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CFD-Based Thermal Analysis and Optimization of Electric Vehicle Battery Packs

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ABSTRACT

The rapid adoption of electric vehicles (EVs) has increased the demand for lithium-ion battery packs with high energy density, fast-charging capability, and long service life. However, heat generated during battery charging and discharging can significantly affect electrochemical performance, ageing, safety, and thermal stability. Therefore, an efficient battery thermal management system (BTMS) is essential for maintaining the battery pack within an appropriate operating temperature range and minimizing temperature non-uniformity. This study presents a computational fluid dynamics (CFD)-based thermal investigation and optimization methodology for a liquid-cooled lithium-ion battery pack. A three-dimensional battery module is developed, and coupled heat transfer between battery cells, cooling plate, and heat-transfer fluid is investigated under different discharge rates and coolant flow conditions. The thermal field is evaluated using maximum cell temperature, temperature difference between cells, pressure drop, and pumping-power requirement. Parametric optimization is proposed by varying cooling-channel geometry, coolant velocity, and channel arrangement. The methodology combines conjugate heat transfer analysis with multi-objective performance evaluation to identify a suitable configuration that provides effective heat removal while limiting hydraulic losses. Previous numerical studies indicate that increasing coolant flow rate generally reduces the maximum battery temperature, although its influence on temperature uniformity can be limited, making channel configuration an important design variable. The proposed framework can be used to develop compact, lightweight, and energy-efficient BTMS architectures for next-generation electric vehicles.

KEYWORDS

Electric vehicle, Lithium-ion battery, Battery thermal management, Computational fluid dynamics, Liquid cooling, Temperature uniformity, Thermal optimization, Pressure drop.

INTRODUCTION

Electric vehicles have emerged as an important technology for reducing dependence on conventional fossil-fuel-based transportation. Improvements in

lithium-ion battery technology have enabled EVs to achieve higher energy density, power density, and driving range. Nevertheless, thermal management remains one of the major engineering challenges associated with high-performance EV battery systems.

During charging and discharging, lithium-ion batteries generate heat due to internal electrochemical and electrical losses. When the generated heat is not adequately removed, the cell temperature can increase substantially. Excessive temperature accelerates battery degradation and may create unsafe operating conditions. Conversely, operation at very low temperatures can reduce electrochemical reaction rates and available battery capacity. Consequently, the BTMS must maintain the battery temperature within a suitable range while minimizing temperature differences among individual cells.

The thermal requirements become more demanding during high-rate discharge and fast charging because battery heat generation increases with current. Temperature non-uniformity is also important because cells operating at different temperatures may experience different ageing rates, resulting in non-uniform degradation of the complete battery pack. Previous research has identified cooling performance, temperature uniformity, system size, mass, and pressure drop as important criteria for BTMS design.

Several cooling technologies have been investigated, including air cooling, liquid cooling, phase-change-material (PCM) cooling, heat pipes, thermoelectric cooling, and hybrid systems. Air cooling offers relatively simple construction but has limited heat-removal capability because of the comparatively low heat capacity and thermal conductivity of air. Liquid cooling provides considerably higher heat-transfer capability and is therefore particularly attractive for high-power EV battery packs.

LITERATURE REVIEW

Battery thermal management research can broadly be divided into air cooling, liquid cooling, PCM-based cooling, thermoelectric cooling, heat-pipe cooling, and hybrid approaches. Early investigations concentrated on air-cooling arrangements because of their simplicity and low cost. However, as EV battery capacity and power requirements increased, liquid cooling became increasingly attractive. Reviews have shown that liquid-based BTMSs provide high heat-transfer capability and are widely used in modern high-performance EV applications.

Pack-level structural design is another important research area. Numerical investigations have demonstrated that the arrangement of battery cells and cooling plates affects both heat removal and temperature uniformity. Poor thermal conductivity between the cell stack and cooling plate can become a significant limitation to heat dissipation.

`CFD has become a powerful tool for analyzing detailed temperature and velocity distributions in BTMSs. It allows researchers to investigate the effects of coolant velocity, channel geometry, cell

spacing, cooling-plate thickness, and coolant properties without manufacturing every candidate design.

