

Review

Research Progress of Enhanced Thermal Evacuation and Cooling Technology for High-Speed Motors

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Abstract: In high-speed motors, there is a huge amount of heat generation from core and winding losses, which may result in thermal failures or motor performance deterioration. In the prevention of heat accumulation, efficient cooling technology is critical for smooth and reliable motor movement. This paper summarizes the diverse application of high-speed motor and thermal requirements, such as in electrical devices, turbo-machinery, and high-precision machine tools. Three paths of case convection—cooling, internal ventilation cooling and spindle core cooling—are analyzed. Methods for configuring thermal resistance and improving cooling efficiency are summarized. Among them, coolant flow characteristics and flow channel shapes, gas supply ventilation systems, and methods to reduce air resistance, as well as axial cooling and integrated heat pipe structures, are extensively investigated. Finally, the development prospects of high-speed motor cooling are also forecasted. At present, the primary research directions are to reduce the heat generated by the heat source, utilize the latent heat of the coolant, optimize the cooling flow path of the shell, design an axial air-cooling circulation system, and enhance the heat dissipation of the spindle.

Keywords: stator; rotor; high-speed motor; heat evacuation path; motor housing; motorized spindle



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1. Introduction

High-speed motors are extensively utilized as driving devices for rotating machinery because of their small size and high power density [1]. Currently, high-speed motors have been applied in the following areas: electric devices, high-speed machine tools, and turbo-machinery [2,3]. In recent years, high-speed motors have developed towards ultra-high speeds, high power density, and miniaturization.

In the operation of a motor, there will be heat generation from core and winding losses. In addition, due to the compact structure, heat traps inside the motor lead to higher spindle temperatures and thermal elongation. Spindle thermal deformation caused by the error is often small, but the impact on the machining accuracy is prominent, and in serious cases, even causes damage to the spindle. Therefore, it is especially critical to provide efficient heat evacuation and address the thermal contortion of the motor spindle caused by temperature increase [4–8].

To study the heat evacuation of high-speed motors, this paper lists the different applications and cooling requirements for high-speed motors. Moreover, the main heat evacuation paths within the motor are evaluated, and the major thermal resistances are summarized. For the main thermal resistances, different optimization approaches for motor heat evacuation are discussed. Finally, the future research direction of motor heat evacuation is predicted.

2. Different Application and Cooling Requirements for High-Speed Motors

The design requirements for motor cooling systems are diverse due to different applications of high-speed motors. The following describes the cooling methods for high-speed motors from different application perspectives.

2.1. Electric Devices

To replace traditional power sources and achieve low-carbon targets, an important application of high-speed motors is driving devices, most of which are applied in electric vehicles and high-speed trains [9,10]. In electric devices, their rated speed requirement is not very high, but their power is often larger [11]. Adequate cooling is therefore essential for stability. Paul et al. [12] designed air-cooling for the high-speed motors of distributed traction high-speed trains, as shown in Figure 1. This high-speed motor is rated at 380 kW with a peak speed of 6000 rpm. Because of its low rotational speed, the motor adopts air-cooling as its form of heat dissipation. Shi et al. [13] developed a water-cooling method for high-speed motors of mangle wheel systems. Excellent heat evacuation is achieved by water-cooling the conductive plates, and a slight boost in propulsion force is produced at low speeds.

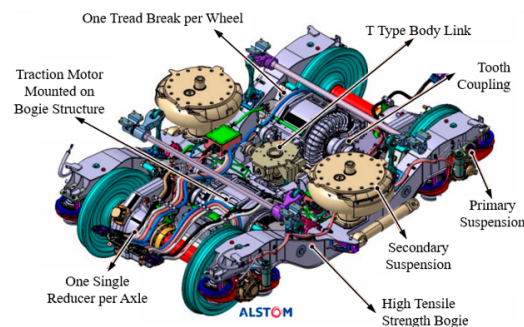


Figure 1. Design of bogies for distributed traction high-speed trains [12].

