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Optimized Design Solutions for Battery and Frame Performance and Safety in New Energy Vehicles

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Abstract. With the rapid development of the economy and society, and the increasing challenges related to energy and the environment, new energy vehicles have emerged as a crucial trend. Their advancement is essential for promoting renewable energy applications and the development of electrified transportation technology, ensuring energy security, mitigating shortages, and enhancing environmental quality. This paper investigates the current state of batteries and frames in new energy vehicles, summarizing and analyzing optimized design solutions that affect their performance and safety. In battery optimization, the focus is on enhancing the battery thermal management system and structure through advanced cooling techniques, material innovations, and structural modifications. Key studies demonstrate the effectiveness of direct-cooled BTMS and optimized liquid-cooled plates in maintaining optimal battery temperatures and safety. Additionally, structural enhancements in battery packs and protective measures significantly improve battery performance and durability. In frame optimization, innovations in frame structure and materials, including the integration of high-strength steel and aluminum foam, have led to improved load-bearing capacity, durability, and lightweight. Multi-dimensional optimization approaches, such as finite element analysis and topology optimization, provide comprehensive solutions for reducing stress concentrations and enhancing structural integrity. The insights gained from this research highlight the need for continued innovation in battery and frame design to achieve greater performance, safety, and sustainability in new energy vehicles, contributing to their widespread adoption and evolution.

1 Introduction

With the ongoing development of the economy and society, along with the increasing challenges related to energy and the environment, new energy vehicles have emerged as a vital trend. Their advancement is crucial for promoting the future application of renewable energy and the development of electrified transportation technology. This development ensures future energy security, mitigates energy shortages, and enhances environmental quality [1]. Despite significant progress through continuous iterative upgrades, the

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performance and safety of new energy vehicles remain key challenges. Among the various components influencing new energy vehicles, the battery and frame play particularly prominent roles. Summarizing recent advancements in the optimized design of batteries and frames for new energy vehicles is essential for further research and development in this field.

2 Optimized design of the battery

2.1 Battery thermal management system optimization

Effective battery thermal management systems (BTMS) are crucial for maintaining the performance, safety, and longevity of batteries in new energy vehicles. These systems regulate the temperature of battery packs, preventing overheating and ensuring uniform temperature distribution among cells, which is vital for optimal operation and safety.

A direct-cooled battery thermal management system (BTMS) was designed for blade batteries, using the Yadi EV model pure electric vehicle as the research subject. The preliminary design included calculations of the battery's heat load, heat production rate, and discharge current. A data model for the blade battery pack and the direct cooling plate was established, followed by temperature field simulations [2]. The results demonstrated that the direct-cooled BTMS effectively maintained the maximum battery pack temperature within 20-40°C, with a temperature difference of less than 5°C between individual cells. This system successfully met the heat dissipation objectives. Among the cooling plate designs, the serpentine structure exhibited superior performance compared to the multi-chamber structure, providing better heat dissipation and enhancing the overall efficiency and reliability of the BTMS for new energy vehicles. Figures 1 and 2 illustrate the structures of the direct cooling plates with multi-cavity and serpentine designs, respectively.

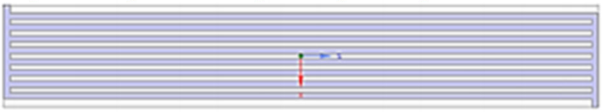

Fig. 1. Multi-cavity structure straight cooling plate structure [2]

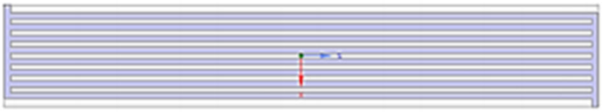

Fig. 2. Serpentine structure straight cold plate structure [2]

