

Optimization of Liquid-cooled Battery Module Design Using Computational Fluid Dynamics Simulation

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In this paper, we present a computational fluid dynamics (CFD)-based study on the optimization of a liquid-cooled battery module design, with the aim of supporting temperature sensing system design in battery packs. Efficient thermal management is essential not only for battery performance and longevity but also for maintaining stable and reliable temperature measurements in battery management systems. CFD simulations were conducted using COMSOL Multiphysics to analyze the thermal–fluid behavior of a liquid-cooled battery module under different operating conditions. The key parameters investigated include coolant types, cooling jacket configurations (counter-flow versus cross-flow), and coolant flow rates. Unlike previous studies that primarily evaluated individual cooling parameters or thermal performance, the novelty of this work lies in integrating coolant selection, flow configuration, flow rate optimization, and sensor-oriented thermal field analysis within a unified CFD framework. This approach improves battery cooling by simultaneously reducing the maximum cell temperature and temperature non-uniformity while providing physically meaningful temperature and flow distributions for sensing system design. The results show that an ethylene glycol–water mixture provides improved flow uniformity and heat transfer efficiency compared with pure water, resulting in a more uniform temperature distribution favorable for distributed temperature sensing. In addition, a counter-flow cooling configuration in stacked casing designs effectively reduces temperature gradients. An optimal coolant flow rate of 2 L/min was identified, maintaining the battery temperature at approximately 26.7 °C with reduced thermal fluctuations. Overall, we demonstrate that CFD simulations can serve as a virtual design support tool for temperature field characterization and sensor layout planning in liquid-cooled battery systems, providing practical guidance for sensor-informed thermal management in advanced battery technologies.

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1. Introduction

The increasing demand for electric vehicles (EVs) and portable electronic devices has driven rapid advances in lithium-ion battery technology. Nevertheless, battery performance, safety, and service life remain highly dependent on effective thermal management. During operation, lithium-ion batteries generate heat, and inadequate heat dissipation can lead to elevated temperatures, accelerated degradation, capacity loss, and, in extreme cases, thermal runaway, posing serious safety risks.⁽¹⁾ Consequently, the development of efficient battery thermal management systems (BTMSs) is essential for the reliable operation and widespread adoption of battery-powered systems. Among various cooling strategies, liquid cooling has emerged as one of the most promising solutions for BTMSs owing to its high heat transfer capability and ability to maintain relatively uniform temperature distributions across battery modules.⁽²⁾ Compared with air cooling approaches, which often struggle with high heat generation rates and pronounced temperature gradients in high-power or densely packed battery systems, liquid cooling provides superior thermal performance and is therefore well suited for advanced battery applications.

However, the design of liquid-cooled BTMSs is inherently complex, involving coupled fluid flow and heat transfer processes within confined geometries. In addition to improving battery safety and longevity, the thermal environment within a battery module directly affects the accuracy and reliability of temperature sensing used in battery management systems.^(3–6) Non-uniform temperature fields, localized hot spots, and steep thermal gradients can introduce sensing uncertainty, delayed sensor response, and spatial mismatch between measured and actual cell temperatures. Therefore, an optimized thermal design not only enhances heat dissipation but also provides a stable and predictable temperature field that supports effective sensor placement and reliable temperature monitoring. Computational fluid dynamics (CFD) has become an indispensable tool for the design and optimization of BTMSs. CFD simulations enable engineers to virtually evaluate design parameters, coolant properties, and operating conditions without extensive physical prototyping, significantly reducing development time and cost while providing detailed insight into thermal–fluid behavior that is difficult to obtain experimentally.⁽⁷⁾

Key parameters such as temperature distribution, pressure drop, and flow uniformity can be accurately predicted, allowing for the early identification of hot spots, stagnant flow regions, and thermal imbalances. Furthermore, CFD-based temperature field analysis can serve as a virtual design support framework for sensor-oriented considerations, including the assessment of temperature gradients and the identification of thermally representative regions within the battery module. This predictive capability enables iterative design refinement before fabrication, leading to safer, more efficient, and sensor-compatible battery systems. In this study, a CFD-based case analysis is conducted using COMSOL Multiphysics to optimize the design of a liquid-cooled battery module. The investigation focuses on key challenges such as flow imbalance and non-uniform heat transfer while examining the effects of coolant type, cooling jacket configuration, and coolant flow rate on thermal performance. The objective is to establish a systematic, sensor-informed design approach in which CFD-derived temperature fields

support both thermal management optimization and the design of temperature sensing systems in liquid-cooled battery packs.