Falcone et al. investigated lithium-ion battery thermal management using CFD and compared air- and water-cooling configurations. Their results demonstrated the importance of cooling geometry and coolant selection in controlling cell temperature.

Recent research has moved toward multi-parameter optimization. For example, serpentine liquid-cooled modules have been investigated using combinations of coolant type, flow velocity, and discharge rate, with thermal performance evaluated together with hydraulic requirements.

Hybrid cooling systems that combine liquid cooling and PCM are also receiving attention because liquid cooling provides active heat removal while PCM can suppress temperature peaks and improve thermal uniformity.

A recent review published in 2026 identified hybrid cooling, AI-driven adaptive control, two-phase cooling, and advanced thermal materials as promising directions for next-generation EV BTMSs.

Objectives of the Study

The major objectives are:

- To develop a three-dimensional CFD model of a liquid-cooled lithium-ion battery pack.
- To predict the temperature distribution of individual battery cells.
- To investigate the influence of discharge rate on battery temperature.
- To study the effect of coolant flow rate on maximum battery temperature.
- To investigate the influence of cooling-channel geometry on temperature uniformity.
- To calculate pressure drop and pumping-power requirements.
- To identify an optimized cooling configuration using multiple performance indicators.
- To establish a methodology suitable for future experimental validation.

Physical Model

A representative battery module consisting of cylindrical lithium-ion cells is considered. The cells are arranged inside an aluminum cooling structure containing coolant channels. Aluminum is selected for the cooling plate because of its relatively high thermal conductivity and low density.

The computational domain consists of three primary regions:

1. Lithium-ion battery cells.
2. Thermally conductive cooling structure.
3. Liquid coolant region.

The battery cells are assumed to generate heat volumetrically during discharge. Heat is transferred through conduction from the battery cell to the surrounding solid structure and subsequently removed by convection to the flowing coolant.

The following design parameters are considered as optimization variables:

- Coolant inlet velocity.

- Cooling-channel hydraulic diameter.
- Number of cooling channels.
- Channel arrangement.
- Distance between adjacent battery cells.
- Cooling-plate thickness.

CFD Methodology

The numerical analysis can be performed using ANSYS Fluent or an equivalent commercial CFD platform.

The complete simulation procedure consists of the following steps:

Step 1: Geometry Development

The battery cells, cooling plate, coolant channels, inlet, and outlet are constructed using a CAD package.

Step 2: Mesh Generation

A hybrid or polyhedral mesh can be generated with local refinement near:

- Battery surfaces.
- Cooling-channel walls.
- Inlet and outlet regions.
- Regions with expected high temperature gradients.

A mesh-independence study should be performed using at least three different mesh densities.

Step 3: Material Properties

Temperature-dependent thermal properties should preferably be used for the battery, aluminum structure, and coolant.

RESULTS AND DISCUSSION

Temperature Distribution

The temperature contours obtained from CFD should be used to identify the hottest region of the battery module. Particular attention should be given to cells located at the downstream portion of the cooling channels because the coolant temperature increases as it absorbs heat.

The optimized channel should demonstrate a more uniform temperature distribution than the baseline configuration.

Effect of Coolant Velocity

The coolant velocity is expected to have a strong influence on convective heat transfer. Increasing velocity generally increases the convective heat-transfer coefficient and consequently enhances heat removal.

However, a continuous increase in velocity is not necessarily economically or energetically desirable because pressure drop and pumping power increase with flow rate.

Therefore, the optimum velocity should be selected based on the point at which additional cooling becomes relatively small compared with the additional hydraulic penalty. Recent CFD studies similarly emphasize the need to evaluate thermal performance together with pressure drop rather than considering maximum temperature alone.

Pressure Drop

The pressure distribution inside the cooling channels should be analyzed simultaneously with temperature distribution.

Complex channels such as serpentine or highly tortuous channels may improve heat transfer by increasing flow mixing, but this benefit can be accompanied by increased pressure drop.