2.2. Turbo-Machinery

High-speed motors can also provide a driving force for turbo-machinery [14–17]. Both rotor speed and power requirements are imposed on high-speed motors. The overall cooling of the motors is the main concern. Abubakar et al. [18] studied the thermal performance of motors in centrifugal blowers. The motor was rated at 225 kW and 34,500 rpm, as presented in Figure 2. The cooling effect was provided by an external fan, which circulated and air-cooled the motor gap. Optimization methods were also investigated, and the results showed that heat dissipation could be improved by changing the shape of the winding slots and selecting a high thermal conductivity liner material.

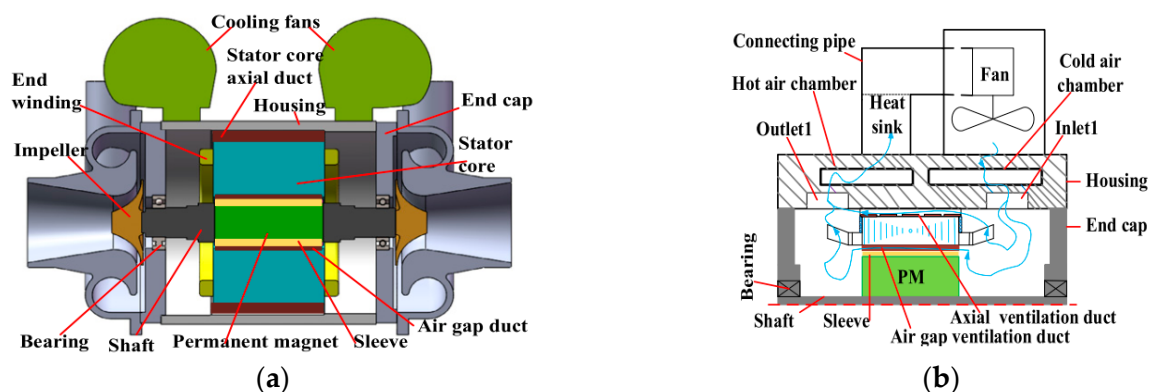


Figure 2. Turbo-machinery cooling system [18]. (a) Prototype structure in 3D cross-section view; (b) 2D cross-section view.

Li et al. [19] designed and optimized the existing high-speed motors used in oil pumps for the aviation industry. This motor, with natural convection cooling, was designed to operate at 5000 rpm and 10 kW. A highly reliable driving system topology was proposed, which enabled the optimized motor to have better heat dissipation performance. Qi et al. [20] investigated a 30 kW high-speed compressor motor with a rated speed of 30,000 rpm. Water-cooling of the motor housing was chosen for heat evacuation. The thermal analysis of the motor was conducted with different cooling water channel structures and water channels. It was found that an eight-turn spiral water channel with a flow rate of 3 m/s was more favorable for heat dissipation.

2.3. High-Speed Machine Tools

The essential core in high-speed machine tool machining is the motorized spindle, as depicted in Figure 3. The motorized spindle is an integral part of machine tools. Machining accuracy is mainly dependent on the performance of the motorized spindle [21–24]. Thermal deformation of a motorized spindle can seriously reduce the machining accuracy. Therefore, cooling and thermal elongation fluctuations of the motorized spindle attract the most attention. Du et al. [25] proposed a symmetric solution to the thermal error issue. Their real-time compensation system was developed for the spindle of a machining center, using the external machine zero shift function of the computer numerical control. The maximum axial thermal error was dramatically reduced from 55 μm to 16 μm , and the radial thermal error was similarly reduced from 15 μm to 6 μm .



Figure 3. View of a high-speed motorized spindle [25].

3. Heat Evacuation Paths and Enhancement

Motor heat should be dissipated immediately to minimize elongation of the motorized spindle due to heat loss during operation [26]. The main heat transfer path is presented in Figure 4. The rotor convects heat with the gap and conducts the heat through the motorized spindle, which then transfers the heat to the spindle's end. Part of the heat created by the stator is convected into the gap, and the other part is delivered to the motor housing by heat conductance. Eventually, the heat is vented into the environment. To boost cooling efficiency, heat evacuation is enhanced by optimizing thermal resistance. In Figure 4, the Roman numeral I represents the thermal resistance between the motor housing and the environment, which is usually utilized by using cooling flow paths on the motor housing. II represents the thermal resistance of the motor housing to the stator. III and IV represent the stator–rotor and air gap convective heat transfer thermal resistance. V represents the thermal resistance of the gas inside the motor to the environment, which is generally optimized by improving external ventilation. VI represents the thermal resistance from the rotor to spindle. VII represents the thermal resistance from the motor spindle to the spindle end.