Although previous CFD studies, including Refs. 8–10, have demonstrated the usefulness of numerical simulations for evaluating liquid-cooled battery thermal management under different operating conditions, in this study, we extend these approaches in two important aspects. First, rather than examining a single thermal or hydraulic parameter independently, coolant selection, cooling flow configuration, coolant flow rate, tank capacity, and pump operating characteristics are considered within an integrated design framework to identify a practical operating combination that simultaneously limits the maximum cell temperature, improves temperature uniformity, and avoids unnecessary pumping demand. Second, the resulting CFD temperature and flow fields are interpreted as virtual sensing information for identifying thermally representative regions, evaluating spatial temperature gradients, and defining monitoring and control targets. Therefore, the contribution of this study is the integration of battery-cooling optimization with sensor-oriented thermal field analysis, thereby extending conventional CFD-based BTMS design toward sensor-informed thermal management.

2. Methodology

All numerical simulations in this study were conducted using COMSOL Multiphysics, a finite-element-based CFD platform capable of handling complex geometries through unstructured meshing. This capability is particularly suitable for accurately modeling the intricate structure of liquid-cooled battery modules, including cylindrical battery cells, cooling channels, and enclosing casings. A detailed three-dimensional model of a double-layer battery pack was constructed to represent the actual spatial arrangement of the cells and the cooling jacket geometry. The computational domain was discretized using an unstructured mesh, with localized mesh refinement applied in regions exhibiting high thermal and velocity gradients to ensure numerical accuracy. The CFD simulations were designed to systematically investigate key factors affecting thermal performance and temperature field characteristics relevant to both thermal management and temperature sensing support. Several parameters were examined, including coolant type, cooling jacket flow configuration, stacked casing design, and coolant flow rate. Two coolants, pure water and an ethylene glycol–water mixture, were evaluated by defining their respective physical properties, such as density, viscosity, specific heat capacity, and thermal conductivity. In the present analysis, the ethylene glycol–water coolant was evaluated using a fixed mixture composition, and the water-to-ethylene glycol ratio was not varied as an independent design parameter. This treatment was adopted to maintain a consistent coolant formulation while isolating the effects of cooling configuration and flow rate. Note that changing the ethylene glycol concentration alters several coupled thermophysical properties, including viscosity, thermal conductivity, specific heat capacity, and density, and therefore can affect both heat transfer performance and coolant flow resistance. Accordingly, the optimization of the mixture ratio requires a combined thermal–hydraulic assessment rather than the consideration of cooling temperature alone. In addition, two inlet–outlet configurations, counter-flow and cross-flow, were analyzed to assess their effects on heat transfer efficiency and temperature uniformity.

A stacked casing design was further examined by comparing counter-flow and parallel-flow arrangements to identify configurations that minimize temperature gradients. The coolant flow rate was varied from 1 to 5 liters per minute (LPM) to determine its effects on cooling effectiveness and thermal stability. To extend the analysis beyond the cooling jacket itself, the system-level parameters related to practical BTMS implementation were incorporated into the simulations. The effects of water tank size and pump motor specifications were investigated by simulating different tank volumes (5, 10, and 15 L) to evaluate thermal buffering capacity, as well as pump power levels (50, 100, and 150 W) and flow control strategies (fixed-speed operation versus variable-speed operation). These factors were introduced through appropriate boundary conditions that represent the thermal mass of the tank and the pumping characteristics of the motor, enabling a more holistic evaluation of BTMS performance under realistic operating conditions. Battery heat generation was modeled on the basis of commonly accepted electrochemical and resistive heat generation mechanisms. The total heat generation rate Q_{gen} consists of reversible and irreversible components, and can be expressed as