Various heat dissipation methods for the thermal management of new energy vehicle batteries—such as air cooling, liquid cooling, phase change material cooling, and heat pipe cooling—were thoroughly summarized. It was found that no single cooling method can achieve optimal temperature control. Thus, the focus should shift toward developing composite thermal management systems that integrate multiple cooling techniques for enhanced performance and efficiency in new energy vehicles [3]. Further, Li Kui Ning et al. studied the liquid cooling cold plate system of a soft-packed lithium-ion battery module for an electric vehicle. They investigated the heat dissipation performance considering the influence of the internal runner structure of the liquid-cooled plate. Structural parameters such as outlet height, rib length, rib width, and the number of runners were evaluated based on existing research and engineering experience. The study found that the rib width should not exceed 173 mm, and increasing the outlet height of the liquid-cooled plate improves performance. An orthogonal test revealed that the optimal performance was achieved with an outlet height of 29 mm, rib length of 175.5 mm, rib width of 0.7 mm, and nine runners. The optimized liquid-cooled plate enhanced the heat exchange capacity by 4% compared to the benchmark model, with negligible change in pressure drop [4]. Table 1 demonstrates the dimensional parameters of the benchmark liquid-cooled plate model.

Table 1. Dimensional parameters of the baseline liquid-cooled plate model [4]

	Basin 1	Basin 2	Basin 3	Basin 4	Basin 5
Number of runners	8	8	8	8	7
Rib length/mm	200	173	173	173	168
Rib width/mm	1	1	1	1	1
Rib height/mm	7	7	7	7	7

Tian Wanpeng et al. investigated the thermal management system of lithium batteries for new energy vehicles and proposed an optimized design. By establishing a calculation model of the battery pack and cooling structure, they analyzed the thermal management system's design, resulting in two optimized schemes: Scheme 1: Positioning the micro-channel cold plate on the side wall of the battery; Scheme 2: Positioning the micro-channel cold plate on both the side wall and the bottom of the battery. Simulations using Fluent software revealed that the maximum temperature of both schemes initially increases, then decreases with prolonged discharge time, before rising again after a period. After 1 hour of discharge, the maximum temperature in Scheme 2 was lower than in Scheme 1. After 5 hours of discharge, Scheme 2 continued to maintain a lower maximum temperature compared to Scheme 1. These results indicate that Scheme 2 achieves a better cooling effect and overall optimization [5].

2.2 Battery structure optimization

An optimized battery pack using 32650 cylindrical batteries has been developed, selected for their plasticity and independence. The design connects the batteries in series and parallel with phase-screwed connections at the head and tail, ensuring easy installation and measurement. Stability is enhanced with auxiliary stabilization devices and special protective shells. The battery arrays are secured with insulating ribbons, and the ends feature a special parallel pole plate and an insulated end cover, forming a structured battery pack with an internal longitudinal space channel. The rationality of this design was validated through static simulation analysis using finite element software, as illustrated in Figure 3 [6].

Fig. 3. Specific structure of the design model [6]

In another study, the structure of new energy vehicle battery pack boxes was optimized. A battery pack model was established, followed by finite element static analysis and shape optimization. Transforming the engineering problem into a mathematical problem involved setting design variables, boundary conditions, and objectives. Using optimization software and high-performance computers, the optimal solution was calculated based on the principles of mechanical design. Morphology optimization techniques determined the optimal layout for reinforcement bars. Results showed the optimized design scheme effectively avoids road excitation frequencies, reducing their impact on the battery pack case. Figures 4 and 5 illustrate the established finite element model and reinforcement distribution of the battery pack, respectively [7].

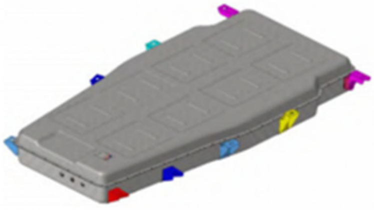

Fig. 4. Finite element model of the battery pack case [7]

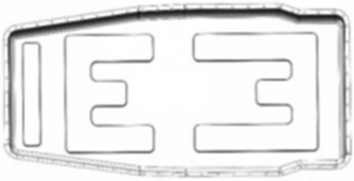

Fig. 5. Distribution of reinforcing bars in the battery pack case [7]

2.3 Battery multidimensional optimization

Design flaws in blade battery guard systems, particularly in their resistance to impact and fire, have been identified. While the guard plate exhibits strong fire resistance, its ability to withstand impacts is weak, increasing failure risk. Additionally, the plastic sealing cover of the blade battery lacks sufficient fire resistance, posing a thermal runaway risk that could spread through the vehicle. The absence of short-circuit protection devices inside the battery further exacerbates safety concerns. To mitigate these risks, it is recommended to strengthen the impact protection of the chassis guard, enhance the fire resistance of the plastic sealing cover, and add short-circuit protection devices within the battery pack [8].

