Design and Optimization of Cooling Plate for Battery Module of an Electric Vehicle

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Abstract* — *Efficient battery cooling is critical for electric vehicle safety and performance, yet existing methods like air and liquid cooling face limitations, including inadequate heat dissipation, complexity, and weight. This research presents a compact and lightweight cooling plate design utilizing high-conductivity aluminum with mini-channels and silicone pads to enhance thermal management. Ethylene glycol-water coolant circulates through the channels, effectively dissipating heat and preventing thermal runaway. By sandwiching the cooling plates between battery cells and leveraging airflow beneath the vehicle, the system achieves uniform temperature distribution, improved performance, and extended battery life while addressing the challenges of conventional cooling methods.

Keywords* — *Electric vehicle cooling system, Battery thermal management, Lightweight cooling design, Thermal runaway prevention, Enhanced battery performance.

1. INTRODUCTION

In the face of life-threatening safety issues, innovation is continuously happening in the electric vehicle industry to improve battery cooling systems. Methods such as air cooling, fan cooling, liquid cooling (using PCM, plates, and heat pipes) are commonly employed in current vehicles. For instance, the Nissan Leaf uses air cooling for its battery pack but has not implemented liquid cooling or other advanced methods. Air cooling is unsuitable for most high-performance applications due to the power density required and the inability to handle large ambient temperature fluctuations. Without adequate cooling, thermal runaway risks remain high. Conversely, manufacturers like BMW and Audi employ liquid cooling systems with varying designs. BMW integrates a refrigerant-based cooling plate system, while Audi uses directional cooling through heat exchangers. However, these systems face challenges such as weight, complexity, and hotspots in battery cells, which can compromise efficiency and safety.

To overcome these issues, this project explores a modified cooling plate design with a mini-channel configuration and advanced cooling pads. By positioning cooling plates between cells and utilizing airflow beneath the vehicle, the proposed design aims to provide efficient thermal management while reducing system weight and complexity.

1.1 OBJECTIVE AND SCOPE

The primary objective of this project is to design and optimize a battery cooling plate for electric vehicles to address the challenges of thermal management and safety. The project focuses on the following objectives:

1. Protect battery cells from damage under failure or abuse conditions.
2. Ensure operator safety by mitigating risks associated with thermal runaway.
3. Maximize battery performance by optimizing power and energy delivery.
4. Maintain the temperature of battery cells below critical limits.
5. Achieve uniform temperature distribution across battery cells.
6. Prolong the service life of the battery pack through effective thermal management.

This project aims to develop a lightweight, compact cooling system that utilizes a mini-channel design and advanced cooling pads to achieve efficient heat dissipation. The proposed solution is expected to enhance the reliability, safety, and performance of electric vehicle batteries, while addressing the limitations of existing cooling methods.

1.2 BACKGROUND OF INVENTION

The demand for innovation in battery cooling systems has grown alongside the increasing adoption of electric vehicles. Conventional methods such as air cooling, fan cooling, and liquid cooling (e.g., using phase change materials, plates, and heat pipes) exhibit limitations. For instance, the Nissan Leaf relies on air cooling, which is insufficient for high-performance applications due to its inability to handle large ambient temperature fluctuations and adequately dissipate heat.

Liquid cooling systems, such as those used by BMW and Audi, improve thermal management but present challenges like increased weight, design complexity, and hotspots within cells. BMW employs a base plate with water-glycol refrigerant from the vehicle's A/C system, while Audi integrates directional cooling with heat exchangers. However, these systems are not without drawbacks, including improper cell cooling and potential electrical isolation issues.

This project addresses these gaps by leveraging a modified cooling plate setup with a mini-channel design and silicone pads, using aluminum for its high thermal conductivity and lightweight properties. The use of ethylene glycol-water coolant ensures effective heat extraction, preventing thermal runaway and providing a compact and efficient solution for EV battery thermal management.

