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Thermal-fluid-machine Co-design and Performance Optimisation of Highly Integrated Electric Drive Systems

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ABSTRACT
Aiming at the challenges of heat dissipation and reliability brought about by the high integration of electric drive systems in new energy vehicles, this paper proposes an innovative integrated cooling scheme based on the core concept of "heat-flow-machine" co-design. By designing a shared substrate for the cooling runners and a direct contact cooling structure with insulating oil, the scheme achieves a deep integration and optimisation of the thermal management system of the motor and inverter. In the study, a high-precision thermal-fluid coupling simulation model is established, and the thermal performance and pumping power consumption of the system are analysed under different cooling oil flow rates under the guidance of active thermal management strategy. The core results show that the maximum junction temperature (T_j)of the SiC chip is stabilized below 140 ℃ under the high ambient temperature of 40 ℃ and the rated load condition, which provides sufficient heat dissipation redundancy; by comparing with the traditional indirect cooling scheme, the present scheme reduces the total thermal resistance of the system by about 37.5%, which significantly enhances the system's heat dissipation performance; moreover, through the trade-off analysis of the pressure loss and the power consumption of pumping, the Q In addition, through the trade-off analysis of pressure loss and pumping power consumption, Q=1.5 L/min is determined as the optimal thermal equilibrium operating point of the system, which achieves the optimal balance between heat dissipation performance and net efficiency of the system. This paper strongly demonstrates the great potential of the integrated thermal-fluid-machine co-design in improving the volumetric power density and operational reliability of the electric drive system.

KEYWORDS
Electric drive system; Heat-fluid coupling; Active thermal management; Power density

1 Introduction

1.1 Research Background and Significance

With the transformation of global energy structure and the enhancement of environmental protection awareness, the new energy vehicle industry is experiencing explosive growth. In this wave, the electric drive system, as the core "heart" of electric vehicles, directly determines the range, power performance and operational reliability of the vehicle. In order to meet the growing consumer demand for high efficiency, high power density, light weight and low cost, the integrated design of electric drive systems has become an irreversible technological trend [1-2]. This integrated design usually integrates the motor, electronic control unit, and reducer into a compact whole, which greatly reduces the size, simplifies the assembly, and improves the overall efficiency of the system [3].

However, a central challenge posed by the high level of integration is thermal management. When motors and electronic control units are tightly packaged together, the heat they generate is highly concentrated, and if it cannot be efficiently dissipated, it will lead to high temperatures of key internal components such as motor windings and power semiconductor devices. This not only seriously affects the system performance, but also accelerates the aging of the components and reduces the stability and lifetime of the system [1]. Therefore, designing an efficient and reliable cooling scheme that is highly integrated with the system has become a key bottleneck in the current design of highly integrated electric drive systems.

1.2 Current Status of Domestic and Overseas Research

In recent years, the integration technology of electric drive systems has been widely researched in academia and industry. In terms of electric motors, the research mainly focuses on direct-drive motor systems, aiming to improve power density and efficiency through optimised design, and exploring their potential in vehicle applications [1]. In power electronics, integration techniques have evolved from traditional modularity to shortening the heat transfer path by packaging the power semiconductors directly inside the motor or sharing the cooling structure with the motor housing [3]. In addition, various thermal management techniques, such as air-cooling, liquid-cooling, oil-cooling, and phase-change cooling, have been intensively studied and applied in order to cope with the heat dissipation challenges associated with high power density [2].

Despite the large number of studies, there are still some shortcomings in the existing work. Most of the studies focus on the optimisation of a single module, such as a separate motor or a separate electronic control, but lack a systematic study on the synergistic design of "motor+electronic control+cooling system" at the beginning of the design. In particular, how to use liquid or oil cooling structure, while achieving rapid heat dissipation, taking into account the system's compactness, efficiency stability and reliability, is still a difficult problem that needs to be solved. Therefore, the purpose of this paper is to explore the key technologies for realising the highly integrated design of "motor+electronic control+cooling system", and to focus on the study of adopting liquid-cooled or oil-cooled structure to achieve rapid heat dissipation and efficiency stability improvement.

