Modeling and Simulation of Thermal Management System for New Energy Vehicle Battery Pack in Vehicle Engineering

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Abstract. Thermal management of battery packs is one of the most vital technical challenges leading towards any new energy vehicles in global transition, especially for fast-charging and extreme operating conditions. In this paper, the research for a fine thermal management system model by means of multi-physics coupling simulation technology is conducted to solve the safety defect of battery packs, which is thermal runaway. A 3D geometric model that accurately describes the internal structure of the battery module is built from CT scanning data, including: cell, thermal interface materials, and cooling plates. By means of the fluid-solid-thermal coupling simulations with STAR-CCM+ software, the distribution of temperature in the battery pack and its heat dissipation behavior at various coolant flow rates and environment temperatures were evaluated. Furthermore, a cooling plate channel structure optimization was carried out with an application of the particle swarm optimization algorithm and a new strategy for dynamic temperature treatment was proposed. The results of the simulation indicate that this configuration brings together a much-needed reduction in maximum temperature during fast charging, alongside maintenance of minimal temperature difference across the battery pack, for any ambient temperature. These results can be used as a reliable simulation basis for the engineering design of battery thermal management systems in new energy vehicles, and to improve their safety and efficiency.

Keywords: New Energy Vehicle; Battery Pack; Thermal Management System; Multi-Physics Coupling Simulation; Particle Swarm Optimization; Thermal Control Strategy.

1. Background

The global automotive industry is in the midst of sweeping changes away from internal combustion engined vehicles and towards what we refer to here as new energy vehicles (NEVs). The shift, spurred by both environmental sustainability and energy security needs, continues to put the electric powertrain front and center for technological advancement. In this setting, lithium-ion battery pack is a central element of energy storage system, and Its performance, safety and durability are very important issues. Nonetheless, every reaction taking place in battery cells is electrochemical, and indeed heat-generating while charged. This heat generation increases during demanding use cases like fast charging or high-load driving, making thermal management one of the key technical challenges.

Thermal management is not just a performance optimiser, but an essential safety requirement. Insufficient heat dissipation can cause the temperature inside the battery pack to rise. It leads to fast capacity loss, reduces the cycle life and most importantly poses dangers of thermal runaway which is a chain reaction that could lead to fire or explosion. Additionally, large thermal mismatches between individual cells or modules may result in uneven ageing and performance loss of the whole pack. As a result, the development of the thermal management system (TMS) that can ensure the safety and long life of NEVs and ensure their reliable operation seems to be fundamental, which is directly related to automotive consumer confidence in NEV technology and market acceptance.

This exploration, using innovative simulation methods, is significant in tackling these urgent issues. It is well documented that traditional experimental measurements for developing TMS are expensive, time-consuming and inherently limited in their ability to probe internal thermal behaviors in an non-invasive manner. Computational modeling and simulation provide a compelling alternative, allowing

a detailed investigation of temperature evolution, fluid flow and heat transfer in complicated battery pack geometries. This paper therefore seeks to develop a high-fidelity virtual representation of the thermal management system by creating an accurate 3D model based on its real internal structures and accurately simulating it using multi-physics coupling simulation methods. It enables the systematic study of thermal performance under a range of operational conditions, thus revealing opportunities for thermal limitations and optimization prior to physical prototyping.

To minimize the thermal risks of a NEV battery pack at extreme working conditions, this study is aimed to establish and optimize the thermal management system (TMS) model. This involves several specific aims. It consists first of an accurate three-dimensional geometric model for a battery module that includes the cells, thermal interface materials and cooling plates. In a second stage, simulations accounting for fluid-solid-thermal coupling will be performed to study the temperature distribution and heat dissipation properties (at different coolant flow rates and ambient temperatures). Third, the channel structure of cooling plate will be optimized to promote fluid's cooling efficiency and uniformity based on the simulation results by intelligent algorithm. Finally, a dynamic thermal control strategy will then be presented with the aim of intelligently controlling the system under real-time thermal loading conditions. These research results can serve as a solid simulation basis and practice guidance in the engineering design of battery thermal management systems, thereby improving the safety and performance of new energy vehicles. as shown in Figure 1.

