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A Review of Cylindrical Battery Thermal Management Systems Based on the Combination of Phase Change Materials and Liquid Cooling

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Abstract — Employing a hybrid battery thermal management system (BTMS) is currently a mainstream approach to improving the safety and stability of battery pack operation, primarily to mitigate the risk of thermal runaway that tends to occur during the charge–discharge process of cylindrical battery packs. The battery thermal management system combining phase change material (PCM) and liquid cooling has become a popular research direction. The hybrid BTMS investigated in this paper uses PCM as the core temperature control unit, leveraging its latent heat storage characteristics to efficiently absorb and dissipate the substantial heat generated on the battery surface, thereby achieving rapid regulation of battery temperature. The liquid cooling circuit promptly removes the heat accumulated in the PCM, quickly restoring its latent heat storage capacity and further enhancing the heat exchange efficiency of liquid cooling. This synergy between PCM temperature control and liquid cooling heat dissipation effectively optimizes the overall heat dissipation performance of the battery pack and significantly reduces the risk of thermal runaway during charge–discharge cycles. However, issues such as increased system complexity, the diversity of PCM materials, and the need for liquid cooling technology optimization have emerged as new challenges for PCM–liquid cooling hybrid BTMS. Therefore, this paper aims to summarize the design and optimization of hybrid BTMS based on the combination of PCM and liquid cooling, and also proposes a multi-objective optimization approach to seek an optimal and reasonable parameter combination for the specific structural complexity of cylindrical battery packs.

Keywords — ***Battery thermal management system, Cylindrical battery pack, Multi-objective optimization, Phase change material***

I. INTRODUTION

Against the backdrop of vigorously promoting energy conservation and emission reduction, China's new energy vehicle industry has experienced vigorous development. The optimization and upgrading of battery thermal management systems (BTMS) is key to technological breakthroughs in new energy vehicles. Heat transfer and dissipation within battery packs have become focal points in BTMS technology. With the advancement of battery management systems and electronic technologies, the demand for improving the fast charge–discharge capability of lithium batteries and for designing and optimizing BTMS has significantly increased compared to the past. Simultaneously, improving heat absorption and dissipation efficiency, as well as the maximum temperature, maximum temperature difference, and temperature uniformity of battery packs, has attracted considerable attention.

Lithium-ion batteries are widely used in new energy vehicles and energy storage fields due to their high energy density, long cycle life, and lack of memory effect [1]. However, they operate efficiently only within 20–40°C [2]. When the temperature is too high, the lifespan of lithium-ion batteries shortens, accompanied by side reactions such as electrolyte decomposition. When the temperature is too low, their discharge capacity decays, potentially leading to internal short circuits caused by diaphragm puncture, resulting in irreversible damage. Cylindrical batteries are widely used due to their high standardization, stable performance, and controllable cost. However, during charge–discharge processes, substantial heat accumulates inside the battery. If not dissipated in time, this accelerates capacity fading and may even trigger thermal runaway [3]. Therefore, BTMS plays a significant role in keeping batteries operating within their optimal temperature range.

