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Structural Optimization and Performance Evaluation of Liquid Cooled Super Fast Charging Cable Based on Multi-Physics Coupling Calculation

Yanrong Ni[1, 2], Shupeng Zhao[3], Xiaohe Zhao[1, 2, *], and Kaituo Zhang[1, 2]

[1]Henan Institute of Technology, Xinxiang 453000, Henan, China
[2]Henan Key Laboratory of Cable Structure and Materials, Xinxiang 453000, Henan, China
[3]Wuxi Xinhongye Wire & Cable Co., Ltd., Wuxi 214101, Jiangsu, China

ABSTRACT: Super fast charging is a key solution to addressing the issue of electric vehicles. In response to the demand for increased current-carrying capacity and lightweight cables in super-fast charging system, optimization design and verification were conducted in this study employing a multi-physics field analysis method. A single-core cable was selected as the research subject, and both the Ohmic loss and temperature distribution were analyzed under the excitation of electric vehicle cold charging current. The influence of different cable core shapes, coolant flow rates, cooling channel structural parameters, and other factors on the maximum temperature rise of the charging cable were compared and analyzed. The calculation results indicated that, under the identical cable core cross-sectional and operating conditions, rectangular cross-section cables exhibited superior heat dissipation performance compared to circular cross-section cables. It was found that the flatter the cable core is, the better the heat dissipation performance is. Under specific operating conditions, the cross-sectional area of the flat linear shape could be reduced appropriately, as increasing the size of the liquid cooling channel would help reduce the overall mass of the cable. These findings provide valuable insights for enhancing the heat dissipation performance and lightweight design of liquid-cooled charging cables in supercharging applications.

1. INTRODUCTION

Under the "carbon peaking and carbon neutrality goals", electrification is a key direction for the future development of automobiles. With the increase in battery capacity and driving range of electric vehicles, fast charging technology has become a critical solution to address range anxiety and facilitate the market adoption of electric vehicles [1, 2]. However, due to the inherent properties of conductors, cable core temperature increases rapidly under high current. This can lead to the accelerated aging and failure of cable insulation at elevated temperatures, potentially causing fires, which significantly limits the promotion and widespread application of electric vehicles [3].

The working environment of electric vehicle fast charging cables is mainly outdoor, so their heat dissipation performance is affected by meteorological parameters. Additionally, for the convenience of operation, the lightweight design of cables is a crucial consideration for fast charging systems [4]. The research on cable cooling technology, enhancing cable heat dissipation efficiency, increasing cable current-carrying capacity, reducing metal consumption, and achieving lightweight design are essential requirements for their commercial deployment of electric vehicle charging cables [7–9]. Liquid cooling technology utilizes circulating low-temperature fluid to remove internal heat from equipment, thereby managing temperature. This technology has been widely applied in temperature management of high-power electrical equipment, due to high heat dissipation efficiency and simple system structure [5, 6]. Currently, liquid cooling is extensively used in energy storage batteries, data centers, and other fields. However, research in the area of charging cables remains relatively limited [10, 11]. The development of liquid-cooled cables is an effective approach to address thermal management in high-current fast charging systems [12]. However, the integration of an additional cooling system will inevitably add complexity to the cable structure and increase its weight, which may hinder the portability of handheld fast charging terminals. Therefore, finding a solution to achieve lightweight cable design while ensuring heat dissipation performance is an urgent challenge.

To further investigate the impact of geometric shape and structural parameters of liquid-cooled cables on their heat dissipation performance and weight in supercharging scenarios, this study established three-dimensional models of liquid-cooled charging cable with different cooling cross-sectional shapes. The models simulate and analyze factors such as load current, flow rate of the coolant, and cooling channel structural parameters. The finding provides valuable insights for further enhancing the heat dissipation performance and lightweight design of supercharging liquid-cooled cables.

* Corresponding author: Xiaohe Zhao (15893860381@163.com).