2 Analysis of Heat Source and Thermal Management of Highly Integrated Electric Drive System

2.1 Analysis of System Heat Source

The thermal management challenges in highly integrated electric drive systems stem from the high coupling of the two main heat sources, the motor and the electronic control. Accurate quantification and localisation of these heat sources is a prerequisite for the design of an efficient cooling system.

2.1.1 Motor Heat Sources

The heat generated by the motor during operation mainly comes from various types of losses within the motor. These heat sources can be divided into the following categories:

(1) Copper loss: also called winding loss, it is the heat generated when the stator winding current passes through the resistance. It is the most important heat source of the motor under load, and its size is proportional to the square of the current, so it is especially significant in high torque output.

(2) Iron loss: hysteresis loss and eddy current loss generated by the stator core under the action of alternating magnetic field. Iron loss is related to the motor speed and flux density, so it becomes one of the main heat sources at high speed [1].

(3) Permanent Magnet Losses: In some specific working conditions, due to the influence of high frequency harmonic magnetic field, the permanent magnet will also generate eddy current losses, thus generating heat [1].

(4) Mechanical loss: including bearing friction and wind resistance, etc., which will produce non-negligible heat under high-speed conditions.

2.1.2 Electronic Control System Heat Source

Electronic control units, especially power semiconductors (e.g., IGBTs and SiC MOSFETs), are another major source of heat in electric drive systems [4]. These devices generate a large amount of heat during switching and conduction, and their junction temperature directly affects the performance and reliability of the system. Other heat generating components include:

(1) Power semiconductor losses: including conduction losses and switching losses. With the increase of switching frequency and power density, the junction temperature of semiconductor devices becomes the primary factor limiting system reliability [4].

(2) Passive component losses: The heat generated by passive components such as capacitors and inductors during charging, discharging and energy storage, although relatively small, must be included in the overall thermal budget consideration in a compact packaging environment [4].

In a highly integrated electric drive system, the heat source is mainly concentrated in the motor and the electronic control unit, and its heat transfer path is shown in Figure 1.

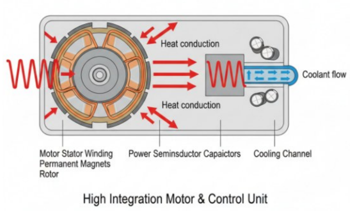


Figure 1 Distribution of main heat sources and heat transfer path of highly integrated electric drive system

2.2 Thermal Management Strategy

In the face of the high heat flow density and complex heat transfer path brought by the highly integrated system, the traditional thermal management scheme can no longer meet the requirements. Currently, efficient thermal management strategies mainly focus on liquid cooling and oil cooling, aiming to quickly remove heat from the core heat source.

2.2.1 Liquid Cooling

Liquid cooling systems typically use a water-glycol mixture as the coolant to dissipate heat through dedicated cooling runners that come into contact with heat-generating components. The advantages of this method are high heat dissipation efficiency and the large specific heat capacity of the coolant, which can take away a large amount of heat. However, liquid cooling also faces a number of challenges, such as the complexity of runner design, the corrosive nature of the coolant, and the need for separate pumps and auxiliary equipment such as heat sinks. In integrated designs, liquid cooling is often combined with the motor's external housing or internal stator runners for compactness.

2.2.2 Oil Cooling

Oil cooling technology is gaining interest in highly integrated electric drive systems due to its unique advantages. Insulating oil can come into direct contact with electrical components such as motor windings and power semiconductors to achieve direct cooling. This approach is more efficient in terms of heat transfer and is able to remove heat directly from the core of the heat source, making it particularly suitable for high power density systems. In addition, the oil cooling system can share the cooling medium with the lubrication system of the motor, further simplifying the system structure [4].