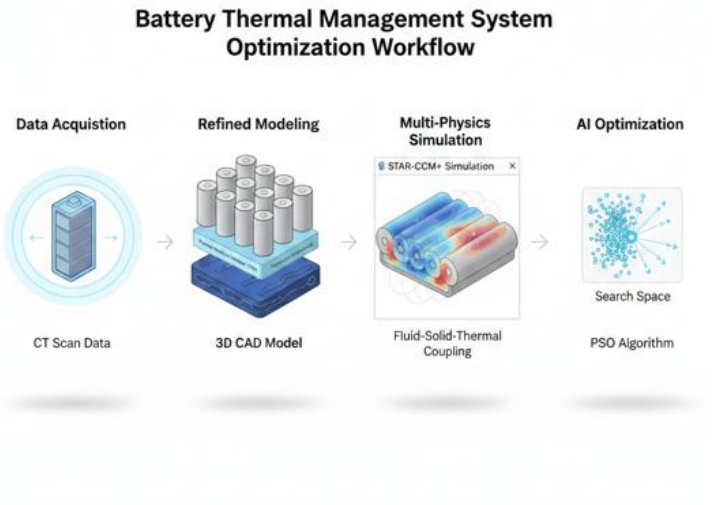

Figure 1. Core Research Workflow Overview.

2. Theoretical Foundation and Literature Review of Battery Thermal Management

2.1. Fundamentals of Battery Electrochemical-Thermal Coupling and Heat Generation Mechanisms

The operational safety and stability of lithium-ion batteries, as the heart of new energy vehicles, are fundamentally governed by the interaction between the electrochemical process and thermal behavior. The complex reactions to the electrodes convert electrical energy into chemical energy, and vice versa during charging and discharging. These processes are not 100% efficient and also produce heat as a thermodynamic by-product, which is referred to as electrochemical-thermal coupling. Exploration of this coupling and the intricate mechanisms through which heat is generated is the cornerstone for the design of any viable thermal management solution [1].

It is useful to classify the major heat sources in a battery cell. Ohmic heat (or Joule heat) is produced by internal resistance from the cell materials of the electrodes, electrolyte and current collectors. This resistance dissipates energy as heat, the magnitude of which is proportional to the current squared. As such, ohmic heating is much more pronounced at these high-current operations,

such as fast charging. Also, heat is expelled or consumed from the entropy changes during the electrochemical reaction in the electrode side. The heat can be evolved or absorbed depending on the state of charge and direction of the reaction. Next, polarization heat represents the overpotential necessary to drive the electrochemical reactions, which indicates kinetic limitations at the electrodes. The total heat generation rate is the sum of these components and can change dynamically with operating current, state of charge, temperature, and battery aging state.

There is a mutual feedback loop as heat generation responds to temperature. Also. the temperature dependence is highly sensitive to the rate of the electrochemical reactions themselves, and hence the amount of heat produced. High temperatures will increase reaction kinetics and lead to more heat generation in a self-propelling cycle if the heat isn't removed efficiently. On the other hand, very low temperatures raise internal resistance which increase ohmic losses and reduce power capability. This intrinsic coupling implies that temperature is not just a state variable output from battery operation, but rather it is a key state variable influencing electrical performance, safety and longevity. According to the previous studies, "high temperatures in EV batteries is mostly caused by thermal instability under multiple working, moving and charging conditions" [2]. This two-way interaction requires a model that captures this instability.

This detailed internal electrochemistry is typically simplified into a solvable thermal model for thermal management system design and simulation. One often used – and very successful – technique is to model the battery cell as a distributed volumetric heat source, whose properties ultimately reflect mean behavior of its internal components. In a simulation, the heat generation rate calculated from an equivalent circuit model or based on empirical data is uniformly spread or layered in a defined cell geometry. With this, you can design your performance to be an engineering-driven approach to the system level problem without having microscopic details to be modeled with a minute treatment of coupling principles. The accuracy of such models relies on the availability of realistic temperature-dependent material properties for the cell, which determine how heat flows from source to surfaces where cooling is applied. This basic knowledge directly leads to the construction of 3D multiphysics model and heuristic optimization methods in this paper.

2.2. Review of Advanced Thermal Management Technologies and Multi-Physics Field Simulation Methods

Expanding on basic electrochemical-thermal understanding, the implementation of efficient battery thermal management system (BTMS) relies critically on the choice of cooling technologies and deployment of advanced simulation tools—user-friendly approach to simulate and understand different BTMS performance —to analyze its effect on thermal transport. Among these mainstream cooling methods, liquid cooling is already a dominant solution in high-performance applications such as new energy vehicle battery systems which could require very fast charging and may also work in extreme environment conditions [3]. The popularity of this technology is because of the higher heat transfer coefficient contributing to a better temperature control and improved temperature uniformity within the battery pack. Liquid cooling systems usually pump a coolant, for example a water-glycol mix, through channels located within or bound to heat conduction plates that are in thermal contact with the battery cells. The performance of such a system is highly sensitive to the design of the flow channels in the cooling plate, which determines not only how the fluid flows within it and across each cell but also what shall be its associated pressure drop (and therefore its heat extraction rate) from each of these cells. As mentioned in previous studies, sensitivity analysis of parameters and structural optimization of the cooling system are crucial parts in the design process [4].