TABLE 1. Physical property parameters of cable material.

structure	Cable core	insulation	Cooling pipe	Cooling fluid
Material	Cu-OF	EPDM	XLPO	Silicone oil
Quality density	8960	1450	920	975
thermal conductivity	400	0.24	0.35	0.15
Specific heat Capacity	385	1700	2000	1630
conductivity	5.59e7	1e-10	1e-8	-
permittivity	-	2.7	2.4	2.17

2. MODEL ESTABLISHMENT

2.1. Geometric Model

This study focuses on a specific certain brand of electric vehicle liquid-cooled charging cable, which operates at voltage of 1000 V and uses Dimethyl silicone oil as the coolant. Currently, the maximum peak power of the liquid-cooled supercharging pile is 600 kW. Considering that future demand for super fast charging, the maximum load current of the charging cable core is set to 1000 A. Based on the typical power curve during the charging process of electric vehicles, in a cold car charging operation, the current is a time-varying parameter. For the purpose of analysis, the current in the cable is approximated as a step function. The study investigates cable heat dissipation and structural optimization under the influence of a typical charging current sequence.

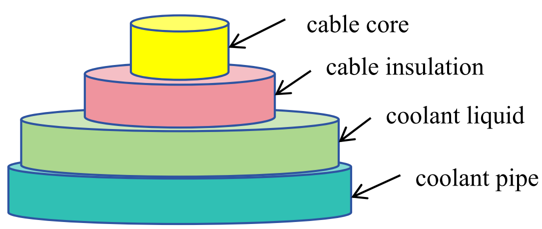

FIGURE 1. Single line structure of liquid-cooled cable.

As shown in Fig. 1, the main structure of the cable consists of a conductor core twisted with thin copper wire, an insulation layer made of silicone rubber, a cooling pipe filled with ethylene glycol coolant, a filling layer, and protective sheath. Under rated conditions, the maximum allowable temperature for the operation of the charging cable is 50°C. To simplify the 3D model, the following assumptions are made.

(1) The operating environment temperature of the charging cable remains constant over time.

(2) There is no thermal resistance at the contact points between the layers of the charging cable.

(3) The materials and structures of each layer of the charging cable are uniform along its length, and their physical properties remain constant.

(4) The inlet temperature and pressure of the coolant are constant values.

(5) The contribution of Ohmic losses in signal and ground wires to heating in cables is neglected.

(6) The cable core is assumed to be coaxial with the coolant pipeline, without considering the influence of cable placement posture on the position of the cable core.

The structure of the liquid-cooled cable core is shown in Fig. 1. The insulated core is positioned within a cooling pipeline filled with coolant. During operation, the coolant circulates through the cooling pipeline driven by an external cooling pump. The Ohmic loss heat from the conductor is transferred to the coolant through thermal conduction and is subsequently carried away by the circulating coolant.

This article aims to achieve lightweight design for cables and provides a comprehensive analysis of the operational performance of various cable structures. Due to manufacturing limitations, the basic cross-sectional shapes of current supercharging cables are mainly circular, rectangular, and flat. Based on the calculation maximum charging current, the nominal cross-section of the conductor is 120 mm^2. The insulation layer has the thickness of 2 mm; the coolant pipe is 3 mm thick; and the average width of the cooling channel is denoted as d. The material parameters of the cable are shown in Table 1.

2.2. Mathematical Model

For liquid-cooled cables with DC superfast charging, only the contribution of conductor Ohmic loss and insulation leakage loss to heat needs to be considered during operation. Therefore, the Maxwell equation can be simplified into the form of a constant electric field, and the calculation of the electromagnetic field also uses a current field module.

$$\begin{cases} \nabla \cdot \mathbf{J} = 0 \\ \nabla \cdot \mathbf{E} = 0 \end{cases} \tag{1}$$

The heat source is Joule heat generated by Ohmic losses.

$$Q = JE \tag{2}$$

where E is the electric field strength, J the current density, and Q the Joule heating power.

In temperature field analysis, solid and fluid heat transfer modules are employed to establish natural coupling between temperature field and flow field.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T - \nabla \cdot k \nabla T = Q + Q_p + Q_{vd} \tag{3}$$

In the formula: ρ represents the material density of each part of the model, C_p the specific heat capacity of the material, T

the temperature, k the thermal conductivity, and Q the volumetric heat source term, mainly derived from Joule heat generated when current passes through the cable. Q_p and Q_{vd} denote the boundary heat source and the fluid heat source, respectively, while $\mathbf{u}$ is the fluid velocity vector.

2.3. Loading of Incentive Sources

Based on the typical current curve in zero-state batteries charging, the charging current is approximated as a stepped current sequence, as shown in Fig. 2. The charging voltage is 1000 V, and the cold vehicle charging capacity is 300 kW·h.