1.3 PROBLEM STATEMENT

Lithium iron phosphate (LiFePO4) batteries, commonly used in electric vehicles (EVs), pose a significant safety concern due to their sensitivity to temperature variations. These batteries have a narrow operating temperature range, and the performance, service life, and cycle stability of the battery cells depend largely on maintaining temperatures within this optimal range. If the temperature exceeds a critical threshold, it can trigger thermal runaway, a dangerous process that may lead to fires or explosions. Therefore, an efficient and reliable thermal management system is essential to ensure the safety, reliability, and longevity of the battery pack, and to prevent the risks associated with thermal runaway in EVs.

2 LITERATURE SURVEY

Kaiwei Chen [1] developed a method for measuring heat generation in prismatic batteries, which is applicable to any prismatic battery, regardless of its chemistry. An experimental setup was created to study the effects of battery operating temperature on discharge characteristics. A constant-temperature thermal bath was used, with a 50-50 water-ethylene glycol solution employed for temperature control. The heat generation rate of a 20Ah prismatic A123 LiFePO4 battery was measured under a wide range of discharge rates (0.25C to 3C) and operating temperatures (-10°C to 40°C). The results showed that the heat generation rate increased with discharge rate and decreased with operating temperature.

Ben Ye et al. [2] developed a methodology for the design and optimization of a cooling plate for a battery module consisting of 15 cells, with a nominal voltage of 3.2V, making the module voltage 48V. A complex heat transfer model was created, including the batteries, cooling plates, and coolant. In the analysis, cooling plates were placed above and below the cells, with a 50-50 ethylene glycol-water mixture used as the coolant. Orthogonal experimental design was applied to optimize the main parameters of the module. Parameters considered included battery gap, cross-sectional size, and the number of coolant channels in the cooling plate. The optimization results showed that as the number of cooling channels increased, the pressure drop decreased when the coolant flow rate at the inlet was constant.

Abdul Haq Mohammed et al. [3] developed a cooling plate featuring staggered pins inside the plate to extend the effective heat transfer area between the plate and the coolant while minimizing coolant pressure drop. The performance of the battery was examined under aggressive discharging during normal operation and thermal runaway of a fully discharged battery. Two different cooling plate designs were constructed, and simulation results indicated that both designs could maintain battery temperature. However, one design had a significantly lower coolant pressure drop, which became the deciding factor for the selection of the cooling plate.

Jian Xu et al. [4] carried out a simulation of a mini-channel cooling plate in the case of nail penetration. Three out of five cells were wrapped by square aluminum mini-channels. Nail penetration was used to release energy, which resulted in a temperature increase. The process involved two mechanisms: short circuit and thermal abuse. The simulation showed that increasing the coolant flow rate could not prevent thermal runaway, and the depth of nail penetration led to a more severe and faster thermal runaway. It was concluded that, at the battery module level, a mini-channel cooling system with independent control of the coolant flow rate for individual cells could prevent the propagation of thermal runaway from one cell to its neighboring cells.

Wang C, Zhang G, Meng L, et al. [5] conducted experiments and simulations to study the cooling capacity provided by cooling plates to the batteries. The material used for the cooling plates was thermal silica, with copper tubes passing through them for water flow as the coolant. Simulations were performed based on various factors, including charge density, number of channels, flow direction, and flow velocity. The experiments demonstrated the non-linear relationship between the battery temperature and the number of cooling plates and liquid channels. Iterations were performed to establish a relationship between the battery capacity rates and the inlet flow rate. For instance, a 5C discharge rate battery required a specific inlet flow rate. The results showed that liquid cooling, combined with PCM, was more efficient than air cooling. Furthermore, it was verified that the direction of coolant flow had little effect on the temperature, but the rate of coolant entry into the channels had a significant impact on performance.

3 METHODOLOGY

3.1 HEAT GENERATION IN BATTERY CELL

Heat generation in a battery cell can be attributed to two primary sources: (1) entropy changes resulting from electrochemical reactions and (2) ohmic heating [6]. Depending on the electrode pair, reaction heat can be either endothermic during charging or exothermic during discharge. Ohmic heating arises from the transfer of current through internal resistances within the battery. The heat generation rate in a cell can be calculated using the following equation:

$$Q = I\,(V_{\text{ox}} - V) - I\,[T\,(dV_{\text{ox}}/dT)]$$

Where:
Q is the heat generation rate,
I is the current,
Voc is the open-circuit voltage,
V is the terminal voltage,
T is the temperature,
(dV_{ox}/dT) is the temperature derivative of the open-circuit voltage.