$$Q_{gen} = Q_{rev} + Q_{irr} = T * (dS/dT) * I + I^2 * R_{ohm}, \quad (1)$$

where Q_{rev} represents the reversible heat associated with entropy changes during electrochemical reactions, Q_{irr} denotes the irreversible heat arising from ohmic and polarization losses, T is the absolute temperature, dS/dT is the entropy coefficient, I is the current, and R_{ohm} is the ohmic resistance. Variations in discharge rate (C-rate) were reflected through changes in current magnitude, directly affecting ohmic heat generation. Higher discharge rates result in increased irreversible heat and elevated overall heat generation, which were accounted for in the simulations. The heat generation formulation adopted in the present study is intended to provide a consistent thermal-loading basis for comparing different cooling system designs rather than to reproduce the complete electrochemical behavior of individual cells. Although the reversible entropy and irreversible resistive terms capture the dominant contributions to battery heat generation, this simplified representation does not explicitly resolve local electrochemical processes such as reaction overpotential, concentration polarization, ionic transport, and spatial variations in current density. Consequently, local heat generation rates and hot-spot intensities may differ from those predicted by a fully coupled electrochemical–thermal model, particularly under high C-rates and rapidly varying operating conditions. Nevertheless, the present formulation is suitable for the comparative steady-state optimization performed in this study because identical heat generation assumptions are applied consistently to all coolant, flow configuration, and flow rate cases.

The present optimization was performed primarily under steady-state thermal–fluid conditions to provide a consistent basis for comparing coolant properties, cooling flow configurations, and coolant flow rates. This treatment isolates the effects of the principal design parameters and enables the direct comparison of their effects on maximum cell temperature and temperature uniformity. However, actual EV operation involves continuously varying current loads during acceleration, cruising, regenerative braking, fast charging, and other operating conditions. Consequently, the associated battery heat generation rate is time-dependent, and the

magnitude and spatial location of local hot spots may evolve during a drive or charge cycle. These transient effects are not explicitly resolved in the present steady-state optimization and therefore define an important scope limitation of the current model. To account for internal temperature gradients and localized heating within the limitations of the present simplified model, the heat generation within each battery cell was represented using a prescribed non-uniform spatial distribution. The cell domain was divided into multiple subregions, including active-material and current-collector regions, and the local heat generation rates were assigned according to the assumed current density distribution and relevant material properties. This treatment provides a more spatially resolved thermal source than a uniform volumetric heat generation assumption; however, it should not be interpreted as a fully coupled electrochemical solution. A physics-based electrochemical model would be required to dynamically determine the local current density, reaction rate, overpotential, and associated heat generation terms. This approach allows for a more realistic representation of internal heat sources and provides a refined temperature field that is particularly relevant for evaluating thermally representative locations within the battery module.

For sensor-oriented analysis, selected locations within the CFD model were treated as virtual temperature-sensing points, enabling temperature field sampling without introducing physical sensors. On the basis of the simulated temperature distribution and coolant flow direction, a preliminary six-point temperature-sensing layout is proposed for the double-layer battery module. Three representative sensing positions are assigned to each battery layer: one near the coolant-inlet region, one near the middle of the flow path, and one near the downstream region where the coolant temperature is expected to be higher. Among these positions, the downstream sensor should be placed close to the CFD-predicted high-temperature region and is assigned the highest monitoring priority. The same upstream–middle–downstream arrangement is applied to the second battery layer, resulting in six distributed temperature-monitoring points for the module. This configuration enables the simultaneous assessment of the longitudinal temperature rise along the coolant path, temperature differences between the two stacked layers, and the development of localized high-temperature regions. The proposed placement strategy follows three principles: spatial coverage, hot-spot sensitivity, and redundancy reduction. The inlet-side points provide reference temperatures before substantial coolant heating occurs, the intermediate points capture the development of the temperature gradient along the flow path, and the downstream points monitor the regions most susceptible to thermal accumulation. If the number of available sensors is limited, priority should be given to the predicted hot-spot/downstream locations and to positions exhibiting the largest temperature differences between the stacked layers. Conversely, additional sensors can be introduced around regions with steep CFD-predicted temperature gradients when a higher spatial resolution is required.

This virtual sensing approach allows the preliminary evaluation of temperature uniformity and spatial thermal gradients at representative locations, and provides physics-based predictive guidance for identifying potential sensor locations and temperature-monitoring strategies in liquid-cooled battery systems. These locations should be regarded as candidate sensing positions derived from the numerical temperature field rather than experimentally validated sensor locations. Simulation results were post-processed to analyze temperature distributions, coolant

velocity fields, and overall heat transfer characteristics. Key performance indicators included the maximum cell temperature and temperature uniformity across the battery module, which are critical metrics for both thermal safety and sensing reliability. To ensure numerical accuracy and solution reliability, a mesh independence study was conducted using three mesh densities: a coarse mesh with approximately 1.5 million elements, a medium mesh with 3 million elements, and a fine mesh with 5 million elements. Mesh refinement was concentrated in regions near battery cells and cooling channels where steep thermal and velocity gradients occur. The maximum cell temperature and coolant pressure drop were monitored for each mesh configuration. Results showed that the maximum temperature varied by less than 0.5% and the pressure drop by less than 0.8% between the medium and fine meshes, indicating convergence. Considering both accuracy and computational efficiency, the medium mesh configuration was adopted for all subsequent simulations, consistent with the best practices reported in previous studies.^(7–9)