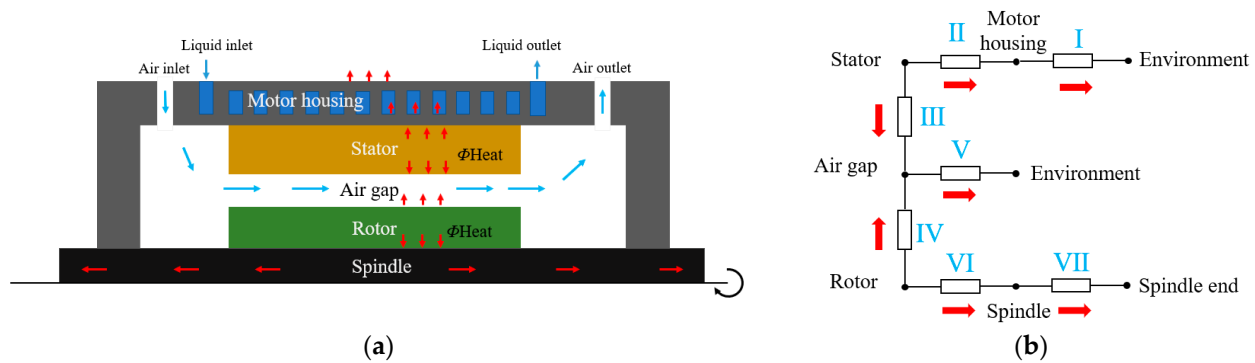


Figure 4. The main heat evacuation path of the motor. (a) Structural sketch; (b) thermal resistance analysis diagram.

For thermal optimization of motors, achieving efficient heat dissipation is usually realized by reducing overall thermal resistance. The research focus of this thermal resistance in the existing published literature is shown in Figure 5. Most of the studies are focused on the optimization of the thermal resistance of the motor housing cooling. For lower thermal resistance, liquid cooling via the motor housing is the most important means of heat dissipation, which necessitates in-depth exploration. Moreover, thermal resistance optimization of spindle heat dissipation and gap convection heat dissipation are also extensively required. Cooling methods for high-temperature heat sources and optimization measures for key sources of thermal resistance are also major research directions.