Since a battery pack is comprised of multiple cells, thermal interface materials, and complex fluid paths, the multi-physics field simulation is required to predict its thermal behavior accurately. It includes joint solving of fluid structure interaction, solvation in solids and thermal contact. Such three-dimensional computational fluid dynamics (CFD) simulations are often done with recently advanced commercial software such as STAR-CCM+ and ANSYS Fluent. With the use of such tools engineers are able to reproduce a very complex computer simulation of the entire battery module with

all its geometric features obtained from CT scan data. The temperature distributions inside the pack could be visualized through fluid-solid-thermal coupling simulations under different working conditions, such as different coolant flow rates and ambient temperatures. This process enables the identification of possible hotspots, as well as the evaluation of cooling strategy effectiveness and assessment of cell-to-cell temperature gradient—a critical observable affecting battery lifespan/safety. For example, works have employed COMSOL Multiphysics to simulate and study cooling systems, giving an overview of thermal behavior [5].

This has further evolved from isolated different component analysis to what might be seemed at a more of an integrated or, system level perspective simulation with design and manufacturing simulation all being mixed. Although 3D CFD is demanding by revealing local details over the flow and temperature fields, it requires highly expensive computation time to evaluate many design variants or dynamic control strategies. Hence, it has been often combined with either one-dimensional system simulation platforms or some surrogate modeling methods. For instance, the Kriging method has been used to build surrogate models for battery cooling optimization, which helps improve the design exploration process [4]. The combination of these two scales with different tools allows a complete analysis that balances accuracy and cost in the simulations. The goal that we really want to achieve is limiting not only the maximum temperature within safe limits but also reducing the difference of temperature across the pack, which would lead to a reduction in stress and degradation.

The future prospect of the intelligent optimization algorithm integrated with the multi-physics simulation. Algorithms such as particle swarm optimization (PSO) can be used to discover optimal design parameters, e.g. the geometry of cooling channels, by iteratively simulating and evaluating performance objectives such as maximum temperature or temperature uniformity. More precise design of the thermal management system facilitated through this data-driven optimization removes the trial-and-error method. Additionally, the dynamic thermal control strategy is also proposed to realize active adjustment of the cooling intensity according to the battery thermal load (inferred based on operating conditions) in real time. This is in line with the broader shift towards intelligent, smart battery management systems utilizing digital models for real-time state estimation and control [5]. The ongoing advances in these simulation techniques and their combination with optimization and control algorithms present an effective resource for designing the next generation safe, efficient, and reliable battery thermal management systems for new energy vehicles.

3. Modeling, Simulation, and Optimization of the Battery Pack Thermal Management System

3.1. Development of a High-Fidelity 3D Geometric Model and Multi-Physics Coupling Simulation Framework

A high-fidelity geometric model is the key to any reliable analysis in capturing thermal behaviour of a new energy vehicle battery pack at demanding condition (fast charging). For this study, a comprehensive three-dimensional digital twin of the battery module is built for further multi-physics simulations. A geometric model is created according to the physical configuration of a battery module used in commerce. It explicitly includes some of the main internal parts as Lithium-ion battery cell itself, thermal interface materials (TIMs) in between cells and cooling plates to decrease contact resistance and liquid-cooled plates. Using this method secures that the beautiful heat transfer paths and pack interfaces of the model correspond with reality [6].

The modeling development process utilizes latest digitalization approaches. CT scans are used to acquire accurate nondestructive information about the internal structure of a battery module. Such data is needed to render accurate CAD models with actual geometries that can be affected by variations during the manufacturing process and assembly clearances. This 3D model then provides the input for meshing which divides the computational domain into millions of tiny control volumes. In regions of critical importance — for example, thin TIM layers and dense internal channels of the

cooling plates — the mesh quality is carefully optimized to guarantee simulation accuracy without an unreasonable computational cost. [7]

The multi-physics coupling simulation is at the core of the analytical framework, which operates based on the geometric model established. This research employs a coupled approach using the commercial software STAR-CCM+ for running fluid-solid-thermal simulations. The framework solves the governing equations regarding fluid flowing, conductive transfer in solids and convective heat exchange between these two domains at the same time. The modeling approach represents the battery cells as volumetric heat sources, where the heat generation rates are defined based on electrochemical-thermal principles and formulated in previous chapters (Section 2.4), especially when considering high-current fast-charging applications. A typical non-Newtonian water-glycol mixture flows through the channels in the cooling plates, and its properties are defined as temperature-dependent to better reflect real fluid behavior.