3. Results and Discussion

In this section, we present the CFD simulation results and discuss their implications for optimizing liquid-cooled battery module design, with additional emphasis on how the resulting thermal fields can support temperature sensing and monitoring in BTMSs. The thermal performance characteristics of an ethylene glycol–water mixture and pure water were first compared at a flow rate of 2 LPM.^(11,12) As shown in Fig. 1, the ethylene glycol–water mixture achieved a more uniform temperature distribution across the battery cells. Although pure water provided effective cooling, it resulted in larger temperature gradients within the module, indicating less uniform heat dissipation. The ethylene glycol–water mixture also promoted a more uniform flow within the cooling channels while maintaining comparable heat transfer

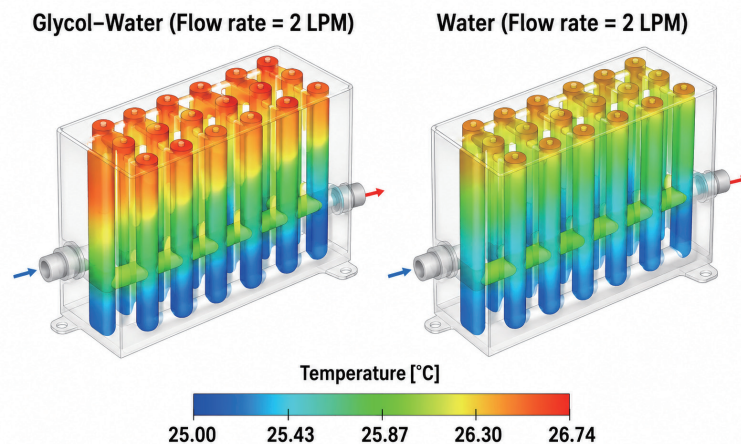


Fig. 1. (Color online) Comparative temperature distribution of battery module with glycol–water and pure water coolants at 2 LPM, illustrating differences in thermal uniformity and heat dissipation patterns.

efficiency. This improved thermal stability is advantageous not only for heat removal but also for temperature sensing, as reduced spatial gradients enhance the representativeness and reliability of measured temperatures.

The coolant comparison in the present study was intentionally limited to pure water and an ethylene glycol–water mixture because both can be evaluated within the same indirect liquid cooling architecture and under consistent operating conditions. Advanced coolants, such as nanofluids and dielectric liquids, may offer additional thermal-management capabilities; however, their application may involve substantially different thermophysical properties, flow resistance, pumping requirements, material compatibility, stability, and cooling system design considerations. In particular, adopting a coolant with markedly different viscosity or heat transfer characteristics may require the modification of the flow channel geometry and pump operating conditions to achieve an appropriate thermal–hydraulic balance. Therefore, a direct comparison of these advanced coolants using the unchanged system configuration adopted in this study may not provide an equivalent design basis. Their evaluation is consequently considered a separate optimization problem and will be investigated in future work using coolant-specific system configurations and operating parameters.

The effect of cooling jacket configuration was examined by comparing counter-flow and parallel-flow arrangements in the stacked casing, as shown in Fig. 2. The advantage of the counter-flow arrangement is reflected primarily in the spatial uniformity of the temperature field rather than simply in the maximum temperature. In the parallel-flow configuration, the coolant in the stacked cooling paths travels in the same direction, causing the coolant temperature to increase progressively along similar downstream regions. Consequently, the cooling capability decreases simultaneously toward the downstream side of the stacked module, resulting in a greater concentration of relatively high-temperature regions and a less balanced temperature distribution between different portions of the battery module. In contrast, the