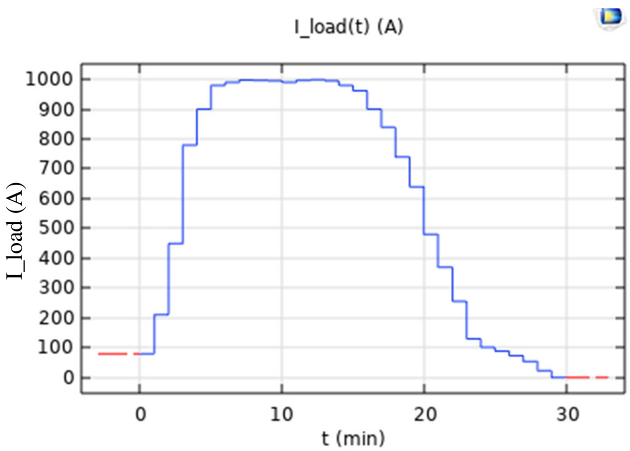

FIGURE 2. Charging current sequence.

The conductor is composed of copper wire twisted in the same direction and tightly compressed, with a compression coefficient of 0.9. The diameter of each stranded conductor is 0.5 mm, and the resistivity of a single conductor at 20°C is not greater than 192 m Ω/m. The conductors consists of 620 strands, with a nominal cross-sectional area of 120 mm^2. After twisting, the resistance per unit length of the conductor does not exceed 0.20 m Ω/m.

2.4. Definition of Boundary Conditions and Coupling Interface of Multiple Physical Fields

In the simulation, a coupled calculation method of electromagnetic field and temperature field is employed, with the coupling interface defined as electromagnetic heat. The electromagnetic calculation uses the current field module in AC/DC, and the calculation area includes a conductor and an insulation area. The outer boundary of the insulation is set as electrical insulation. The temperature field is calculated using solid and fluid heat transfer modules, covering the entire model area. Based on the physical properties of the cable, the coolant is set as a fluid with a flow rate along the cable axis. The outer boundary of the cable is treated as a thermal insulation boundary, meaning that there is no heat exchange between the surface of the charging cable and the external environment. The boundary condition for the fluid field is a noslip boundary, which implies that the velocity of the coolant on the wall of the cooling channel is zero.

Consider the calculation model as a local cable section, with symmetrical boundaries applied at both ends of the model.

3. RESULTS AND DISCUSSION

3.1. Temperature Rise Curve and Temperature Field Distribution

The temperature field distribution along the cable axis at 12 minutes after the start of charging is shown in Fig. 3. The temperature is the highest in the conductor with a relatively uniform spatial distribution. In contrast, the temperature of other materials gradually increases along the flow of the coolant, forming a longitudinal temperature gradient. Under the same operating conditions, the conductor temperature of circular cross-section cables is the highest, while the conductor temperature of flat cross-section cables is the lowest.

The temperature rise at the center point of the conductor is taken as the research object. When the coolant circulation speed is 0.1 cm/s, the curve of temperature rise with time is shown in Fig. 4. As illustrated, the temperature of the conductor gradually increases from the initial as the current sequence is applied. At the 18th minute after the start of charging, the temperature rise reaches its maximum value, after which it gradually decreases. The temperature rise curves for conductors with different shapes vary due to different heat dissipation conditions. The maximum temperature rise values of circular, square, and flat interface conductors are 67.5 K, 60 K, and 42 K, respectively.

Based on the above analysis results, the temperature rise at a specific point in the conductor at $t = 18$ min is selected as the research focus. The study investigates the effects of cooling pipe area and coolant flow rate on the temperature rise of cable conductors with different conductor cross-sections types.

(1) The influence of coolant flow rate

Figure 5 illustrates the effect of varying flow rates of dimethyl silicone oil on the maximum temperature of the liquid-cooled charging cable core. The ambient temperature is 20°C; the coolant inlet temperature is 20°C; and the loading current is the current sequence, shown in Fig. 2.