BTMS is mainly divided into two categories: active cooling and passive cooling. Active cooling includes air cooling, cold-plate cooling, immersion cooling, direct refrigerant cooling, and thermoelectric cooling. Passive cooling includes traditional natural cooling and novel phase change material (PCM) cooling as well as heat pipe cooling. In active cooling, liquid cooling uses liquid as the cooling medium. Zhiguo An [4] experimentally demonstrated that air cooling consumes 2–3 times more energy than liquid cooling to achieve the same cooling effect. Therefore, compared to air cooling, coolants possess higher thermal conductivity and specific heat capacity, exhibiting superior cooling performance and ensuring stable battery operation under high loads. Xie et al. [5] proposed a hybrid battery thermal management system (HBTMS) integrating immersion cooling with PCM under low-temperature conditions to meet the thermal insulation requirements of lithium-ion batteries during high-rate discharge and low-temperature environments. Experimental simulations verified that the optimally designed system effectively provides thermal insulation for approximately 3 to 7 hours when the ambient temperature varies from −40°C to 0°C. This demonstrates that the hybrid system in Xie et al. [5] not only adapts to high-rate discharge but is also suitable for low-temperature insulation environments. Additionally, the integrated design consists of flow deflectors and annular fins attached to the electrode surfaces, further optimizing internal flow field distribution and heat transfer capability, thereby enhancing the regulation of thermal–fluid coupling [1]. Currently, the mainstream research direction in BTMS focuses on optimizing and upgrading liquid-cooling-based BTMS. In passive cooling, PCM cooling is highly favored due to its advantages of zero energy consumption, no need for additional component complexity, high compactness, and low maintenance costs [7]. Its principle involves absorbing high latent heat during phase transition and continuously releasing heat to maintain temperature uniformity, thereby extending battery life and improving the operational safety of lithium batteries. However, a single liquid cooling method not only increases the complexity of the battery structure but also poses a risk of leakage. Similarly, single PCM cooling has many shortcomings. Huang Silu et al. [6] found that pure PCM cooling can effectively reduce the maximum temperature and temperature difference of batteries, but under high discharge rates, the cooling effect of pure PCM is limited. Moreover, as PCM thickness increases, the phase transition time lengthens, the temperature rise rate decreases, and the time to reach complete phase transition slows down. This indicates that PCM generally has low thermal conductivity, limited cooling range, low cooling efficiency under high current rates, and potential leakage issues during solid–liquid phase transition [3].

Currently, in research on hybrid thermal management using PCM, domestic and international researchers have mainly focused on two aspects: air–PCM and liquid–PCM thermal management technologies. Although air–PCM hybrid technology offers good heat dissipation capacity and relatively simple structure, it has no advantage over liquid–PCM technology in terms of heat exchange capacity, continuous heat dissipation capability, and temperature uniformity. Liquid–PCM hybrid technology enhances cooling capacity by arranging pipes inside the PCM. Furthermore, it can cool the internal PCM more timely and effectively under high-rate discharge conditions of the module. Therefore, this has become the research focus in the design and optimization of BTMS combining PCM and liquid cooling [8]. For liquid + PCM mode BTMS, based on the liquid cooling structure, it can be divided into liquid cooling tube + PCM composite thermal management systems [9] and liquid cold plate + PCM thermal management systems [10]. Rao et al. [11] designed a BTMS combining microchannel liquid cooling with PCM. Their research found that microchannel liquid cooling can effectively and rapidly remove heat from the internal PCM, thereby avoiding PCM failure due to reaching its heat absorption limit. Akbarzadeh et al. [10] proposed integrating PCM with a liquid cooling plate to form a composite liquid cold plate. Simulation experiments demonstrated that this composite cold plate reduces self-weight by 36% compared to a traditional aluminum cold plate of equal volume, and it also reduces energy consumption and improves temperature uniformity. Ba et al. [12] found that placing a water cooling plate close to the battery electrode area can effectively remove most of the substantial heat generated during discharge, while the PCM between adjacent batteries improves temperature uniformity. This study successfully demonstrated that designing a hybrid BTMS combining liquid cooling and PCM is highly feasible and advantageous. The liquid–PCM hybrid thermal management system, which fully exploits the advantages of both liquid cooling and PCM cooling, offers the benefit of effectively reducing energy consumption. Kong et al. [13] adopted a monitoring approach that controls the coolant flow rate and inlet/outlet temperatures by monitoring the PCM and ambient temperatures. This method improves the cyclic thermal performance of the battery pack under different ambient temperatures and reduces unnecessary losses during the liquid cooling process. This paper starts from the perspectives of liquid cooling–fins–PCM and PCM material optimization, aiming to find an optimal solution that reduces structural complexity and excessive volume without sacrificing the thermal efficiency of the battery system.