The second term, $I\,[T\,(dV_{\text{ox}}/dT)]$ represents the heat generated or consumed due to the reversible entropy change from electrochemical reactions within the cell. The first term, $I\,(V_{\text{ox}} - V)$ accounts for the heat generated by ohmic and other irreversible effects. In practical electric and hybrid electric vehicle (EV/HEV) applications, the second term is generally negligible compared to the first.

Accurately characterizing the heat generation rate in batteries is challenging due to the complexity of vehicle operating conditions. Calorimetric experiments are typically conducted to determine the heat generation rates under various discharge rates and operating temperatures. Table No. 1 shows the heat generation rate for different discharge rates of a 20 Ah LiFePO4 prismatic battery.

Battery Temperature (°C)	Discharge Rate - Watts (W)		
	0.25C	0.5C	1C
10	1.43	4.37	8.87
20	0.87	3.32	4.9
30	0.85	1.86	4.56
40	0.71	1.62	3.7

Table No. 1

3.2 DESIGN OF A CELL

For this study, a Li-ion battery, specifically $LiFePO_4$ with a nominal capacity of 20Ah, is selected for the analysis. It is assumed that the heat generated within the cell and its thermophysical properties are uniform across the structure. The energy conservation equation governing the temperature distribution within the cell is given by:

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q$$

Property	Parameter
Cell Type	Prismatic
Capacity	20 Ah
Nominal Voltage	3.2 V
Discharge Cut Off Voltage	2.3 V
Specific Heat	$733\,J\cdot kg^{-1}\cdot K^{-1}$
Conductivity	$2.7\ W\cdot m^{-1}\cdot K^{-1}$
Density	$1958.7\ kg\cdot m^{-3}$
Height	140mm
Width	100mm
Thickness	20mm

Table No. 2

3.3 DESIGN OF COOLING PLATES

The cooling plate for this system is made of aluminum 6061, chosen for its lightweight nature, high strength-to-weight ratio, and excellent thermal conductivity. The dimensions of the aluminum plate are 5mm x 100mm x 140mm. Circular holes with a diameter of 3mm are extruded into the plate, with a total of 28 holes per plate. These mini channels enhance the flow rate of the coolant, ensuring minimal pressure drop and reduced pumping power. To improve thermal performance, silicone pads of 1.5mm thickness are placed between the outer surface of the cell and the aluminum plate. These silicone pads, known for their low hardness and high compressibility, serve as effective gap fillers, bridging any uneven surface and reducing thermal contact resistance. The complete system design is shown in Figure 1, with Figure 2 providing an enlarged view of the cooling plate. The material properties of the aluminum plate and silicone pads are summarized in Table No. 3.

Parameter	Units	Aluminium 6061	Silicone
Density	$kg.m^{-3}$	2700	3050
Specific Heat	$J.kg^{-1}k^{-1}$	900	0.832
Conductivity	$W.m^{-1}k^{-1}$	201	6
Height	mm	140	140
Width	mm	100	100
Thickness	mm	5	1.5

Table No.3

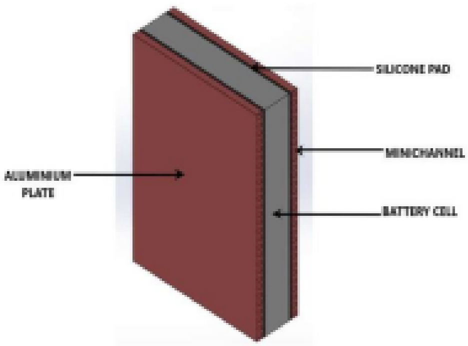


Fig. 1. Cooling System Design

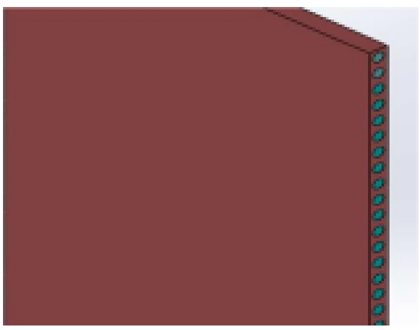


Fig. 2. Enlarged View of Aluminium Plate

3.4 SELECTION OF COOLANT

Water is known to be the most efficient heat transfer fluid; however, it has limitations such as poor anti-freeze and anti-evaporative properties. These issues are addressed by mixing glycol with water, which enhances its performance. The glycol-water solution can last for 12 years or longer, provided the corrosion inhibitor strength is maintained.

