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Optimizing the Structural Design of Computing Units in Autonomous Driving Systems and Electric Vehicles to Enhance Overall Performance Stability

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Abstract: *In the rapid development of autonomous driving systems and electric vehicles, the thermal management of computing units has become a key factor affecting system performance and stability. This article explores how to enhance the heat dissipation efficiency of computing units through optimized structural design, thereby enhancing the overall performance stability. Firstly, aluminum alloy casings are an ideal material choice for computing units due to their excellent thermal conductivity, lightweight characteristics, and processing flexibility. We analyze the heat conduction mechanisms in detail and consider design based on thermal conductivity formulas. To improve heat dissipation efficiency, we adopt a fin design that increases the heat dissipation surface area, utilizing air convection to accelerate heat dissipation. We also discuss the design of fin sizes and spacing, aiming to balance the molding process's feasibility and heat dissipation efficiency. Secondly, the structural optimization of the heat dissipation module is conducted by integrating the material characteristics of copper blocks with those of aluminum alloy casings. We propose a "disassembly" design concept, considering the use of localized materials to enhance thermal conduction efficiency. For areas with high heat generation from electronic components, the high thermal conductivity of copper blocks quickly transfers heat to the aluminum alloy casing, achieving a cooling effect. Furthermore, when the aforementioned heat dissipation methods are insufficient to meet higher cooling demands, liquid cold plate technology may become an effective cooling solution. By integrating the liquid cooling system of the computing unit with the cooling system of the electric vehicle battery pack, we can achieve thermal load balancing, enhancing the system's energy efficiency and stability. This multifunctional cooling system maximizes the utilization of internal vehicle space while improving thermal management efficiency, catering to the high-performance demands of electric vehicles and autonomous driving systems. This study proposes diversified solutions for the thermal design of computing units in autonomous driving systems and electric vehicles, aiming to enhance the performance and stability of the computing units. Through the integrated use of fin design, optimization of cooling modules, and liquid cold plate technology, it provides effective and economical management strategies for the thermal management of future electronic devices, with broad application prospects.*

Keywords: Autonomous driving systems; Electric vehicles; Computing units; Heat dissipation; Structural design.

1. Introduction

As the demand for autonomous driving systems continues to rise, various sensors, radars, cameras, and other perception devices installed in vehicles generate a large amount of data that needs to be processed in real-time to support the safety and accuracy of autonomous driving. To achieve this goal, the vehicle's computing unit requires powerful processing capabilities, as well as stable thermal management and operational efficiency, which places extremely high demands on the entire technical architecture.

Firstly, autonomous driving systems need to perform high-frequency data processing and calculations to ensure immediate responses, especially in highly dynamic and complex traffic environments. The computing unit must react within milliseconds. The vehicle must accurately analyze road conditions, obstacles, pedestrian movements, and other factors, the precision and speed of this information analysis directly affect the safety of autonomous driving. Therefore, the performance of the autonomous driving computing unit determines the system's efficiency. A high-performance computing unit can effectively process data from various devices and provide immediate responses, which is crucial in the process of technology development and market promotion.

At the same time, with the increasing demand for data processing inside vehicles, the heat generated by the computing units has also significantly increased. The rise in computing density presents new challenges for heat dissipation, especially in hot environments, where these computing devices are prone to overheating, which can affect operational stability and even compromise vehicle safety. Therefore, the heat dissipation efficiency of the computing units is particularly important in this process.

In autonomous driving systems and electric vehicles, computing units often use aluminum alloy metal casings to assist with heat dissipation. This is mainly due to the multiple advantages of aluminum alloys in terms of heat dissipation characteristics, structural strength, and weight control. The following explains:

a. Superior Thermal Conductivity of Aluminum Alloys

Aluminum alloys possess a high thermal conductivity, with the thermal conductivity of die-cast aluminum alloys ranging from approximately 90 ~ 130 W/m·K. This allows them to quickly transfer the heat generated by the operation of the computing unit from the inside to the outside, helping the device dissipate heat more effectively.

b. Lightweight Advantage of Materials

In vehicle applications, weight management is one of the key considerations in design. Aluminum alloys are classified as lightweight materials among metals, with a density of about 2.7 g/cm^3. Compared to steel or copper, aluminum alloys are significantly lighter. Without sacrificing structural strength, the use of aluminum alloys can effectively reduce the overall weight of the vehicle, contributing to improved range and energy efficiency of electric vehicles. Additionally, electric vehicles are often constrained by interior space, and using aluminum alloy materials allows for lighter and smaller enclosures for the computing units, enabling more flexible use of limited installation space.

c. Mechanical Strength and Processing Flexibility

Aluminum alloys exhibit a good balance between strength and toughness, allowing them to maintain a certain degree of ductility while providing strength, which is particularly important for the protective performance of computing units in electric vehicles. Computing units often need to withstand dynamic environments such as vibrations and impacts, and aluminum alloy enclosures can provide adequate protection to prevent damage to internal components. Furthermore, computing units often have relatively complex structures due to various requirements, and to facilitate processing and shaping, die-casting techniques are commonly used to manufacture the enclosures.