II. COMPREHENSIVE RESEARCH ON FIN DESIGN AND LIQUID COOLING TECHNOLOGY OPTIMIZATION IN THE COMBINATION OF PCM AND LIQUID COOLING

Studies have found that liquid cooling tube and liquid cold plate-based PCM thermal management systems have improved cooling capacity. However, each of these two approaches suffers from issues such as uneven cooling and structural complexity due to their respective size constraints. Therefore, introducing a battery thermal management system composed of a combination of liquid cooling tubes, fins, and phase change material (PCM) can effectively address the above two problems, while offering the dual advantages of compact size and improved cooling uniformity [14].

2.1 Addition of Fins to the PCM Cooling Channel and Fin Design

In the design of the internal PCM cooling channel, Wu Junhui et al. [14] proposed that the liquid cooling system and the phase change material (PCM) are connected via thermally conductive fins to ensure thermal management performance while reducing the economic cost of the system. Their research showed that when fin thickness increases to a certain extent, further increasing the fin thickness has little effect on the maximum temperature and temperature difference of the battery module. Therefore, it was demonstrated that seeking the optimal value is key to improving the thermal management performance of the module. Zhao Haodong et al. [15] conducted research based on the novel structure proposed by Zhang et al. [16], which adds fins to the PCM cooling channel. They also drew on the work of Akula et al. [17], who combined metal fins with composite PCM to enhance the thermal conductivity of FPCM, and Ahmad et al. [18], who used air-cooled metal fins to reinforce the PCM system, along with many other scholars' studies on modifying fin structures or combining PCM with fins. By selecting appropriate PCM materials and synthesizing a new type of composite PCM, Zhao et al. [15] further conducted experimental validation through a multi-objective optimization approach. Their experiments found that embedding composite PCM with metal fins not only enhances the composite PCM but also improves the heat transfer effect and cooling efficiency of lithium-ion batteries. Keyhani-Asl et al. [19] developed a novel hybrid battery thermal management system that integrates PCM with porous fins and porous copper foam for liquid cooling. Compared to the study by Zhao Haodong et al. [15] on adding fins to the PCM channel, Keyhani-Asl et al. [19] conducted a more in-depth investigation into the influence of fin design and PCM integration on heat transfer performance. To study this system, Keyhani-Asl et al. [19] employed the enthalpy-porosity model, the Darcy-Brinkman-Forchheimer model, and both local thermal equilibrium and local thermal non-equilibrium models for experimental simulations. Their experimental conclusions revealed that porous media and metal foam effectively enhance the heat transfer performance of battery thermal management, while porous media provide a larger surface area for heat dissipation, thereby improving heat dissipation capacity and temperature uniformity. Furthermore, the study by Keyhani-Asl et al. [19] also identified a gap in fin design and PCM integration within HBTMS: although the adoption of porous fin integration can improve heat transfer performance compared to traditional solid fins, reduce system weight, and increase energy density, this approach has not been fully explored. Zhu Xijiao et al. [20] reviewed the research progress on liquid-cooled battery thermal management systems, emphasizing that many researchers have enhanced the temperature control performance of cooling plates by adding fins. This aligns with the idea proposed by Zhao Haodong et al. [15] and Zhang et al. [16] regarding the addition of fins to the PCM cooling channel as a novel structural concept. In Zhu's article, she cited studies including Lee et al. [21] on inclined fins to improve heat transfer coefficients, Wang et al. [22] comparing airfoil fin channels with U-shaped and serpentine channels (finding that airfoil fin channels exhibited the best heat dissipation performance), Zhang et al. [23] on Y-shaped fins to enhance the thermal performance of liquid cooling plates, and Jiang et al. [24] on V-shaped fins to explore secondary heat transfer enhancement mechanisms. By referencing numerous research studies, Zhu Xijiao et al. [20] concluded that various flow channel structures and fin designs can significantly improve the thermal management performance of electric vehicle battery packs. This also points to a design and optimization research direction for battery thermal management systems combining PCM and liquid cooling.