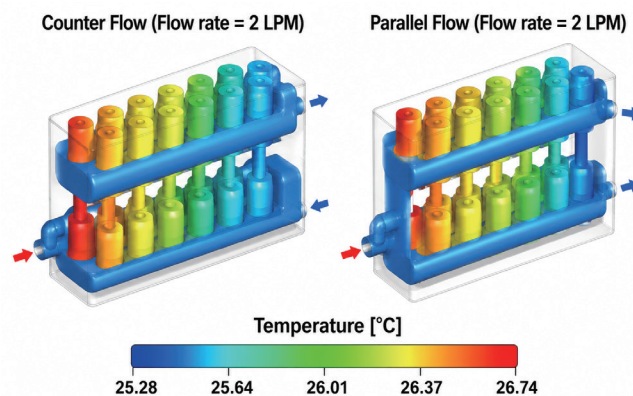


Fig. 2. (Color online) Comparison of temperature distributions in the battery module using glycol–water coolant under counter-flow and parallel-flow configurations in the stacked casing design at 2 LPM. The temperature contours illustrate differences in spatial thermal uniformity and the distribution of high-temperature regions between the two flow arrangements.

opposite coolant flow directions in the counter-flow configuration provide complementary cooling along the stacked flow paths. A region located downstream with respect to one coolant path is closer to the upstream, low-temperature coolant region of the opposing path. This complementary heat removal mechanism suppresses the accumulation of high-temperature regions and produces a more spatially balanced temperature field across the stacked battery module, as indicated by the more uniformly distributed temperature contours in Fig. 2. Therefore, the counter-flow configuration is considered more favorable in terms of temperature uniformity and the suppression of localized thermal gradients. From a sensing perspective, a more uniform and predictable temperature field may also reduce strong spatial variations between candidate sensing locations and improve the representativeness of temperature measurements.

The effect of coolant flow rate on thermal performance was investigated by varying the flow rate from 1 to 5 LPM. The results, presented in Fig. 3, show a strong dependence of maximum cell temperature on flow rate at lower values. Increasing the flow rate from 1 to 2 LPM led to a significant reduction in maximum cell temperature, whereas further increases beyond 2 LPM resulted in diminishing returns. Considering pump size, power consumption, and system complexity, an optimal flow rate of 2 LPM was identified, maintaining the battery temperature at approximately 26.7 °C.^(8,10) This operating condition represents a practical balance between effective cooling and energy efficiency, and defines a suitable target for flow monitoring and control in sensor-assisted BTMS operation. On the basis of the combined CFD results, an optimized liquid-cooled battery module design was established, consisting of an ethylene glycol–water coolant, a counter-flow stacked casing, and a nominal flow rate of 2 LPM. These findings demonstrate the capability of advanced numerical modeling to balance accuracy, computational efficiency, and engineering relevance in battery thermal management.

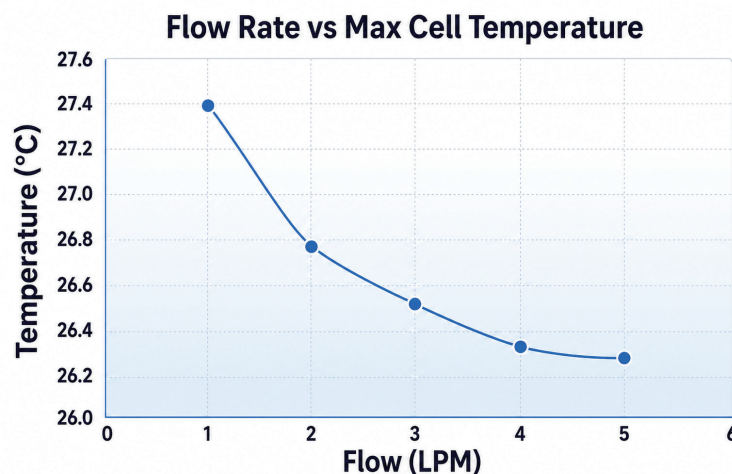


Fig. 3. (Color online) Flow rate vs maximum cell temperature with glycol–water coolant by counter-flow in a stacked casing design.

The present coolant comparison should therefore be interpreted as a comparison between fixed coolant formulations rather than an optimization of ethylene glycol concentration. A systematic mixture-ratio study would require varying the water-to-ethylene glycol composition while recalculating the corresponding temperature-dependent thermophysical properties. Increasing the water fraction may improve thermal conductivity and specific heat capacity, whereas increasing the glycol fraction can alter viscosity, flow resistance, pumping requirements, and low-temperature operating capability. In future work, we will therefore investigate the mixture ratio as an additional design variable and evaluate its effects on maximum cell temperature, temperature uniformity, pressure drop, and pumping demand to identify an appropriate compromise between thermal performance and practical operating requirements.