2.2.3 Active Thermal Management and Co-Design

To maintain stable operation and long-lasting reliability of the system under different operating conditions, more refined thermal management is required: Active Thermal Control (ATC) ensures that the system operates in the optimal temperature range by monitoring the temperature of critical components in real time and dynamically adjusting the flow rate of the coolant, its temperature, or the cooling power. This helps mitigate thermal stresses on power semiconductors during transient or overload conditions and is a key means of improving long-term reliability [5]. Future design trends require that the cooling system must be deeply coupled to the structure of the motor and electronic control from the early design stage. This means that cooling runners, power module layouts, and electromagnetic designs need to be co-optimised to achieve the best possible thermal balance [2].

In order to more systematically evaluate the strengths and weaknesses of existing thermal management techniques and to identify innovative directions for this research, a performance comparison of several common electric drive train cooling schemes (air-cooled, water-glycol-liquid-cooled, oil-cooled, and refrigeration-cooled) has been conducted. Table 1 summarises the advantages and limitations of these schemes in terms of cooling media, structural features, thermal efficiency and application scenarios. The comparison results clearly indicate that traditional cooling schemes can hardly satisfy the multiple demands of high power density systems for efficient heat dissipation, compact structure and insulation safety at the same time, which leaves room for innovation in the integrated co-design proposed in this paper.

Table 1 Performance comparison of several common thermal management technologies for electric drive systems

Cooling method	Cooling medium	Advantages	Disadvantages	Application Scenario
Air Cooling	Air-cooled	Simple sructure, low cost	Low heat dissipation efficiency, not suitable for high power density systems	Low power electric drive system
Liquid cooling (water-glycol mixture)	Water-glycol mixture	High heat dissipation efficiency, large specific heat capacity of the medium, stable cooling performance	Relatively complex structure, independent cooling system, media conductive	Mainstream cooling solutions for new energy vehicles
Oil cooling (spray/immersion)	Insulating oil	Very high heat dissipation efficiency, can directly contact the heat source, simplify the system structure	Requires additional oil pump, insulating oil and compatibility requirements	High power density, highly integrated electric drive system
Refrigerant cooling	Refrigerant	Cooling temperature can be lower than the ambient temperature, strong heat dissipation ability	High energy consumption, complex system, high cost	Few applications pursuing extreme performance

3 Innovative Cooling Solution Design And Analysis

3.1 Overall Design Concept

The innovative cooling scheme proposed in this paper is based on the core concept of "heat-fluid-machine" integrated co-design, which means that the thermal management, fluid and mechanical structure of the system are regarded as a whole and jointly optimised. It aims to solve the problems of high heat flow density and complex heat source coupling in highly integrated electric drive systems. The solution is based on the structural trend of co-axial integration [7], where the motor and the electronic control unit are physically tightly integrated and thermally balanced by designing a shared and efficient cooling circuit [8].

3.2 Key Structure and Cooling Circuit Design

The core of this proposal is to optimise the physical layout of the motor and inverter and to achieve a synergistic design of the cooling runners. The proposed innovative integrated structure with key cooling runner layout is shown in Fig. 2, aiming to fundamentally solve the thermal coupling problem in the system.

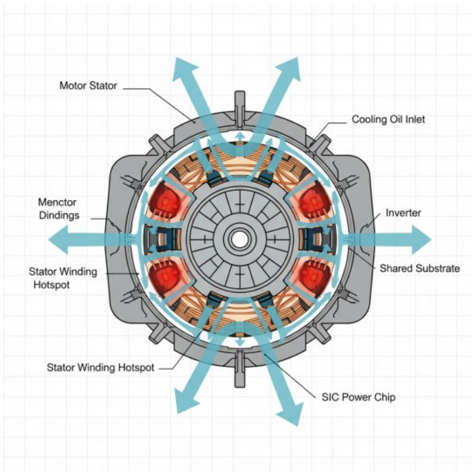


Figure 2 Section schematic of the innovative cooling scheme of the highly integrated electric drive system

3.2.1 Integration of Inverter And Motor Structure

The inverter is designed to be mounted directly on the motor rear end cap or housing to form a compact whole. The power semiconductor modules (especially the high heat flow density SiC devices) are mounted on a customised shared cooling substrate [6]. This integration significantly shortens the path of heat from the semiconductor junction to the coolant.