Blade batteries offer several safety and performance advantages, including a longer short-circuit path and larger surface area, which reduce the risk of spontaneous combustion. Their structural characteristics allow for higher weight-specific energy density, reaching 180 Wh/kg, and increased space utilization from 40% to 60%. This results in a 20% to 30% increase in charge capacity and range, up to 600 km. The effective thermal management system of blade batteries ensures stable performance even in cold environments, maintaining at least 90% discharge capacity at -20 °C [9].

Thermal runaway in new energy vehicle battery packs can be attributed to uncontrolled heat dissipation, electrochemical factors, and mechanical and electrical issues. To address these, several optimization strategies have been proposed. Enhancements include optimizing the safety protection box frame structure with fire-resistant materials like mica, employing vibration mirror laser welding for improved strength, and using aerogel pads for thermal isolation. Additionally, implementing thermal runaway detection systems ensures timely disconnection of high-voltage lines during emergencies. Further optimizations in the safety protection system, such as monitoring, liquid cooling, isolation, and forced cooling subsystems, are recommended. Maintenance practices, including optimized working conditions, battery charging protocols, and maintenance operations, are also emphasized to enhance safety and performance (Figure 6).

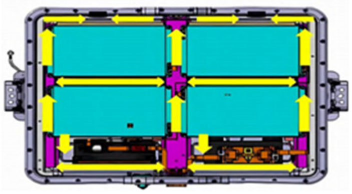

Fig. 6. Locations to avoid for cabling or other elements [10]

To address the thermal runaway issue in new energy vehicle batteries, three effective solutions have been identified. First, improving thermal stability and battery safety can be achieved by using new materials. Second, replacing traditional collectors with composite ones enhances battery flame retardancy and energy density. Third, employing solid electrolytes instead of liquid ones not only improves thermal stability but also reduces the likelihood of liquid leakage and increases energy density [11].

In terms of battery technology and energy storage, several optimization strategies have been proposed. Analyzing the functions and requirements of energy storage systems has revealed the importance of optimizing cycle life and safety through better cycling conditions, temperature management, and charging protocols. Additionally, advancements in material R&D, process improvements, nanotechnology, and advanced battery systems are crucial for reducing costs and increasing energy density. Implementing circular economy models also plays a significant role in enhancing sustainability and efficiency in battery technology [12].

These insights collectively emphasize the need for innovative materials, advanced technologies, and comprehensive management strategies to improve the safety, performance, and cost-effectiveness of new energy vehicle batteries.

3 Optimized design of the frame

3.1 Frame structure optimization

To meet the requirements of carbon fiber composites molding and mechanical substitutability, a new integrated structure of the frame and battery tray has been designed. The analysis of the original miniature new energy vehicle's separated frame and battery tray structure led to combining these components into a single integrated structure. Structural gaps were filled, unnecessary protruding parts were eliminated, and certain structural elements were modified while maintaining the external dimensions [13]. Using HyperWorks software, a finite element model was created to perform static analysis under full-load bending, emergency braking, and sharp turning conditions. The results indicated minimal displacement and a sufficiently high safety coefficient. Consequently, the composite material's thickness and layup can be optimized to further reduce weight while meeting displacement and safety standards. The OptiStruct module in HyperWorks facilitated optimization through free size, size, and layup layer sequence steps, achieving a balance between safety and lightweight goals (Figure 7).

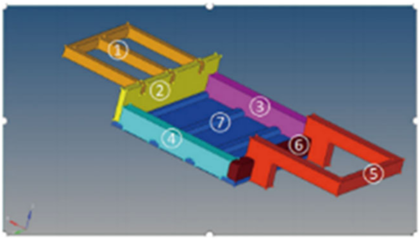

Fig. 7. Integrated frame-battery tray design structure [13]

In another study, an oil-to-electric electric vehicle with a frame length of 2405mm, a width of 1285mm, and a Q345 structural steel side-beam frame were analyzed for structural defects. Finite element analysis under static, bending, and emergency braking conditions identified the main beam as the most vulnerable area. To enhance strength and durability, the optimization involved reshaping the main beam plate, extending the right-side plate to the left-side bottom plate, and reducing openings on the left-side plate. The optimized design resulted in reduced frame deformation and maximum stress, improving the frame's overall performance. Figures 8 and 9 illustrate the structural changes before and after optimization [14].