As shown in Fig. 5, even at high flow rates, the charging cable with a circular cooling channel still experiences relatively high temperature rise due to the limitation of the heat dissipation surface area. The flat cooling cross-section has better heat dissipation performance than other shapes. When the flow rate is $0.01 \sim 1$ cm/s, the temperature of the liquid-cooled charging cable core drops rapidly. However, when the flow velocity is greater than 1.5 cm/s, the temperature reduction becomes more gradual. At a flow rate of 0.5 m/s, the flat charging cable is decreased by 6.9°C and 6°C compared to circular and rectangular cables, respectively. Increasing the flow velocity enhances the convective heat transfer coefficient, reduces the boundary layer, promotes turbulence, and allows the coolant to more effectively remove heat, significantly improving cooling efficiency. However, once the coolant flow rate reaches a certain level, factors such as the nonlinear increase in convective heat transfer coefficient, the limits of material thermal conductivity, and the reduced temperature difference due to the increase in coolant temperature limit the further reduction in temperature. This results in temperature stabilization at high flow rates. Although high flow rates can improve cooling efficiency, they also introduce issues such as increased power con-

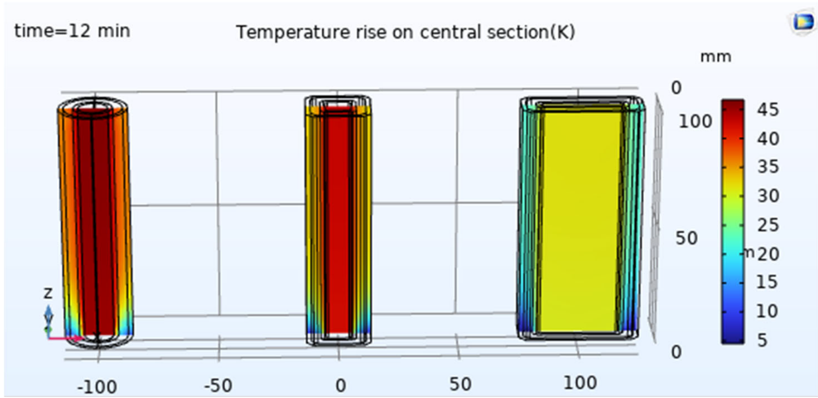

FIGURE 3. Temperature field distribution.

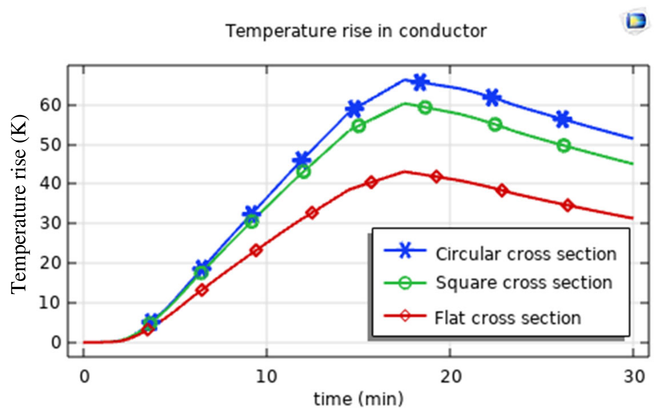

FIGURE 4. Cable temperature rise curve.

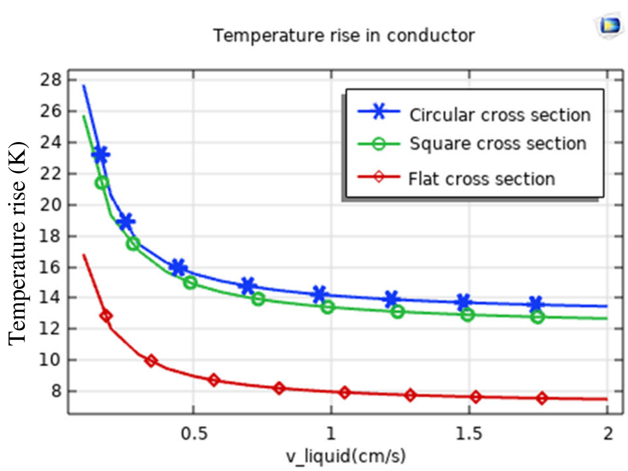

FIGURE 5. Maximum temperature rise under different coolant flow rate.