Moreover, the CFD-derived temperature and velocity fields provide preliminary quantitative guidance for sensor-oriented design. On the basis of the predicted temperature gradients and coolant flow paths, a six-point distributed layout is recommended as an initial configuration, with three sensing positions—upstream, intermediate, and downstream—assigned to each battery layer. The downstream positions, particularly those adjacent to the predicted high-temperature regions, are given a higher monitoring priority because they are more sensitive to coolant heating and local thermal accumulation. This arrangement provides the coverage of the temperature evolution along the coolant path while also enabling the comparison between the two stacked battery layers. Because these positions are derived from numerical predictions, their suitability for actual sensor placement requires confirmation through experimental temperature measurements.

To assess the consistency and reliability of the numerical methodology, the present results were compared with the results of previous numerical studies on liquid-cooled BTMS optimization. Prior CFD investigations have emphasized the importance of coolant flow distribution and heat transfer efficiency, such as the cell-to-pack cooling analysis reported by Zhang *et al.*⁽²⁾ and the thermal interface material study by Gu *et al.*⁽⁷⁾ Bamrah *et al.*⁽⁸⁾ and Goyal *et al.*⁽¹⁰⁾ further demonstrated the applicability of CFD across different operating conditions and system scales. The superior performance of the ethylene glycol–water mixture observed here is consistent with the findings by Joshi *et al.*,⁽¹¹⁾ while the advantages of counter-flow heat exchange align with the established thermal engineering principles reported in the literature.^(9,12,13) This agreement strengthens the credibility of the simulation framework and confirms the general applicability of the identified design trends. Although the agreement with previous numerical studies supports the consistency of the predicted thermal trends, the experimental validation of the present battery module has not yet been conducted. This represents a limitation when translating the CFD predictions to practical battery systems, where contact thermal resistance, manufacturing tolerances, coolant property variations, environmental heat losses, and sensor measurement uncertainty may affect the actual thermal response. Future validation will therefore employ a laboratory-scale liquid cooling platform corresponding to the simulated battery module. Thermocouples or resistance temperature detectors will be placed at representative cell locations to measure local and maximum cell temperatures, while inlet and outlet coolant temperatures and flow rates will be monitored simultaneously. Infrared thermal imaging will also be considered to characterize the surface temperature distribution and identify

possible hot-spot locations. The comparison of these experimental measurements with the CFD-predicted temperature distributions will enable the quantitative assessment of model accuracy and provide a basis for subsequent model calibration and refinement.

A detailed evaluation of thermal performance metrics further supports the optimized design. The maximum cell temperature of approximately 26.7 °C lies well within the recommended operating range for lithium-ion batteries and reduces the risk of accelerated degradation or thermal runaway. Temperature uniformity was significantly improved, with a maximum temperature difference across the module of less than 2 °C, compared with values exceeding 5 °C in less optimized designs. Such uniformity benefits not only balanced cell aging but also the consistency of temperature measurements across multiple sensing points. These results clarify the practical improvement achieved by the proposed integrated optimization. In particular, the optimized combination of the ethylene glycol–water coolant, counter-flow stacked casing, and 2 LPM operating condition maintains the maximum cell temperature at approximately 26.7 °C while limiting the module temperature difference to less than 2 °C. Compared with the temperature differences exceeding 5 °C observed for less optimized configurations, this represents a substantial improvement in thermal uniformity. Importantly, increasing the coolant flow beyond 2 LPM produces only limited additional cooling, indicating that the proposed design achieves improved thermal performance without relying on excessive coolant circulation and associated pumping demand. The contribution is therefore not simply the identification of a high-flow cooling condition, but the determination of a thermally uniform and practically efficient operating point that can also provide a more stable thermal field for temperature monitoring.

In addition, the pressure drop across the cooling channels remained manageable at the optimal flow rate, enabling effective cooling with moderate pumping power. This balance is critical for practical applications where energy efficiency and long-term reliability are key considerations. The effects of auxiliary components were also examined. Simulations with different water tank volumes (5, 10, and 15 L) showed that larger tanks provide enhanced thermal buffering, stabilizing coolant inlet temperature and reducing temperature fluctuations during transient conditions. Regarding scalability, the present double-layer battery module can serve as a basic design unit for extension to larger EV battery packs. However, increasing the number of cells and cooling channels may lead to greater flow maldistribution, pressure drop, and temperature non-uniformity. Therefore, direct geometric scaling may not be sufficient, and larger systems may require multiple coolant branches, optimized manifold designs, and appropriate pump capacity to maintain a balanced coolant distribution. The proposed CFD framework can be extended to these larger configurations by re-optimizing the flow distribution, cooling channel arrangement, and operating conditions according to the pack size.