3.2.2 Innovative Cooling Runner Design

Spiral or parallel microchannels are designed inside the motor stator housing or on the back of the stator core [7]. The cooling medium flows through these channels and efficiently removes the heat from the copper losses generated by the motor stator windings. Inside the substrate for cooling power semiconductors and inverter modules, optimised microchannel structures (e.g., serpentine runners or pin-fin structures) are designed especially for SiC modules with high heat flow density, as shown in Fig. 3, to ensure that the cooling medium can closely fit the power chips, enabling efficient direct-contact cooling to increase the surface area of the heat transfer and improve the local heat transfer coefficient [6].

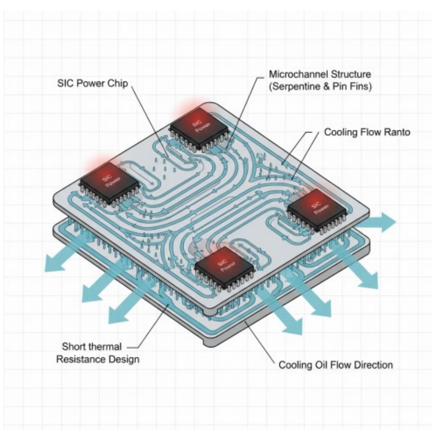


Figure 3 Detailed view of the microchannel structure and heat source layout of the shared cooling substrate

In addition, in order to cope with the heat generation of the rotor and windings during high-speed operation, the scheme considers spray cooling of the stator end windings directly by the cooling medium, or the use of centrifugal force to achieve oil flinging cooling of the rotor inner cavity. This direct contact cooling method can solve the problem of internal heat source which cannot be reached by traditional indirect cooling [8].

3.3 Cooling Medium Selection and Thermal Performance Analysis

3.3.1 Media Selection

Considering that the cooling medium needs to be in direct contact with electrical components such as motor windings and power semiconductors, its insulation is the primary consideration. Therefore, this programme chooses to use insulation cooling oil as the working medium. Insulating cooling oil not only meets the insulation requirements, but also has a higher thermal conductivity and heat capacity than air, enabling efficient direct contact heat transfer [4].

3.3.2 Performance Advantages

Through the use of insulating oil and integrated runner design, this solution avoids the thermal resistance of multiple thermal interface materials and air gaps, ensuring that heat can be transferred to the cooling medium quickly. By collaboratively designing the runners, the local hot spot temperatures of the motor and the electronic control module can be more effectively controlled to avoid excessive temperatures of a single heat source, thus prolonging the life of the system [5].

3.4 Thermal Analysis Models and Simulation Methods

Table 2 Key input parameter settings for coupled thermal-fluid simulation

Parameter type	Parameter name	Value/Model	Source/Rationale
Geometric model	Motor type and power class	Permanent magnet synchronous motor (PMSM), 150kw class	3.2 Design Options
	Power Module Type	SiC MSOSFET module	Design options, high power density requirements [4], [6]
Fluid properties (synthetic ester oil)	Cooling medium	Synthetic ester oil	High insulation and thermal conductivity, industry trend
	Density (ρ)	1000kg/m$^{(3)}$ (Ref. 50 ℃)	Typical synthetic ester oil parameters
	Specific heat capacity (Cp)	1800J/(kg·K) (Ref. 50 ℃)	Typical synthetic ester oil parameters
	Thermal Conductivity (λ)	0.15W/(m·K) (Ref. 50 ℃)	Typical synthetic ester oil parameters
	Kinematic viscosity (ν)	15×10$^{(-6)\ m2}$/s (Ref. 50 ℃)	Key parameters affecting pumping power consumption
Heat source definition	Total motor stator loss (P_{Motor})	1.8kW (uniform volume heat source)	Typical loss values at rated operating conditions [7]
	Total power semiconductor loss (P_{PE})	1.2kW (surface heat flow dense loading)	Calculated based on SiC module model [6]
Flow Modelling	Turbulence model	k-ϵ turbulence model (or k-ω)	Standard model widely used in engineering
Boundary conditions	Ambient temperature (T_{amb})	40 ℃	According to vehicle regulations (high ambient temperature conditions)
	Cooling oil inlet temperature (T_{in})	60 ℃	Cooling system design temperature
	Cooling oil inlet flow rate (Q)	0.8L/min, 1.5L/min, 2.2L/min (multiple operating conditions)	With active thermal management strategy [5]
	Outer wall heat transfer	Natural convection, h=8W/(m$^{(2)\ ·K}$)	Simplified treatment

