ΔT , T_{max} , A_{mfg} , A_{mnt} , and A_{sfty} . The VIKOR ranking identified Design-VI as the best overall compromise solution for hot-climate EV applications. The rankings obtained from the MCDM technique, in descending order, are as follows: Design-VI > Design-IV > Design-V > Design-VII > Design-I > Design-II > Design-III.

In our future research, we intend to examine these LC-BTMS designs under dynamic discharge rates, considering different drive cycles, HTF flow rates, and ambient temperatures, to gain a more complete understanding of their behavior across various operating environments. We also plan to study long-term reliability aspects, such as vibration effects, TCR, thermal cycling, and leakage tendencies, to better reflect the real operating conditions of EVs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.applthermaleng.2026.130436>.

Data availability

Data will be made available on request.

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