2.2 Advances in Liquid Cooling Technology for BTMS

Liang Qinqin et al. [25] investigated liquid cooling technology in battery thermal management systems. Their study noted that water-based coolants are widely used in electric vehicles and energy storage fields, that low-velocity fluids can improve heat transfer efficiency, and that nanofluid technology can enhance heat exchange efficiency. These findings provide technical support for the optimization of liquid cooling technology and offer design and optimization ideas for combining phase change materials with liquid cooling. Regarding nanofluid technology, the study by Zhao Haodong et al. [15] also mentioned the advantages of nanofluid technology, namely good stability and strong thermal conductivity. Both studies collectively demonstrate that nanofluid technology has high practical value when applied to battery thermal management systems. Additionally, Liang Qinqin et al. [25] examined recent advances in liquid cooling technology and found that optimization efforts are mainly focused on three aspects: cold-plate liquid cooling, immersion liquid cooling, and spray liquid cooling. Their research found that cold-plate liquid cooling primarily involves optimizing coolant properties, innovating flow channel structures, improving thermal management systems, and optimizing system integration; immersion liquid cooling offers better temperature uniformity than traditional air cooling; and spray liquid cooling, in addition to the advantages of the former two, also provides superior thermal safety protection capability. Based on these findings, Liang et al. [25] concluded that although cold-plate liquid cooling has a simple structure and strong adaptability, it suffers from contact thermal resistance issues; immersion liquid cooling offers high heat dissipation efficiency and good temperature uniformity but faces limitations in coolant cost and system sealing; spray liquid cooling provides high flexibility but requires optimization of nozzle design, among other aspects [25]. Zhou Feifan et al. [26] studied the combination of liquid cooling and PCM. They drew on the research of Chung et al. [28], who placed the bottom of a battery module in contact with a liquid cooling plate and arranged metal fins between batteries, the comparative study by Tang Huaiyu et al. [28] on single serpentine flow channels versus multiple parallel flow channels, and other studies on PCM-liquid cooling integration. Using experimental validation based on an electro-thermal coupled model, liquid cooling heat transfer calculations, and geometric modeling with mesh generation, they concluded that the hybrid thermal management approach combining PCM and liquid cooling can reduce energy losses and optimize temperature uniformity. Furthermore, adding fins to the PCM structure can increase the solid-phase recovery rate, thereby supporting cyclic heat transfer of the PCM. Compared with the studies by Zhao Haodong et al. and Zhu Xijiao et al., this research further reveals that adding fins to the PCM in a PCM-liquid cooling hybrid system not only enhances the heat transfer performance of the battery thermal management system but also increases the PCM solid-phase recovery rate to enable cyclic heat dissipation, thereby reducing cooling costs.

2.3 Selection and Optimization of Composite Phase Change Materials in BTMS

On October 15, 2025, Zi et al. [29] investigated a hybrid battery thermal management system combining pipe liquid cooling and phase change material cooling. Different from the aforementioned studies focusing on adding fin structures to PCM or liquid cooling technology, Zi et al. [29] innovatively chose to improve BTMS performance from the perspective of the PCM itself. They employed n-octadecane and RT35HC as the phase change materials in their study, aiming to address heat accumulation and uneven temperature distribution in battery packs. By constructing a physical model of the LPC-BTMS and mathematical models including a battery model, PCM model, and fluid cooling model, and employing experimental and numerical methods such as single-cell heat generation tests and grid independence verification, they obtained the following results: (1) Under high discharge rates, SA-LPC-BTMS exhibited superior heat dissipation performance compared to RA-LPC-BTMS. (2) The resistance and maximum temperature of the LPC-BTMS decrease with increasing L and D, thereby improving battery thermal safety and temperature uniformity. (3) Under larger D and L values, LPC-BTMS using RT35HC provides superior temperature uniformity compared to the system using n-octadecane as the PCM. (4) The FV&FT configuration exhibits excellent heat dissipation capability under extreme conditions. Gu et al. [30] proposed a BTMS technology based on composite phase change materials and a variable-wall liquid cooling plate. By establishing a numerical BTMS model, optimizing the CPCM structure using a genetic algorithm, and fitting the relationship between BTMS structural parameters and EOP through orthogonal experimental data for experimental validation, they found that after implementing the variable-wall LCP, the maximum temperature of the battery pack was reduced by 1.81°C. The optimized EOP reached 0.07°C/g, with a temperature difference of 0.56°C. Kumar et al. [31] conducted a comprehensive analysis of modeling, simulation, and experimental studies on liquid cooling for PCM-based BTMS, emphasizing its effectiveness in improving thermal control under dynamic operating environments. Their review explores the fundamentals of hybrid cooling techniques, evaluates the challenges of using standalone cooling technologies, and discusses optimization techniques for hybrid systems.