(1) Physical parameter treatment: the synthetic ester oil physical parameters shown in the table are reference values at 50 ℃. In the actual thermal-fluid coupling simulation, the density and kinematic viscosity of the cooling oil are defined as a function of temperature (instead of fixed constants) to ensure the accuracy of the flow field feedback to the thermal field. (2) Heat Source Basis and Allocation: The loss values for the motor and power module are based on electromagnetic calculations and loss modelling for the 150 kW rated operating point of the system. The loss allocation (1.8kW for motor and 1.2kW for electronic control) is in line with the typical loss share of highly integrated electric drive systems of this power class. (3) Simplification of external heat transfer: The external boundary condition adopts a fixed heat transfer coefficient h=8 W/(m^2 · K) for natural convection, which is a conservative simplification of the complex forced convection condition in real driving. This treatment is intended to focus computational resources on verifying the heat dissipation efficiency of the internal flow channels and to ensure that the prediction of critical hotspot temperatures is biased towards a safe, conservative upper limit.

Based on the establishment of an accurate geometrical and physical model, the boundary conditions and input parameters of the simulation are strictly defined in this study. The key simulation input parameter settings used in order to support the subsequent multi-case analysis and active thermal management proof of concept are shown in Table 2.

These parameters include the physical parameters of the cooling oil (based on typical values of synthetic ester oils), the rated loss heat sources of the motor and power modules, as well as the ambient temperatures and multiple sets of flow conditions. In this paper, a coupled thermal-fluid simulation method is used. The method requires firstly constructing an accurate 3D geometrical model containing not only the motor stator, rotor, permanent magnets, etc., but also finely delineating the structure of the inverter power modules and the shared cooling substrate runners [7]. On this basis, the simulation must be fed with an accurate heat source model: the motor losses (copper and iron losses) are used as a volumetric heat source, while the power semiconductor losses are loaded as surface heat flux densities in the corresponding hot spot regions [6]. In the fluid model, the physical properties of the cooling oil need to be defined and a turbulence model such as k-ϵ or k-ω is used to accurately capture the flow and heat transfer characteristics of the fluid in the complex flow channel. During the simulation process, multiple sets of ambient temperatures and cooling oil inlet flow rates will be set as boundary conditions to reflect the dynamic impact of the active thermal management idea on thermal performance as mentioned in [5]. Ultimately, the quantitative research objective is to obtain and analyse the maximum temperature and temperature uniformity of key components (e. g., winding hot spots, power semiconductor junction temperature), as well as to accurately calculate the total pressure loss in the cooling circuit, so as to comprehensively validate the superiority of the new scheme in achieving efficient heat dissipation while improving the stability of system efficiency.

The meshing details of the thermal-fluid coupling model of the integrated electric drive system established in this study are shown in Fig. 4. The total grid volume of the model reaches 6 million grid cells. In order to ensure the convergence and accuracy of the simulation, grid refinement is carried out in the following key regions: Fig. 4b clearly demonstrates the boundary layer mesh delineation at the walls of the cooling runners, which is used to accurately capture the high thermal gradient at the fluid-solid interface; Fig. 4c and Fig. 4d show the local mesh refinement in the power chip region and the winding-core interface, respectively, which is aimed at ensuring the reliability of the prediction of the hot spot temperatures at the core of the system.