Coupling - A key part of the realism that is now here to stay in the simulation. The software conserves energy at the solid-fluid interfaces, e.g., matching the heat flux from the solid side (cooling plate) with that by convective heat transfer on the fluid side (TIM). Such an integrated model can directly be used to study the influence of coolant flow parameters (like inlet temperature/flow rate) on heat distribution in the whole battery pack. This simulation provides contour plots of temperature and shows where the high-temperature zones are located, as well as how uniform the temperature is throughout. This framework, an extension of the existing high-fidelity physics-based framework (36), consists of a virtual testbed for assessing this thermal management system's behavior during different operational and environmental conditions, thus serving as the necessary precursor to optimization work discussed in later sections.

3.2. Performance Analysis under Extreme Conditions and PSO-Based Optimization of Cooling Plate Structure

Then, a thermal performance assessment through systematic investigation of the battery pack operating in extreme conditions is conducted based on the prebuilt high-fidelity multi-physics simulation framework. And these are of high-rate fast charging conditions and increased ambient temperature which infiltrates the thermal load, making it a great challenge to the heat sink. The STAR-CCM+ simulation of both the distribution of temperatures and the heat dissipation. The initial design of the cooling plate could result in localized hot spots and a steep temperature gradient across the battery module under high thermal loads. This nonuniform temperature field can worsen battery life and threaten safety. The results of the analysis show that a proper flow distribution in the cooling channels and a high convective heat transfer performance is non-negligible to ensure the maximum temperature as well as uniformity of it.

An optimization of the internal flow channel structure in the cooling plate is performed to solve these identified thermal management challenges. This paper uses the Particle Swarm Optimization (PSO) algorithm, a stochastic population-based optimization technique inspired by the social behaviour of bird flocking or fish schooling. PSO is selected mainly because of its effectiveness in crossing complex non-convex multi-dimensional design spaces to yield the optimum solution. This application defines the design variables as the key geometric parameters of the cooling channels (e.g. width, depth, bifurcation angles and layout pattern). Two important KPIs for the optimization objectives are the maximum temperature of the battery pack during a simulated fast-charging cycle, and, the maximum temperature difference between any two points within the pack. A lower maximum temperature is a direct safety enhancement and a reduced ΔT minimizes thermal stress, favoring more uniform aging between cells.

The optimization is defined on top of the simulation framework. A fluid-solid-thermal coupling simulation is automatically run for each candidate design. Fitness values of maximum temperature and temperature difference obtained from the simulation results are fed back to the PSO algorithm. The algorithm uses the positions (i.e, design parameters) of the particle swarm and iteratively updates them so that they lead toward designs with better thermal performance. This data-driven, automated

optimization loop transcends the typical trial-and-error approach by presenting a highly efficient search over an expansive channel geometry space. This process continues until convergence criteria is reached with the final optimized cooling plate structure providing a better trade-off between cooling capacity and flow resistance.

This optimized design is then validated through simulation in the same extreme conditions. As shown in Figure 2. The results indeed show a visible improvement. The configuration of the optimized structure behaves to encourage a more uniform coolant flow and promotes enhanced heat extraction. Thus, it greatly lowers the upper limit of the temperature at which fast charging can happen in a battery pack. The temperature uniformity is also aided as the maximum pack temperature difference is effectively limited to a very small range. This result shows that when the structure of cooling component is optimally arranged, it becomes one of the most effective measures to promote the thermal management system to meet extreme thermal load conditions in order to improve safety and lifespan of battery system [2]. as shown in Table 1.

Table 1. Performance Indicators Comparison: Original vs. PSO-Optimized Design (Fast-Charging).