2.4 Safety Protection of BTMS Combining PCM and Liquid Cooling

Regarding research on the design and optimization of PCM and liquid cooling integration, the addition of metal fins in the PCM cooling channel to optimize the heat transfer and cooling efficiency of lithium batteries, advancements in liquid cooling technology, and the use of nanofluid technology in liquid cooling to enhance heat exchange efficiency represent the vast majority of research directions in this field. However, on August 29, 2025, Jin Pengfei et al. [32] emphasized the importance of battery voltage measurement accuracy, which provides safety assurance for battery thermal management systems. Jin Pengfei et al. [32] designed a safety protection scheme for a liquid-cooled battery thermal management system based on a three-level control architecture: battery management unit, battery cluster management unit, and battery system management unit. This scheme employs the ADS1120, TI's precision ADC, and primarily utilizes cluster current, cluster voltage, and insulation detection methods to optimize battery safe operation and battery voltage precision measurement. Jin Pengfei et al. [32] verified the feasibility of this protection scheme through battery management system testing. This scheme not only addresses battery voltage measurement accuracy and battery operational safety but also reminds researchers that when studying the design and optimization of battery thermal management systems combining PCM and liquid cooling, maintaining the safe operation of the battery thermal management system is equally important.

III. CURRENT TECHNICAL LIMITATIONS

Previous battery thermal management systems had significant limitations, typically focusing on a single objective, such as merely minimizing temperature. Even though the vast majority of batteries today have long abandoned the use of single battery thermal management cooling technologies and have shifted to hybrid thermal management systems to maximize the efficiency of battery heat absorption and dissipation, thereby maintaining the battery within its optimal temperature range, the core bottleneck of current battery thermal management systems lies in the deep-seated contradictions among system reliability, temperature control precision, energy efficiency, and adaptability to multiple operating conditions. Moreover, many hybrid systems often come at the cost of increased structural complexity or increased volume. These issues not only constrain the range and safety of new energy vehicles but also serve as key barriers hindering the industry's pursuit of superior performance and development.

IV. RESEARCH METHODOLOGY TRENDS

There are numerous adjustable parameters in hybrid cooling systems for lithium-ion batteries, and many of these parameters may conflict with the performance objectives. Traditional single-objective approaches combine objective functions through weighting and adjust the weights according to specific requirements and constraints to achieve a balance among different objectives. However, these approaches may neglect certain objectives. For example, early liquid cooling methods aimed to reduce the maximum temperature but introduced drawbacks such as increased maximum temperature difference and structural volume. Later, to avoid the risk of leakage, phase change materials (PCM) were introduced, providing passive cooling and avoiding this risk, but at the cost of reduced cooling efficiency, making it difficult to meet the operational requirements of batteries under high current rates. Today, hybrid PCM-liquid cooling-fin battery thermal management systems greatly improve cooling efficiency and reduce volume but at the same time increase structural complexity. From the above status, it is evident that single-objective methods can no longer meet the growing demands for high efficiency, high sustainability, and long lifespan of lithium-ion batteries. Therefore, we can adopt a multi-objective approach combined with hybrid battery thermal management system technology. Since hybrid cooling systems have numerous adjustable parameters that may conflict with performance objectives, multi-objective optimization is the key to resolving these conflicts. It can automatically explore a large number of design variable combinations through algorithms, thereby approaching the global optimum.