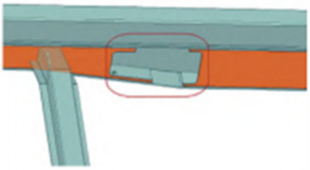

Fig. 8. Structure before optimized design [14]

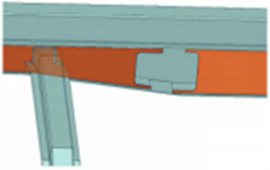

Fig. 9. Structure before optimized design [14]

Bench tests on the rear subframe of a new energy vehicle revealed significant cracking issues. During the vertical durability test, the left position of the process leakage hole on the subframe cross-tube beam (Φ 16mm) developed cracks after approximately 80,000 cycles, with the crack length extending to about 2/3 of the tubing. A subsequent test on a subframe model with the left side crack led to the right side of the hole cracking at around 90,000 cycles in a similar manner [15]. Finite element modeling and analysis of the rear subframe using Hypermesh software, which included stiffness, strength, and fatigue analyses, identified local stress concentration at the leakage holes as the primary cause of the fatigue failure. The fatigue damage value at these points exceeded acceptable standards under prolonged reciprocating loading. To address this issue, the process leakage holes were filled and reanalyzed for fatigue properties. The results showed a significant reduction in the fatigue damage value, indicating a substantial improvement in durability. This optimization was validated through process validation and further bench strength tests, confirming the effectiveness of the modification [15]. Figures 10 and 11 illustrate the cracking in the left and right process leakage holes and the finite element model of the rear subframe, respectively

Fig. 10. Cracked left and right process leakage holes [15]

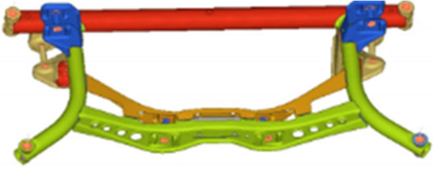

Fig. 11. Finite element model of the rear subframe [15]

Zhang Bo et al. studied a new energy commercial vehicle frame arrangement structure and found that it is better to adopt a variable cross-section fish-belly high-strength steel longitudinal beam structure to cope with the trend of new energy commercial vehicle platform design. Through CATIA 3D design and vehicle layout, CAE finite element modal, and strength analysis, it can meet the needs of BEV, HEV, PHEV, FCEV and other new energy technology routes such as vehicle platform layout, the lightweight effect is obvious, and assembly is convenient [16]. Figure 12 shows the longitudinal beam structure used in the frame.

Fig. 12. Frame longitudinal beam structure [16]

3.2 Frame material optimization

The application of aluminum foam in the structural design of new energy vehicles has demonstrated significant advantages. Aluminum foam exhibits low density, high specific stiffness, bending stiffness 1.5 times that of steel, and superior impact absorption, meeting the lightweight, low energy consumption, and comfort requirements of new energy vehicles. Its high-temperature resistance, fire resistance, and absence of toxic gas emissions under heat conditions further enhance vehicle safety. When aluminum foam is filled into tough square steel, coupled deformation occurs under loading, optimizing the load transfer path and extending the cracks in the aluminum foam, thereby enhancing the mechanical properties of the steel [17].

In the structural design of new energy bus bodies, material selection is crucial. A comparison of various materials revealed their cost-effectiveness in achieving lightweight designs, reducing energy consumption, and providing corrosion resistance, tensile strength, and energy-absorbing properties. Steel is suitable for body skeletons and structures; aluminum alloys and aluminum-magnesium alloys are ideal for cylinder blocks, cylinder heads, rims, buffers, radiators, and condensers. Fiber-reinforced polymers (FRP) are used for front bumpers and ceilings, while carbon fiber composites are preferred for wheels, brake blocks, and driveshafts, and have broader applications in sports and formula racing cars [18].