This study conducts an in-depth exploration of fin design, optimization of cooling modules, and liquid cold plate technology, aiming to effectively enhance the heat dissipation efficiency of the computing units.

2. Design of Heat Dissipation Fins

2.1 Heat Transfer Mechanism and Thermal Conductivity Formula

Heat conduction is a natural phenomenon where thermal energy is transferred from a high-temperature region to a low-temperature region. When there is an imbalance in the temperature distribution within a material, heat will move from the high-temperature area to the low-temperature area until the overall system reaches thermal equilibrium. In describing the heat conduction process, thermal conductivity (λ) is an important parameter that indicates the amount of heat energy passing through a unit cross-sectional area per unit time under a unit temperature gradient. The following is the formula for heat conduction:

$$\Delta Q = -\lambda \frac{dT}{dx} \Delta S \, \Delta t \tag{1}$$

In the formula: ΔS is the cross-sectional area, ΔQ is the energy passing through the section, Δt is time, dT/dx represents the temperature change in the x direction, λ is the thermal conductivity [w/(m•k)], and the negative sign indicates that the direction of heat transfer is opposite to the direction of the temperature gradient, meaning heat will transfer from the high-temperature region to the low-temperature region.

2.2 Heat Dissipation Design Principles

To effectively transfer heat from heating components to the casing and ultimately release it into the external environment, the internal structure design of the casing typically considers placing high-power heating components as close to the casing as possible to accelerate heat conduction. This can shorten the distance for thermal energy to travel from the component to the casing, thereby improving overall heat dissipation efficiency. However, once heat is conducted to the casing, if it cannot be quickly dissipated to the external environment, the interior will still face heat accumulation issues. When thermal equilibrium is reached, the internal temperature of the casing will gradually rise, failing to achieve effective heat dissipation. To address this issue, we need to design external structures to enhance heat dissipation performance. According to the thermal conductivity formula, increasing the cross-sectional area can increase the amount of heat transferred. Therefore, a common practice in heat dissipation design is to add fin structures to the surface of the casing.

2.3 Application of Fin Structures

The design of fins is primarily aimed at increasing the contact area between the casing and the external environment, thereby accelerating heat dissipation. The diverse design of fins can increase the contact area with air, effectively promoting heat release. When air flows over the fins, the heat on the surface of the fins is continuously carried away, facilitating the heat dissipation process.

In addition, the distribution density and shape of the fins also affect the heat dissipation efficiency. The more fins there are and the denser they are, the larger the heat dissipation area can be, but if the distribution density is too high, it may obstruct air circulation, affecting the overall heat dissipation efficiency. Therefore, the design of the fins needs to comprehensively consider thermal conductivity and air circulation to achieve optimal heat dissipation. The optimization of fin design includes two important factors [1,2]: how to achieve the goal with lower costs and space. Generally, there are two methods: first, using the relationship between the shape and cross-sectional area of the fins, and the overall volume of the fins in the heat dissipation base to determine the optimal depth of the fins; second, using the number of fins and their volume to find the optimized depth and geometric shape of the fins.

2.4 Considerations for Fin Size Design

In the heat dissipation design of aluminum die-cast parts, the thickness of the material and the design of the fins are crucial for heat dissipation efficiency and structural strength. The following are design specifications and recommendations for these two points, which can be appropriately adjusted based on actual application needs:

a. Material Thickness

It is generally chosen to be between 1.5 ~ 4 mm. If the thickness is too large, it will increase costs and may easily lead to molding defects such as air holes and shrinkage cavities; if it is too thin, it may result in poor molding or insufficient structural strength.

Thicker materials have a higher thermal capacity, which helps with heat conduction and diffusion, but if they are too thick, it will increase cooling difficulty and prolong cooling time, affecting production rhythm. Therefore, to ensure good molding and cooling efficiency, a balance must be struck in the design.

b. Fin Design

The width, height, and spacing of the fins significantly affect the heat dissipation performance and should be optimized based on cooling requirements and the feasibility of the die-casting process.