Thus, the final design should not simply correspond to the geometry having the lowest battery temperature. Instead, it

should provide an appropriate compromise between:

- Heat-transfer capability.
- Temperature uniformity.
- Pressure drop.
- Pumping power.
- Weight.
- Manufacturing complexity.

Validation Strategy

Numerical validation is essential before the proposed CFD model can be used for publication as an experimentally supported research result. A battery module with the same geometry and operating conditions should be tested experimentally.

Thermocouples or RTDs can be attached to selected battery surfaces. Coolant inlet temperature, coolant outlet temperature, flow rate, and battery electrical operating conditions should be recorded.

Comparison with Existing Studies

Previous studies have demonstrated the importance of pack-level cooling configuration. For example, structural optimization of liquid-cooled battery packs has shown that suitable arrangements can simultaneously improve cooling performance and temperature uniformity while controlling additional volume, weight, and pressure drop. A 2024 numerical review concluded that channel and cold-plate configurations are among the commonly investigated architectures for cylindrical and prismatic cells, respectively. It also reported that increasing heat-transfer-fluid flow rate is effective for reducing maximum temperature, but its benefit for reducing temperature non-uniformity can be comparatively limited.

More recent work has expanded the design space toward immersion cooling. A 2025 study reported substantial improvements in thermal uniformity using optimized forced immersion cooling under high discharge conditions. These findings support the central premise of the present study: BTMS optimization should be treated as a coupled thermal-hydraulic problem rather than a simple temperature-minimization problem.

Practical Engineering Implications

The proposed CFD-based methodology has several practical implications for EV battery-pack design. First, CFD can reduce the number of physical prototypes required during cooling-system development. Second, it enables engineers to identify local hot spots that may not be evident from average temperature measurements. Third, simultaneous analysis of pressure drop allows the cooling system to be designed with lower auxiliary energy consumption. For automotive applications, the final BTMS should also satisfy requirements related to:

- Compact packaging.
- Low weight.
- Low manufacturing cost.
- High reliability.
- Resistance to coolant leakage.
- Ease of maintenance.
- Thermal runaway mitigation.
- Compatibility with battery-management systems.

The literature increasingly points toward hybrid and adaptive BTMS architectures as promising approaches for

balancing thermal performance, energy consumption, safety, and scalability.

FUTURE SCOPE

Future research can extend the present work in several directions. A coupled electrochemical-thermal model can be developed to predict heat generation more accurately. AI and machine-learning algorithms can be integrated with CFD to reduce computational time during optimization.

Immersion cooling, PCM-liquid hybrid cooling, two-phase cooling, and dielectric coolants can also be investigated. Recent research suggests that hybrid and advanced cooling technologies are becoming increasingly important for high-power and fast-charging EV applications. Furthermore, digital-twin technology can be combined with real-time battery-temperature sensors to enable adaptive thermal management during actual vehicle operation.

CONCLUSIONS

A CFD-based methodology for thermal analysis and optimization of an electric vehicle lithium-ion battery pack has been presented. The study emphasizes that effective BTMS design requires simultaneous consideration of battery temperature, temperature uniformity, coolant flow distribution, pressure drop, and pumping power.

The following conclusions are drawn:

1. Battery heat generation increases significantly with increasing electrical loading and discharge rate.
2. Liquid cooling provides an effective mechanism for removing heat from high-power battery modules.
3. Coolant velocity strongly influences maximum battery temperature through its effect on convective heat transfer.
4. Excessively high coolant flow rates may produce diminishing thermal benefits while increasing pressure drop and pumping power.
5. Cooling-channel geometry plays a major role in controlling both temperature uniformity and hydraulic losses.
6. The optimum BTMS configuration should therefore be determined using a multi-objective thermal-hydraulic optimization approach.
7. CFD provides an effective platform for screening and optimizing battery cooling configurations before experimental prototyping.
8. Experimental validation remains essential for establishing the accuracy of the proposed numerical model.

The proposed framework provides a foundation for developing lightweight, compact, and energy-efficient battery thermal management systems for next-generation electric vehicles.

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