However, this improvement must be balanced against increased system volume and weight. Pump motor specifications were likewise found to be critical. Variable-speed pumps outperformed fixed-speed pumps by maintaining the target 2 LPM flow rate more precisely under varying thermal demands. For example, a 100 W variable-speed pump achieved higher flow stability and energy efficiency, whereas underpowered or oversized pumps led to compromised thermal performance or unnecessary energy consumption. These results highlight

that optimal thermal management depends on the integrated design of the cooling jacket, coolant, and supporting infrastructure. Overall, the CFD results demonstrate that an optimized liquid cooling design not only enhances thermal management performance but also produces a stable and predictable temperature field that supports temperature sensing, monitoring, and control in battery systems. By linking thermal optimization with sensor-oriented considerations, we provide practical guidance for the development of safer, more reliable, and more efficiently monitored liquid-cooled battery modules.

In this study, we demonstrate the effectiveness of CFD simulations (implemented in COMSOL) for optimizing liquid-cooled battery modules to achieve stable and efficient thermal management, while also supporting sensor system design for battery packs. In practice, reliable temperature and flow sensing (or estimation) depends strongly on the underlying thermal–fluid field; thus, the present CFD model can be used as a preliminary physics-based tool to identify candidate sensor locations, define predicted thermal indicators (e.g., hot-spot tendency, flow maldistribution, and pressure drop limits), and establish initial control targets for BTMS operation. Experimental validation is required before these predictions are directly applied to practical sensor placement and closed-loop control. The results confirm that coolant selection is a dominant factor for thermal performance. Compared with pure water, the ethylene glycol–water mixture provides improved flow uniformity while maintaining comparable heat transfer capability, yielding a more stable thermal environment that reduces hot-spot risk and improves temperature consistency across cells. The cooling jacket configuration is also critical: the counter-flow stacked-casing design achieves more effective heat exchange than the parallel-flow arrangement, leading to a more uniform temperature distribution. In addition, the coolant flow rate study indicates clear diminishing returns beyond moderate flow rates; an optimal value of 2 LPM maintained the module temperature at approximately 26.7 °C with reasonable pumping demand and system complexity, as shown in Fig. 4. Together, these findings show how CFD-

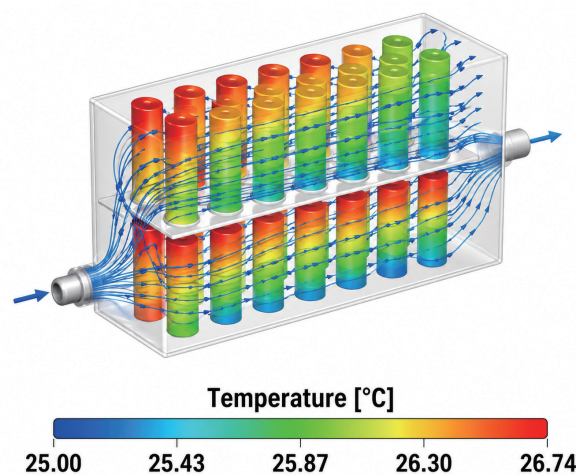


Fig. 4. (Color online) Optimal flow rate and thermal management performance considering water tank size and motor specifications with glycol–water coolant by counter-flow in a stacked casing design at 2 LPM.

based design space exploration can rapidly converge on practical BTMS parameters and simultaneously provide a physics-based basis for thermal-state monitoring and diagnostic sensing strategies.

From an application perspective, the proposed workflow offers a roadmap for developing compact and reliable liquid-cooled battery systems for EVs and high-power electronics, and it can be extended to sensor-driven operation by linking CFD outputs to measurable quantities (temperature gradients, inlet–outlet ΔT , pressure drop, and inferred heat generation) for real-time monitoring and control. Future work should address several limitations. An important limitation of the present study is that the optimization is primarily based on steady-state operating conditions. Although this approach provides a controlled basis for identifying the effects of coolant type, flow configuration, and coolant flow rate, actual EV batteries experience continuously varying thermal loads during acceleration, cruising, regenerative braking, and charging. Under these conditions, changes in current and heat generation rate may cause the maximum cell temperature and hot-spot location to evolve with time. Therefore, the steady-state temperature field obtained in this study should be interpreted as a design reference rather than a complete representation of dynamic EV thermal behavior. Nevertheless, the optimized coolant and flow configurations identified here provide a useful baseline for subsequent transient analysis because they establish the fundamental heat removal capability of the cooling system.