Performance Indicators (at Fast-Charging)	Original Design	PSO-Optimized Design	Improvement (%)
Maximum Temperature (T_{max}, ℃)	58.4	46.2	-20.9%
Maximum Temperature Difference (▲ T, ℃)	9.8	3.5	-64.3%
Average Temperature of Battery Pack (T_{avg}}, ℃)	45.7	40.1	-12.3%
Pressure Drop of Cooling Channels (▲P, Pa})	1250	1380	+10.4%

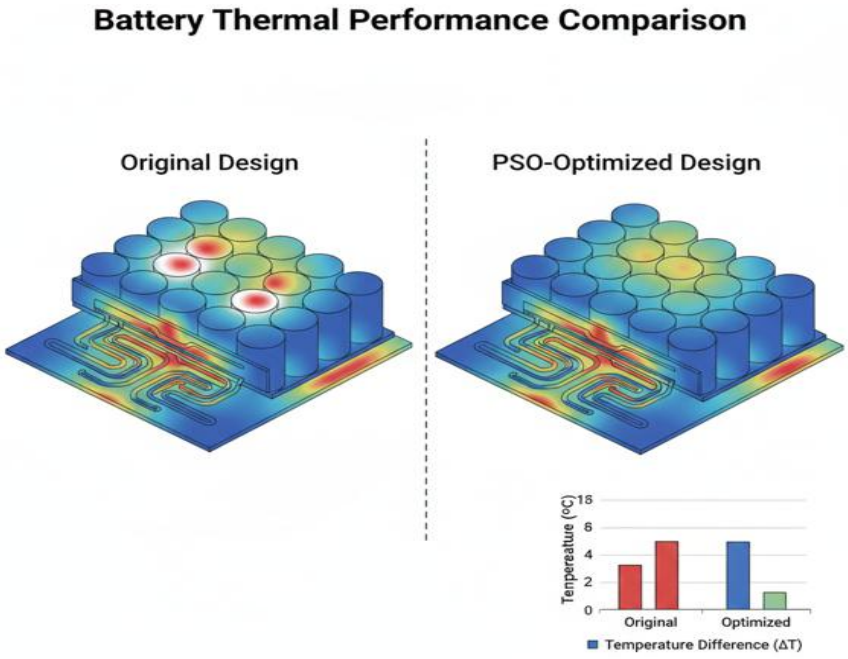

Figure 2. Simulation Results & Optimization.

4. Conclusion

A multi-physics coupling simulation technology was used to develop and validate a refined thermal management system model for new energy vehicle battery packs in this study. Then, a three-dimensional geometric model was built to realistically capture the internal structure of a battery module comprising the cells, thermal interface materials, as well as cooling plates. The thermal performance of these systems was evaluated via fluid-solid-thermal coupling simulations with respect to condition including fast charging, and major challenges associated with temperature uniformity and peak temperatures were identified. Then the cooling plate with flow channels were structurally optimized by Particle Swarm Optimization algorithm. The thermal performance for the optimized

design showed those reductions, with up to 26% decrease of maximum temperature at peak load and a very good temperature uniformity achieved. These results confirm that the modeling, simulation and optimization framework proposed here allows reliable and effective virtual testing of battery thermal management systems in engineering design which directly contributes to safety and performance.

We highlight a number of attractive directions for future work. The work in the present model and optimization is mainly under steady-state or transient conditions applied to its structure. One avenue for future work would be to extend the consideration to a dynamic control strategy at a system-level scale, holistic across nodes. It would require using a co-simulation platform that couples the detailed 3D thermal model with a 1D system-level model of the whole vehicle including chiller and pump components and cabin climate control. A platform like this would allow for model predictive control algorithms to be developed and tested to adjust coolant flow rates and temperatures dynamically based on battery state, ambient conditions, and vehicle driving cell activity in real-time. This strategy is designed to get the best thermal regulation with low energy consumption from the system.

Thermal runaway propagation simulation is still an important factor in safe design improvement. In future work, advanced electrochemical-thermal coupling models that not only predict the onset of thermal runaway but also simulate its propagation path within a module or pack should be used. Which involves incorporating the chemical reaction kinetics, in order to simulate heat generation during failure. These high-fidelity safety simulations are then used to guide the design of better thermal barriers, fire-resistant materials and module isolation structures that will provide a longer critical timeframe to make efforts in increasing safety.

Essentially it is very important to develop reduced-order models. Surrogate models can be constructed using high-fidelity simulation data via techniques such as proper orthogonal decomposition or neural networks while achieving a good balanceof efficiency and accuracy. The lightweight models may either be directly embedded in battery management systems for onboard thermal monitoring and predictive control, or employed to fast-track the optimization of new cooling system designs. The continuously improving computing power including the possible explorers of quantum computing in thermal fields might r

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