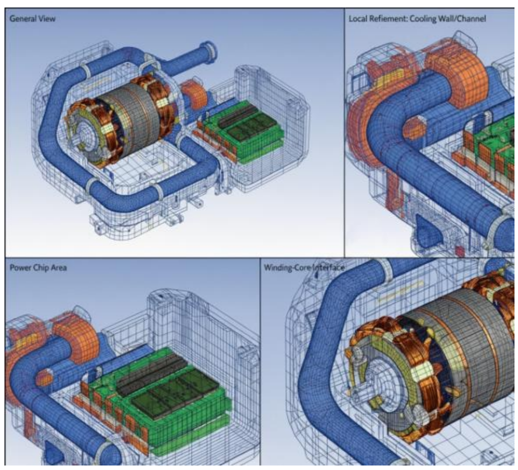


Figure 4 Thermal-fluid coupling simulation meshing model

4 Simulation Results and Performance Evaluation

In this chapter, based on the thermal-fluid coupling simulation model established in Chapter 3, the proposed innovative cooling scheme for the highly integrated electric drive system is numerically solved, and the results are thoroughly analysed and evaluated. The evaluation focuses on the thermal performance, system efficiency and the determination of the optimal thermal equilibrium point.

4.1 Analysis of Hot Spot Temperature and Thermal Performance

The purpose of this section is to verify the heat dissipation capability of the innovative solution under high power density and high ambient temperature conditions, focusing on monitoring the power semiconductor junction temperature ($T_{j)}$and the motor winding hotspot temperature ($T_{hotspot)}$.

4.1.1 Overall Temperature Field Distribution

Fig. 5 shows a cloud view of the temperature field distribution of the system at the rated operating flow rate (Q = 1.5 L/ min). From the figure, it can be seen that the highest temperature points of the system are concentrated in two main localised regions: the junction region of the SiC power chip and the end hotspots of the motor stator windings.

The analysis of the results shows that the heat generated by the electronic control module is rapidly conducted to the coolant, effectively avoiding the inefficient thermal coupling of heat between the module and the motor due to the adoption of the shared cooling substrate and insulating oil direct contact cooling strategy [4]. The temperature rise of the cooling oil is in a reasonable range after flowing through the stator runners, proving that the oil circulation design is efficient and has load-bearing capacity.

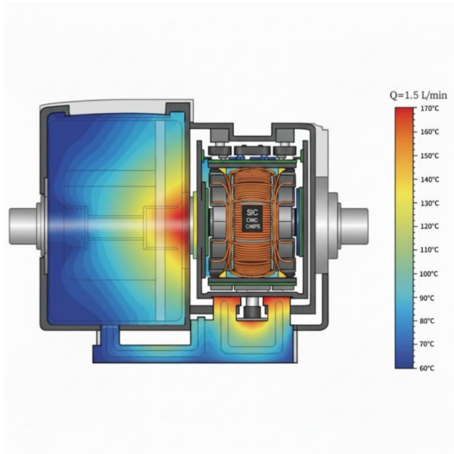


Figure 5 Temperature field distribution cloud of the integrated electric drive system at rated operating condition (Q=1.5 L/min)

4.1.2 Temperature Versus Flow at Key Hot Spots

In order to verify the feasibility of the active thermal management strategy, we analysed the variation rules of $T_j$and $T_{hotspot}$with the cooling oil flow rate Q. The simulation data curves are shown in Figure 6. Figure 6 shows the simulation data curve: with the increase of Q from the lowest 0.8 L/min to the highest 2.2 L/min, the temperature of the key hotspot of the system shows a significant decreasing trend: $_{the}$junction temperature of the SiC chip (T_j)is significantly reduced from the highest 155 ℃ to 130 ◦ C. This decreasing amplitude proves that the flow rate has a decisive impact on the efficiency of the convective heat transfer in the microchannel, and that the accelerated flow rate can effectively peel off the thermal boundary layer and reduce the junction temperature. The faster flow rate can effectively peel off the thermal boundary layer and reduce the junction temperature. Winding $_{hotspot}$ temperature ($T_{hotspot}$): from 170 ℃ to 150 ℃. This result proves that the accelerated flow rate of the cooling oil in the stator runner effectively improves the heat dissipation capacity of the motor section and ensures a safe margin for the insulation of the motor winding.