The fin width is typically chosen to be between 1 ~ 3 mm, as this width usually ensures that the die-casting flow channel is filled and maintains stable heat dissipation efficiency. If the width is too large, it will affect the heat dissipation surface area and reduce cooling effectiveness; if it is too small, there is a risk of deformation and damage during the die-casting process.

The fin height is usually controlled between 10 ~ 25 mm. If the height is too high, it will affect the fluidity of the molten aluminum, impacting the stability of the die-casting process and leading to a decrease in yield; if the height is too low, it will not provide sufficient heat dissipation area.

The fin spacing is typically between 2 ~ 5 mm, and the spacing affects air flow and the uniformity of heat dissipation. If the spacing is too large, it will reduce the effective heat dissipation area; if it is too small, it will hinder air flow, reduce convective cooling effectiveness, and also affect the manufacturing and processing of the die-casting mold.

3. Design Optimization for Cooling Modules

In the current design of computing units for autonomous driving systems and electric vehicles, achieving efficient and stable heat dissipation is crucial. These computing units typically require a sealed and fanless design to avoid dust contamination caused by fan operation. Fine particles in the environment, if drawn in by the fan, may accumulate inside and damage electronic components, affecting system stability. However, since these systems often need to handle a large amount of high-density computations, they generate significant heat, and excessive temperatures may lead to reduced performance of the computing units or even system crashes. Therefore, effectively addressing the fanless cooling issue under high-density computing conditions has become a design challenge.

In the absence of fans, the optimized design of heat dissipation fins is the preferred choice. However, when the design of the heat dissipation fins has reached its limit and cannot further reduce the high temperatures of electronic components, it is necessary to explore adjustments in materials and structures to enhance heat dissipation performance. From the perspective of material properties, gold, silver, and copper all have relatively excellent thermal conductivity, but considering cost issues, copper and aluminum become the most commonly used thermal conductive materials. In heat dissipation systems, copper has a higher thermal conductivity coefficient, allowing it to quickly absorb and conduct heat generated by components; however, although aluminum's thermal conductivity is slightly inferior to that of copper, it performs better in terms of heat dissipation efficiency and cost control. Aluminum is lighter and dissipates heat relatively quickly, which is why aluminum alloys are often chosen as the primary material for computing unit casings. Therefore, the design incorporates a combination of copper and aluminum, meeting thermal conductivity requirements while controlling costs and weight.

In this design, the parts close to the heat-generating electronic components are made of copper to optimize thermal conduction performance. When heat is conducted from the high-temperature electronic components to the copper block, the copper block can quickly absorb this heat and transfer it to the surrounding aluminum alloy structure. The aluminum alloy casing then further disperses this heat to the external environment, significantly enhancing the overall heat dissipation effect. This design concept employs a "disassembly" approach, dividing the aluminum alloy casing into a cooling module and the main structure, specifically targeting high-heat areas for localized optimization, achieving dual utilization of materials and structures [3], as illustrated in Figure 1.

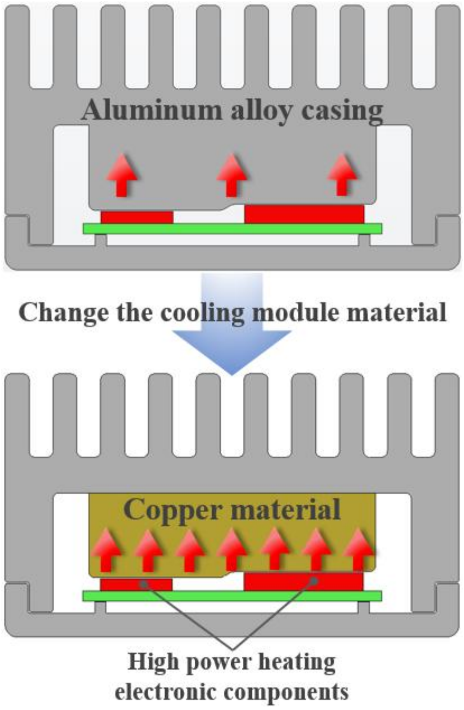

Figure 1: Diagram of changing the cooling module material.