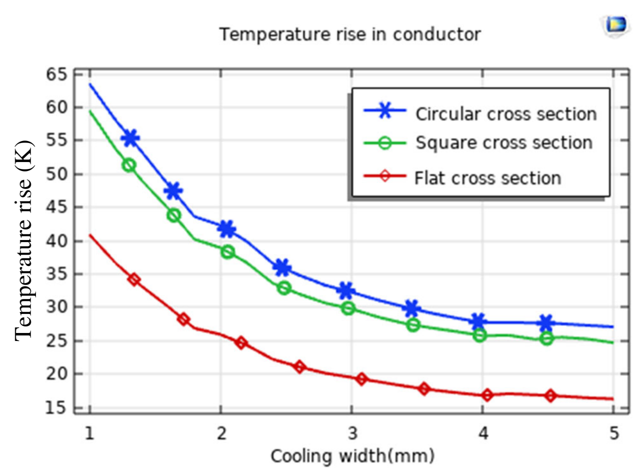

FIGURE 6. The temperature rise under different cooling channel sizes.

sumption, equipment wear, and noise. Therefore, in practical applications, the optimal flow rate is selected as 0.5 cm/s.

(2) The influence of cooling channel size

As shown in Fig. 6, the maximum temperature rise of cables with different cross-sectional shapes was simulated and calculated as a function of the size of the cooling channel at an ambient temperature of 20°C and a coolant flow rate of 0.5 cm/s. The results indicate that increasing the size of the cooling channel significantly enhances the coolant flow rate, improves the convective heat transfer effect, and effectively enhances the heat dissipation performance of the charging cable, leading to a decrease in the maximum temperature of the cable core. Among the different shapes, cables with circular cross-sections exhibit the highest temperature rise, while cables with flat cores experience the lowest temperature rise.

When the cross-sectional area of the cable core is constant, an increase in the size of the cooling channel corresponds to an increase in the cross-sectional area of the cooling channel. Under the excitation of the load current sequence, when the width of the cooling channel ranges from 1 to 3 mm, the maximum temperature rise of the cable core decreases significantly, with temperature differences of 31.2°C, 25.3°C, and 21.2°C, respectively. However, when the width varies from 3 to 5 mm, the temperature change in the cable core is minimal, with a temperature difference only about 2.5°C. Additionally, as the width of the cooling channel increases, more coolant is required per unit length, which is not conducive to the lightweight design of the cable. Therefore, it is possible to reduce the size of the cooling channel appropriately to achieve lightweight design while ensuring safe and stable operation of the charging cable under high-current conditions.

(3) The influence of the aspect ratio of rectangular cable cores on temperature rise

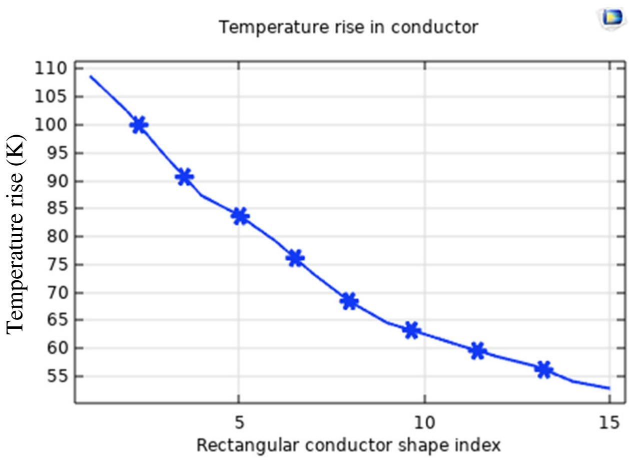

FIGURE 7. Temperature rise under different geometric shapes of conductor.

Based on the above analysis results, as shown in Fig. 7, compared to the circular cross-section cable structure, the rectangular cross-section cable provides a larger contact area between the core and the coolant, which enhances heat dissipation. The length-to-width ratio of the rectangular conductor core is defined as the geometric index k of the conductor. The maximum temperature rise of the rectangular conductor core as a function of the length to width ratio was simulated and calculated at an ambient temperature of 20°C and a coolant flow rate of 0.5 cm/s. As shown in the figure, when $k = 1$, the cross-section of the conductor is square, and the maximum temperature rise of the cable is 108 K. As k increases, the cable core becomes gradually flatter, and its temperature rise gradually decreases. However, an excessively flat core structure increases the difficulty of cable manufacturing to some extent and also alters the shape and capacity of cable cooling pipelines.