The integration of aluminum foam in new energy vehicle frames optimizes mechanical properties. Filling aluminum foam into steel square tubes results in coupled deformation, optimizing load transfer and preventing crack propagation in the foam. The porous structure of aluminum foam provides high damping performance, reducing structural rattling. The material's energy absorption mainly occurs in the compression stress-strain curve's collapse stage, with an energy absorption efficiency exceeding 0.8 and a capacity of up to 490-3430 kJ/m^3. This is critical for vehicle lightweighting and vibration damping. Mathematical and mechanical model analyses confirm that aluminum foam significantly optimizes both lightweight design and vibration-damping performance in new energy vehicles [19]

3.3 Multi-dimensional optimization of the frame

The design of the frame for new energy commercial vehicles has been optimized through a detailed analysis of bending stresses and load distributions. By determining the main cross-section dimensions of the longitudinal beams and the coordinates of the inflection points of the variable cross-section, the bending load was clarified. After evaluating component loads, assembly uniform loads, and cargo box and material loads, the frame cross-section was calculated. Finite element analysis suggested that the frame longitudinal beam and cross member should utilize a C-type cross-section, with the longitudinal beam made of 700 L high-strength steel. To reduce the vehicle's center of gravity, a center-of-gravity lowering structural design was implemented for the front suspension. The main body employs a high-strength steel variable cross-section fish-belly longitudinal beam, further lowering the center of gravity. Standardized frame apertures and electrification components mounted on standardized brackets enhance assembly convenience and reduce axle load impact [20].

The topology optimization of a new energy vehicle frame structure was performed using the variable density method in finite element software. The frame structure was divided into three parts: the front section for engine or motor installation, the middle section for battery pack installation and rider mass, and the rear section for the trunk. Considering the battery pack's thickness and vehicle stability during driving, the middle section is designed lower than the front and rear sections. Using ANSYS finite element software, linear variable density topology optimization calculations under bending conditions confirmed that the frame structure meets load-bearing requirements. Further finite element analysis under torsion conditions validated the structural soundness. Figure 13 illustrates the preliminary design finite element model structure for the topology optimization of the new energy vehicle frame [21].

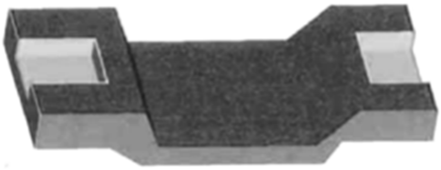

Fig. 13. Finite element model structure for the preliminary design of the topology optimization of the new energy vehicle frame [21]

4 Conclusion

This paper investigates the current state of batteries and frames in new energy vehicles, analyzing optimized design solutions that enhance performance and safety. It also offers predictions for future developments in this field. The optimization of batteries and frames in new energy vehicles is critical to advancing their performance, safety, and overall efficiency. Through various studies and simulations, significant progress has been made in the design of battery thermal management systems (BTMS) and battery structures. Effective BTMS solutions, such as the direct-cooled BTMS for blade batteries and liquid-cooled plate systems, have demonstrated improved heat dissipation, ensuring batteries maintain optimal temperatures and operate safely under various conditions. Furthermore, innovative structural designs and materials, including optimized rib dimensions and the use of new composite materials, have enhanced battery safety and performance.

Frame optimization also plays a crucial role in the performance of new energy vehicles. Advances in frame structure, such as integrated frame-battery tray designs and variable cross-section longitudinal beams, have significantly improved the durability and load-bearing capacity of frames. The use of high-strength materials, such as aluminum foam, has contributed to lightweight and improved mechanical properties, leading to better energy efficiency and safety. Moreover, multi-dimensional optimization approaches, including topology optimization and finite element analysis, have provided comprehensive solutions for reducing stress concentrations and improving the overall structural integrity of vehicle frames.

Overall, the continuous innovation in battery and frame design underscores the importance of an integrated approach to enhancing new energy vehicles. Future developments are expected to focus on further refining thermal management systems, incorporating advanced materials, and leveraging sophisticated optimization techniques to achieve even greater performance, safety, and sustainability. These advancements will not only address current challenges but also pave the way for the widespread adoption and evolution of new energy vehicles, contributing to energy security and environmental sustainability.

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