Among these algorithms, the Fast Non-dominated Sorting Genetic Algorithm with Elite Strategy (NSGA-II) is one of the most representative and widely used algorithms in the field of multi-objective optimization. It features low complexity, strong robustness [33], better convergence of the solution set, and faster optimization speed. Its principle is to simulate the logic of biological evolution to find optimal solutions among conflicting objectives. The working principle of the NSGA-II algorithm is as follows: The process begins by randomly generating an initial parent population PGen of size N, calculating the objective function value for each individual, with Gen = 1. In the second step, if the initial population is selected to generate the first offspring population, a new population QGen is obtained with evolutionary generation Gen = 2, also of size N; otherwise, non-dominated sorting is performed, followed by selection, crossover, and mutation operations, and the above operations are repeated until all populations have evolved to the next generation of offspring. In the second step, the parent and offspring populations are merged to obtain a new population RGen. Next, if this population is selected to generate a new parent population, non-dominated sorting is performed; otherwise, fast non-dominated sorting is carried out, and individuals in the population are divided into different non-dominated fronts according to their non-dominated rank. Subsequently, the crowding distance of the population is calculated, and suitable individuals are selected to form a new parent population, which then returns to the cycle of the second step until all populations have undergone non-dominated sorting. In the third step, the new parent population undergoes a new round of selection, crossover, and mutation to generate an offspring population. Finally, based on the generation count, if Gen is less than the maximum generation number, the process returns to the second step to synthesize a new offspring; otherwise, the process ends [34]. Fig. 1 shows the workflow diagram of NSGA-II.

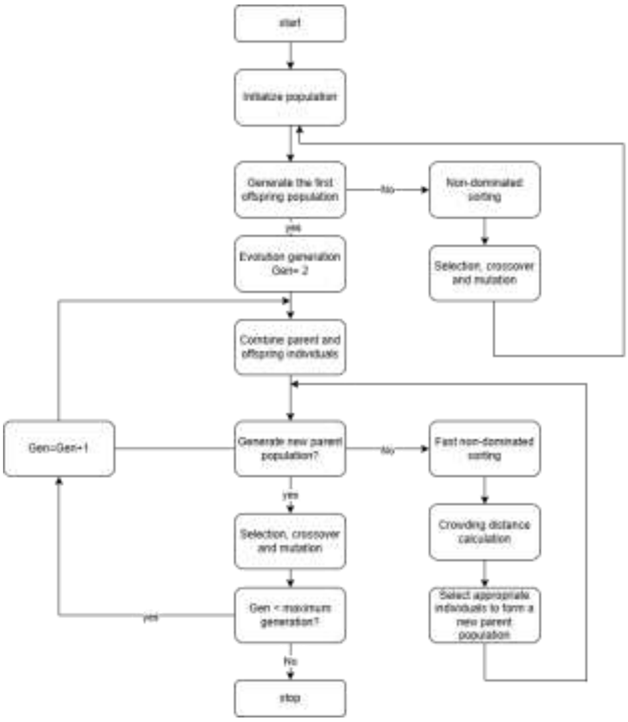

Fig.1 NSGA- II flowchart

Therefore, to improve battery thermal management performance and meet the requirements for heat dissipation and energy consumption reduction under different power levels, the maximum temperature $T_{\max}$, maximum temperature difference $\Delta T_{\max}$, and pressure ΔP difference can be taken as optimization objectives. These multiple sets of data can be regarded as the initial population, and the above process can be executed to find the optimal solution for battery operation. The formula is as follows [35]:

$$\text{find } \mathbf{x} = [x_1, x_2, x_3, x_4] \quad (1)$$

$$\min \begin{cases} T_{\max}(x_1, x_2, x_3, x_4) \\ \Delta T_{\max}(x_1, x_2, x_3, x_4) \\ \Delta P(x_1, x_2, x_3, x_4) \end{cases} \text{s.t.} \begin{cases} 0.02 \le x_1 \le 1 \\ 6 \le x_2 \le 8 \\ 16 \le x_3 \le 20 \\ 37 \le x_4 \le 47 \end{cases} \quad (2)$$