Under the rated flow rate of Q=1.5 L/min, the junction temperature of the SiC chip stabilises below 140 ℃, which is significantly lower than the safety threshold of 175 ℃, and this proves that the integrated solution has sufficient thermal redundancy under the high ambient temperature condition of 40 ℃.

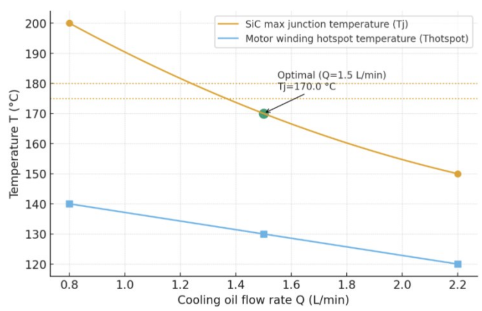


Figure 6 Variation of system critical hotspot temperature with cooling oil flow rate

4.2 Pressure Loss and System Efficiency Evaluation

An efficient thermal management design must take into account its own energy consumption to improve the net efficiency of the system. This section analyses the trade-off between pressure loss (ΔP) and pumping power consumption (P_{pump})in the cooling circuit.

4.2.1 Cooling Circuit Pressure Loss Analysis

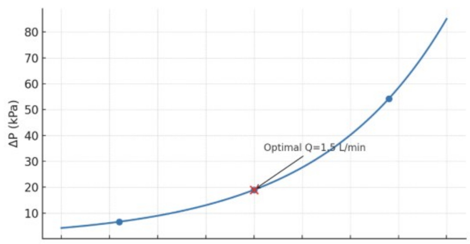
Figure 7a illustrates the variation of the total pressure loss (ΔP) of the cooling oil as a function of flow rate Q as it flows through the entire integrated loop, including the motor flow path and shared substrate microchannels. Due to the frictional resistance of the fluid within the complex microchannels, ΔP tends to increase non-linearly and exponentially with increasing Q. The total pressure loss (ΔP) of the cooling oil in the integrated loop is shown in Fig. 7a. At Q=2.2 L/min, the pressure loss reaches a maximum value, posing a higher challenge to the system seals and the structural strength of the flow path.

4.2.2 Pumping Power Consumption and Optimal Thermal Balance Points

The pumping power consumption ($P_{pump)}$is a key measure of the energy consumption of the cooling system, which is determined by ΔP and Q together. Figure 7b illustrates the variation of $P_{pump}$with Q. The results reveal that the pumping power consumption in the thermal management is not the sameas the pumping power consumption.

The results reveal a key performance trade-off in thermal management: while increasing the flow rate from 1.5 L/min to 2.2 L/min further reduces $T_j$by about 10 ℃, the required P_{pump}increases significantly. This suggests that in the low-flow region, the improvement in cooling performance is cost-effective, but in the high-flow region, the energy cost required to continue cooling is extremely high.

Based on this trade-off, the optimal heat balance operating point was identified: at Q = 1.5 L/min, the critical hot spot temperature of the system has met all safety requirements (T_j< 140℃) and the pumping power consumption is at a reasonable minimum, so this point was determined to be the optimal operating parameter that balances the cooling performance with the net efficiency of the system.



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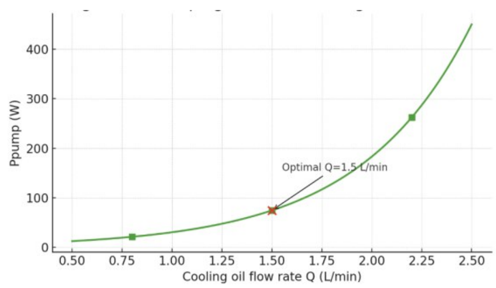

7b

Figure 7 Variation of cooling system pressure loss and pumping power consumption with flow rate

4.3 Comparative Analysis of Innovative Solutions

In order to quantify the advantages of the present integrated cooling scheme, we compare the simulation results with a reference scheme based on conventional indirect liquid cooling (motor water jacket + independent flat plate inverter cooling), as shown in Table 3.