Based on this design concept, thermal simulation software was used to test and analyze the improved structure. The simulation results showed that by adding copper blocks around particularly high-heat electronic components, the temperature of these components could be reduced by at least 5 °C, with the specific cooling effect varying according to the size of the copper blocks. This design effectively reduces the accumulation of high temperatures in electronic components, extending their lifespan and enhancing system stability. However, it should be noted that both the price and weight of copper are higher than that of aluminum, so a balance must be struck between the volume of the copper blocks and their heat dissipation performance. While increasing the volume of the copper blocks can further lower the component temperature, it also brings issues of increased weight and cost.

In future cooling system designs, this "disassembly" design approach provides a practical reference. As computational demands grow, the need for fanless and sealed high-efficiency cooling solutions will become increasingly significant. This design concept can be applied not only to autonomous driving systems but also to other high-power electronic devices that require stable heat dissipation, helping to enhance product competitiveness and market acceptance.

4. Application of Liquid Cold Plates Technology

In the thermal design of electronic components, when traditional heat sink solutions reach their physical limits, and localized optimization methods for high-heat areas cannot meet further cooling demands, designing the interior of aluminum alloy casings as a liquid cold plate structure is a solution worth considering.

The liquid cold plate technology utilizes coolant flowing inside the cold plate to directly absorb and carry away heat from high-temperature areas. It belongs to direct contact cooling technology, where the coolant is introduced into a metal cold plate. After absorbing heat, the coolant continuously flows through the channels within the cold plate, transferring heat to other cooling devices (such as radiators) or dissipating it into the external air. Compared to traditional heat dissipation fins, the design of the liquid cold plate can effectively accelerate the rate of heat conduction from high-heat components, making it particularly suitable for applications involving high power density computing units, further enhancing cooling efficiency and overall performance stability.

In electric vehicles, the battery pack also requires strict temperature control management to protect battery life and performance. Integrating the liquid cooling system of the computing unit with the battery pack cooling system can bring multiple advantages. First, sharing the cooling system can reduce the number of cooling modules within the vehicle, simplifying the overall structure of the cooling system. This integrated design reduces the number of coolant circuits, thereby lightening the vehicle's weight and lowering manufacturing and maintenance costs, while also improving system energy efficiency.

Secondly, a shared cooling system allows the coolant to flow through both the computing unit and the battery pack within the same circuit, facilitating heat exchange between different heat sources. The thermal load of the computing unit and the battery in electric vehicles typically fluctuates with the vehicle's operating conditions. By integrating the cooling system, the system can more effectively regulate cooling resources during peak demand, balancing the thermal load and preventing overheating of individual components.

The uniformity of temperature can also be significantly improved. A unified liquid cooling system can ensure that the computing units and battery packs operate within a stable temperature range, further enhancing system reliability. In addition, the integration of a single cooling system reduces space requirements, which is particularly effective for electric vehicles with strict internal space utilization, especially in compact layouts. This integrated liquid cooling design not only meets the demands for efficient heat dissipation but also contributes to the overall integrity and modularity of vehicle design, providing an efficient and economical thermal management solution for future electric vehicles.

5. Conclusion and Outlook

With the proliferation of autonomous driving technology and electric vehicles, the stability and performance of computing units have become core factors determining system performance. Since autonomous driving systems need to process vast amounts of data and respond quickly, strong processing performance and a stable cooling system are fundamental to their successful operation. This study first analyzes the advantages of aluminum alloy as a casing material, showcasing its ideal application effects in-vehicle computing units from multiple aspects, including thermal conductivity, lightweight characteristics, and processing flexibility. At the same time, we explored the optimized design of fin structures, effectively increasing the heat dissipation surface area and optimizing air circulation by adjusting the size and layout of the fins, further enhancing heat dissipation efficiency. In response to the challenges of high power density heat dissipation, we propose a design that combines aluminum alloy casings with copper blocks. This design utilizes the high thermal conductivity of copper to quickly absorb and transfer the heat generated by electronic components, which is then released to the external environment through the aluminum alloy casing. This innovative design balances cost, weight, and heat dissipation performance, and thermal simulation tests have shown significant cooling effects, making it suitable for use in fanless and sealed computing units.

Looking ahead, the demand for efficient cooling systems in autonomous driving systems and electric vehicles will further increase, and liquid cooling technology is expected to become one of the key solutions. Based on liquid cold plate technology, we have explored the potential of a shared cooling system for computing units and battery packs. This design not only reduces the number of cooling modules and simplifies the system structure but also balances the thermal load between different heat sources, further enhancing the cooling efficiency and reliability of the system. Future research directions will focus on the design of flow channels for liquid cold plates, optimization of coolant flow rates, and exploring ways to improve the cooling efficiency of liquid cold plates.

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