Among them, x_1 is the coolant mass flow rate, x_2 is the pipe diameter, x_3 is the CPCM thickness, and x_4 is the pipe spacing.

From the experiments of Wang Xu et al. [36], it was found that stable optimization results can be obtained after two hundred iterations of the initial population. The crossover operation is the main global search method in the algorithm, and the crossover probability is set to 0.8, which helps improve the diversity of solutions. The mutation operation maintains population diversity and preserves a certain local search capability to prevent the population from becoming too concentrated and falling into a local optimum. The Pareto front obtained after optimization is shown in Fig. 2, which contains one hundred Pareto optimal solutions. By comparing with the previous data from reference [36], it was found that one parameter increased by $T_{\max}$ 0.26 degrees Celsius, while two other parameters $\Delta T_{\max}$, ΔP decreased by 15.87 percent and 90.07 percent, respectively. Therefore, it can be concluded that the optimization algorithm can assist the battery thermal management system in improving cooling efficiency while also reducing the maximum temperature difference and pressure difference of the battery, providing new ideas for future research.

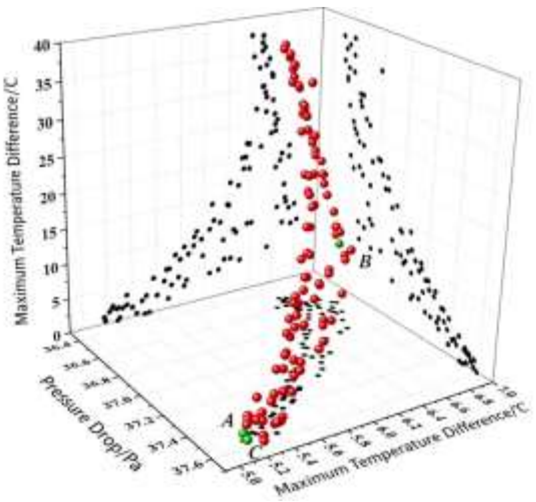

Fig.2 3D Pareto frontier Source: [35]

V. CONCLUSION

This study primarily focuses on cylindrical battery thermal management systems based on the combination of phase change material and liquid cooling. It mainly discusses the addition of fins in the phase change material cooling channel, fin design, and fin optimization to enhance the heat dissipation performance and temperature uniformity of the battery thermal management system. The study also mentions the optimized selection of phase change materials. Not only can traditional paraffin PCM be used, but n-octadecane and RT35HC can also be selected as phase change materials. This choice offers superior heat dissipation performance and improves battery thermal safety and temperature uniformity. This calls for innovative use of different phase change materials to explore and optimize the operation of battery thermal management systems. Furthermore, this paper discusses that optimizing liquid cooling technology using nanofluid technology and low-velocity fluid technology has become an important direction for improving the heat transfer efficiency and stability of battery thermal management systems. At a time when battery thermal management systems are undergoing rapid technological innovation, paying attention to battery charge and discharge safety is an indispensable part. This paper also emphasizes that while researching the design and optimization of battery thermal management systems combining phase change materials and liquid cooling, ensuring the safe operation of the battery thermal management system is equally important. Finally, this paper proposes using one type of multi-objective optimization algorithm, the Fast Non-dominated Sorting Genetic Algorithm with Elite Strategy (NSGA-II), to find the optimal ranges of maximum temperature, maximum temperature difference, and pressure difference. This approach ensures that the battery operates within its optimal working range while greatly avoiding structural complexity and unnecessary energy waste to reduce costs.

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