4. LIGHTWEIGHT ASSESSMENT OF CABLES

Based on the results of above analysis, the temperature rise of cables with circular conductor structures is higher than that of cables with rectangular conductor cross-sections under the same working conditions. The temperature rise of cables is influenced by the shape of the conductor, the size of the heat dissipation channel, and the flow rate of the coolant. The heat dissipation index of cable structures is defined as μ.

$$\mu = \frac{S_{\text{fluid}}}{S_{\text{conductor}}}$$

If the cross-sectional area of the conductor is S, the length to width ratio of the rectangular conductor is k; the average width of the cooling channel is d; the structural heat dissipation parameters are as follows, assuming that the thickness of the insulation layer is ignored.

$$\mu = \frac{2\left(k+1\right)\sqrt{\frac{S}{k}}d + 4d}{S}$$

The weight of the cable is influenced by the shape of the cable conductor and the size of the heat dissipation channel. According to Equation (3), the ratio of the unit length mass of a rectangular cross-section cable to that of a circular cross-section cable is defined as the cable weight index.

$$G = \frac{\sum \rho_i S_{i\_\text{rect}}}{\sum \rho_i S_{i\_\text{circle}}}$$

The design of lightweight, high-performance heat dissipation super-fast charging cables is a critical requirement for advancing the commercialization of fast charging for electric vehicles. Based on the above analysis, the comprehensive performance index function η is defined as follows.

$$\eta = \frac{G}{\mu}$$

A smaller η indicates a better comprehensive performance index for the cable. When cable structures are designed, the influence of conductor shape and liquid cooling channel size should be comprehensively considered within the allowances of manufacturing.

In the lightweight design of cables, the influence of coolant circulation flow rate can be ignored. The lightweight index and comprehensive index of cables will be functions of cable structural parameters and coolant channel width. The flatter the cable core and the wider the fluid channel are, the better the heat dissipation performance of the cable is. However, excessively flat wire cores will increase the difficulty of process and product quality control. Meanwhile, an increase in the width of the fluid channel will inevitably lead to a less compact cable structure, which is not conducive to portable operation. Therefore, in structural design, cable structural parameters should be selected reasonably according to process requirements.

Based on the above analysis, in the preliminary design of cables, flat wire structures should be prioritized, provided that the manufacturing process allows. Additionally, the selection of the average width of the heat dissipation channel should be optimized based on the coolant circulation parameters.

5. CONCLUSION

Using finite element simulation software and coupling multiple physical fields, a multifactor analysis was conducted on liquid-cooled charging cables in overcharging scenarios. The cross-sectional geometry and structural parameters of singlecore liquid-cooled charging cables were optimized. The following conclusions were drawn:

(1) Compared with circular section conductors, rectangular section conductors have a larger surface area for the same cable core cross-sectional area. Multicore twisted structures can further increase surface area, promote airflow, optimize heat conduction paths, and enhance mechanical stability. These factors effectively reduce the operating temperature of charging cables thereby improving their reliability and service life.

(2) The flow rate has a critical impact on the heat dissipation performance of liquid-cooled charging cables. A high flow rate cooling fluid can significantly improve heat exchange efficiency and reduce cable temperature. However, it also introduces challenges such as increased energy consumption, noise, and system complexity. In the overcharging scenario, the coolant flow rate of 0.5 cm/s is selected for the liquid-cooled charging cable to achieve optimal heat dissipation performance and system efficiency.

(3) Altering the geometric shape can enhance heat dissipation performance. Under the excitation of cold car charging current and with the same cooling channel and cable core cross-sectional area, flat charging cables exhibit the best heat dissipation performance, while circular cables show the poorest heat dissipation performance. The maximum temperature rise of the flat liquid-cooled charging cable core decreases with the increase of the cross-sectional aspect ratio k of the cable core. When $k > 10$, effective heat dissipation can be achieved with a smaller coolant channel size. However, an excessively high k value will result in a cable structure that is too flat, increasing the difficulty of the process.

The optimized liquid-cooled charging cable has significant application potential in high-power electric vehicle charging. It can operate at higher currents, reduce the charging time of electric vehicles, improve user experience, and contribute to the widespread adoption of electric vehicles. This study offers a reference for further improving the heat dissipation performance and lightweight design of liquid-cooled charging cables. Future research can focus on experimental verification based on the simulation results and further optimization of the structural parameters of multi-core charging cables.

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