Future work will extend the present CFD framework to transient operating conditions by introducing time-dependent current and heat generation profiles representative of EV drive and charge cycles. The transient model will track the temporal evolution of maximum cell temperature, cell-to-cell temperature difference, hot-spot location, coolant inlet–outlet temperature difference, and cooling response time. Particular attention will be given to high-load acceleration and fast-charging periods, during which rapid heat accumulation may temporarily exceed the heat-removal capability predicted from steady-state conditions. Coupling the transient CFD model with a physics-based electrochemical model will further enable spatially and temporally varying heat sources to be predicted rather than prescribed. In such a coupled framework, local electrochemical variables, including current density, reaction overpotential, state of charge, and concentration distributions, can be used to determine reversible heat, ohmic heat, reaction-related irreversible heat, and other polarization losses throughout the cell domain. The resulting volumetric heat generation field can then be transferred to the CFD thermal model as a time-dependent heat source. This electrochemical–thermal coupling would be particularly important during high-C-rate discharge, rapid acceleration, and fast charging, where strongly non-uniform reaction rates may produce transient local hot spots that cannot be fully reproduced by the simplified heat generation model used in the present study. Consequently, such an extension is expected to improve the prediction of hot-spot magnitude, location, and migration, and to provide a more physically realistic basis for evaluating cooling system response and temperature sensor placement. Such an extension will also be valuable for sensor-oriented BTMS design because dynamic hot-spot trajectories can be used to evaluate sensor response requirements, optimize sensor locations, and develop adaptive coolant flow control strategies under realistic EV operating conditions. Finally, long-term aging and degradation effects should be integrated, since sustained temperature non-uniformity

accelerates capacity fading; combining thermal, aging, and control-oriented sensing models would support BTMS designs that are not only efficient in the short term, but also reliable over the full battery lifetime.

4. Conclusions

In this study, we employed CFD simulations using COMSOL Multiphysics to systematically optimize the design of a liquid-cooled battery module while positioning the thermal analysis as a design support tool for temperature sensing systems in battery thermal management. By evaluating coolant type, cooling jacket configuration, flow rate, and system-level components, the results demonstrate that an ethylene glycol–water mixture combined with a counter-flow stacked casing design provides superior thermal uniformity and effective heat dissipation. An optimal coolant flow rate of 2 LPM was identified, maintaining the battery temperature at approximately 26.7 °C while balancing cooling performance and energy efficiency. The principal contribution of this study, beyond the individual cooling parameters examined in previous investigations, is the establishment of an integrated CFD-based optimization framework that simultaneously considers coolant properties, flow configuration, operating flow rate, and system-level components. The optimized design maintains the maximum cell temperature at approximately 26.7 °C and limits the temperature difference across the module to less than 2 °C, demonstrating improved thermal uniformity without requiring excessive coolant flow. Furthermore, by treating the simulated temperature and flow distributions as virtual sensing information, the proposed framework connects cooling optimization with temperature sensor placement, thermal-state monitoring, and control target definition. This sensor-informed perspective represents an extension of conventional CFD-based battery cooling studies and provides a practical pathway toward integrated thermal management and monitoring in advanced battery systems. Beyond improving thermal management performance, the CFD-derived temperature and flow fields offer quantitative insights that are directly relevant to sensing applications, including the identification of thermally representative regions, the assessment of temperature gradients, and the definition of stable operating envelopes for monitoring and control. The improved temperature uniformity and manageable pressure drop achieved by the optimized design contribute to more reliable temperature sampling and support sensor-informed BTMS operation. Overall, the results confirm that CFD-based modeling can serve not only as an effective optimization tool for liquid-cooled battery modules but also as a virtual sensing framework that supports sensor placement, flow control strategies, and safety threshold definition. The proposed approach provides practical guidance for the development of safer, more reliable, and more efficiently monitored battery systems and establishes a foundation for the future integration of transient simulations, physics-based electrochemical–thermal coupling for spatial–temporal heat-source prediction, and sensor-assisted control in advanced BTMSs.

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