Ethylene glycol is chosen for several reasons:

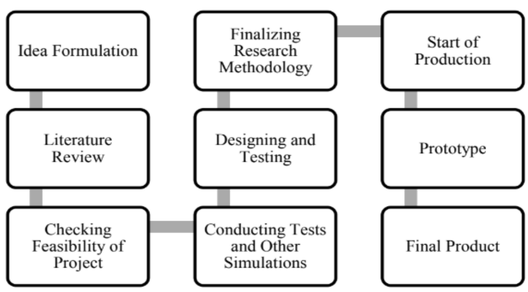
1. To offer freeze and burst protection.
2. To provide anti-corrosive properties to the coolant.
3. To increase the heat capacity of water when required.

While higher flow rates improve cooling, they also lead to higher pressure drops, increased energy consumption, and greater wear on the equipment. Therefore, it is crucial to determine the minimum concentration of glycol required to maintain system efficiency. Although ethylene glycol has lower heat transfer efficiency than water and is denser, resulting in higher volumetric flow rates, an optimal solution of ethylene glycol and water can balance cooling performance and system efficiency. In this design, a 50-50 ratio of ethylene glycol and water is used to achieve the desired properties. The properties of this solution are outlined in Table No. 4.

Parameter	Units	50-50% Ethylene Glycol Water Solution
Density	$Kg.m^{-3}$	1092
Specific Heat	$J.Kg^{-1}k^{-1}$	3200
Conductivity	$W.m^{-1}.k^{-1}$	0.405
Kinematic Viscosity	m^2s	9×10^{-6}

Table No.4

4 DEVELOPMENT & EXECUTION



5 RESULTS & DISCUSSION

The temperature results predicted by the single battery thermal model were in good agreement with experimental data, with a discrepancy of less than 5%. This indicates that the heat generation model and its assumptions were reasonable. A methodology for the design and optimization of the cooling plate for the battery module was proposed. A comprehensive heat transfer model for the entire module was developed, incorporating batteries, two cooling plates, silicone gel pads, and coolant. Orthogonal experimental design was employed through numerical analysis to optimize the main parameters of the module. The geometry of the cooling plate was further optimized using the surrogate model method. Upon applying the optimized geometry, the cooling plate was reconstructed within the module's thermal model for analysis. The comparison revealed that the maximum and minimum temperature differences in the cooling plate were reduced by 5.24%, while the pressure drop was decreased by 16.88%.

From the orthogonal design analysis, it was concluded that both the battery temperature difference and the pressure drop decreased as the cross-section and number of coolant channels increased, while keeping the coolant flow rate constant at the inlet. Sensitivity analysis of the plate indicated that the maximum temperature and pressure drop were most influenced by the center channel distance (L1) and the size of the inlet plenum.

6 RESULTS & DISCUSSION

This paper addresses the challenges, prospects, and significance of thermal management in electric vehicles (EVs) and hybrid electric vehicles (HEVs). Based on the new design and simulation, several key conclusions can be drawn:

1. The new design results in a reduction in the overall battery size and weight, leading to a decrease in both manufacturing and operational costs.
2. The compact design and strategic placement of the cells increase available space, enhancing the packaging efficiency of the module by utilizing a sandwich-type structure of batteries and cooling plates.
3. The liquid cooling system proves to be more effective in extracting heat generated by the prismatic cell, ensuring the battery operates within an optimal temperature range.
4. The design helps reduce the issue of unbalanced cells, extends the cycle life of the cells, and improves user safety.
5. The use of silicone pads in the model serves as an efficient gap filler between the aluminum plates and the battery, significantly reducing thermal contact resistance.

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