Table 3 Performance comparison between the innovative scheme and the conventional scheme

Performance metrics	This innovative integrated scheme (1.5L/min)	Traditional indirect liquid cooling scheme (reference)	Performance Improvement
Total system thermal resistance ($R_{th, total}$)	0.25K/W	0.40K/W	Reduction of about 37.5%
SiC chip junction temperature (T_j)	140 ℃	165 ℃	25 ℃ reduction
System volume power density	10.0 kW/L	7.5 kW/L	33.3% improvement

The results show that the total thermal resistance of the innovative scheme is greatly reduced due to the sharing of cooling structure and the optimisation of flow path synergy, especially in the thermal management of electronic control [6]. This strongly demonstrates the effectiveness of the integrated thermal-fluid-machine co-design in improving the power density and reliability of the electric drive system.

5 Conclusion

In this study, based on the thermal challenges of highly integrated electric drive systems, an innovative cooling scheme of integrated thermal-fluid-machine co-design is proposed, and the thermal performance and efficiency of the scheme are quantitatively evaluated by thermal-fluid coupling simulation. The results demonstrate the significant advantages of the scheme in improving the power density and reliability of the system.

The main research conclusions are summarised as follows:

(1) High efficiency of the innovative structure: in this paper, we design a compact structure with co-axial integration of the motor and the inverter, and share the substrate with cooling runners, which eliminates multiple thermal interfaces and air gaps at the structural level. This design greatly shortens the heat conduction path from the junction region of the SiC power chip to the cooling medium, radically reducing the total thermal resistance of the system.

(2) Excellent heat dissipation performance: At a high ambient temperature of 40℃ and rated load conditions, with a cooling oil flow rate of Q=1.5 L/min, simulation results show that the maximum junction temperature $T_j$of the SiC chip is stabilised at less than 140 ℃, which is much lower than the safety threshold of 175 ℃. This proves that the innovative scheme has sufficient thermal redundancy under high heat flow density conditions.

(3) Optimisation of system efficiency: By analysing the pressure loss (ΔP) and pumping power consumption ($P_{pump)}$, this study identifies Q=1.5 L/min as the optimal heat balance operating point. At this point, the system meets all thermal safety requirements while maintaining the energy consumption of the cooling system at the lowest reasonable level, achieving the best trade-off between thermal performance and net system efficiency.

Quantification of Comparative Advantages: Compared to the conventional indirect cooling scheme, this innovative integrated scheme reduces the total thermal resistance of the system by about 37.5% and lowers the junction temperature of the SiC chip by about 25 ℃, which significantly improves the volumetric power density and operational reliability of the electric drive system.

6 Research Outlook

Although this study has achieved positive results in theoretical design and simulation verification, the following directions are still worthy of in-depth exploration and improvement in the future:

(1) Multi-physical field coupling optimisation: this study mainly focuses on thermal-fluid coupling, and in the future, the electromagnetic field, thermal stress and flow field can be optimised in a deeper level of three-field or even four-field coupling. For example, consider the effect of fluid on the winding vibration and noise, or the coupling effect of the cooling runner structure on the electromagnetic performance of the motor.

(2) Dynamic condition verification and active control: Future research should be extended to verify the system performance under dynamic transient conditions in real vehicles, including start-up, rapid acceleration and rapid stop. Meanwhile, based on the concept of active thermal management [5], the control algorithm of the variable flow cooling oil pump should be further developed and optimised to adjust the flow rate Q in real time to accurately match the power demand and minimise P_{pump}.

(3) Manufacturing process and experimental validation: The simulation-optimised complex runner structures (e. g., microchannels and showerheads) are combined with advanced manufacturing technologies (e. g., additive manufacturing/3D printing or precision die-casting) to produce a prototype. The simulation results are experimentally tested and verified by building an experimental bench to comprehensively assess the long-term reliability, sealing and durability of the integrated solution in actual operation.

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