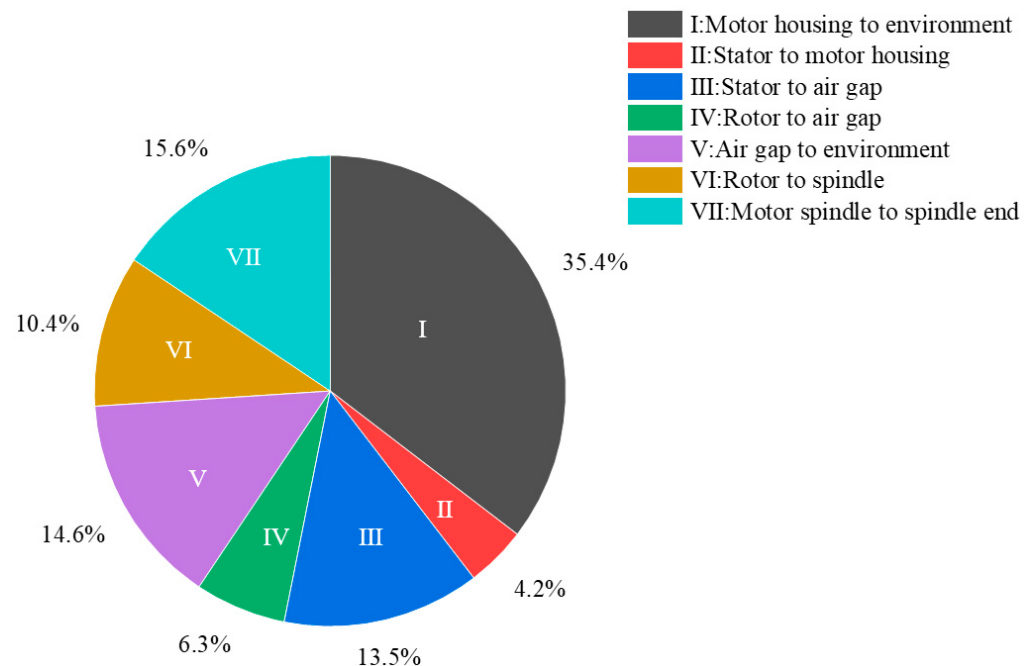


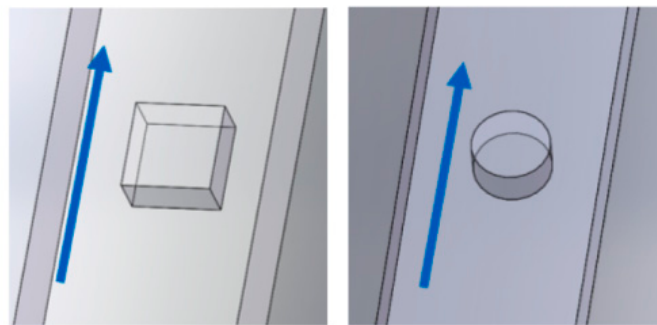
Figure 5. The main heat evacuation path of the motor.

3.1. Motor Housing

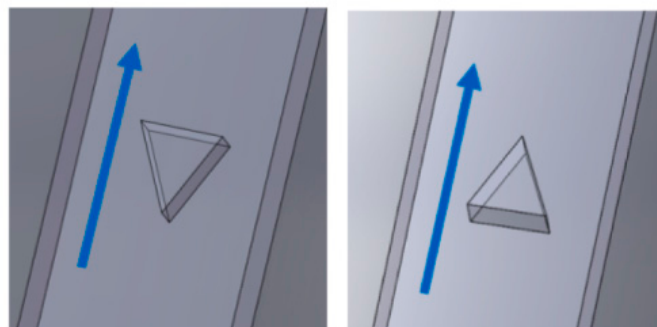
Internal heat is mainly dissipated through the motor housing to the outside due to the compact overall structure of the motor. Therefore, improving the thermal efficiency of the housing and optimizing the thermal resistance is a very important part of motor cooling. In normal practice, effective heat dissipation from the housing by means of liquid cooling is the most common approach.

3.1.1. Flow Channel Configuration

The cooling effect is enhanced by the increase in convex structure and is not elevated after a certain value. The flow heat transfer efficiency is dramatically affected by the shape of the coolant flow path. Tang et al. [27] investigated the impact of convex structure shapes and numbers in water-cooled flow channels on cooling efficiency. The convex structure was found to considerably enlarge the strength of the fluid vortices, thereby enhancing cooling efficiency, as shown in Figure 6. Among the different convex structures, the triangular convex structure has the best effect in respect of low flow loss. With the number of convex structures reaching as high as twelve, the convective heat transfer of the cooling water increases significantly, and the cooling effect of the water-cooled channel reaches its maximum value.



(a) Cuboid convex structure; (b) Cylindrical convex structure



(c) Triangular prism convex structure; (d) Inverted triangular prism convex structure

Figure 6. Four main convex structure types for motor housing cooling channels [27].

Additionally, heat evacuation performance is significantly affected by the configuration of the coolant channels. Koch et al. [28] studied the thermal efficiency of heat evacuation under different forms of coolant channel in the motor housing. Three commonly used cooling sleeves are shown in Figure 7. Under the same working conditions, the best cooling effect can be achieved with a spiral curved flow path, which can be structurally optimized and designed. This is due to its small flow losses, the maximum flow velocity and the minimum temperature gradient between the flow channels in this structure. Weber et al. [21] also investigated the influence of cooling channel shape on heat evacuation efficiency. Cooling efficiency is subject to flow loss, temperature uniformity, heat transfer efficiency and other factors. It has been found that the most widely used water-cooled runners have four main structural forms, as shown in Figure 8. Among these forms, the quasi-series possesses the best cooling effect based on a combination of flow loss and heat transfer efficiency.

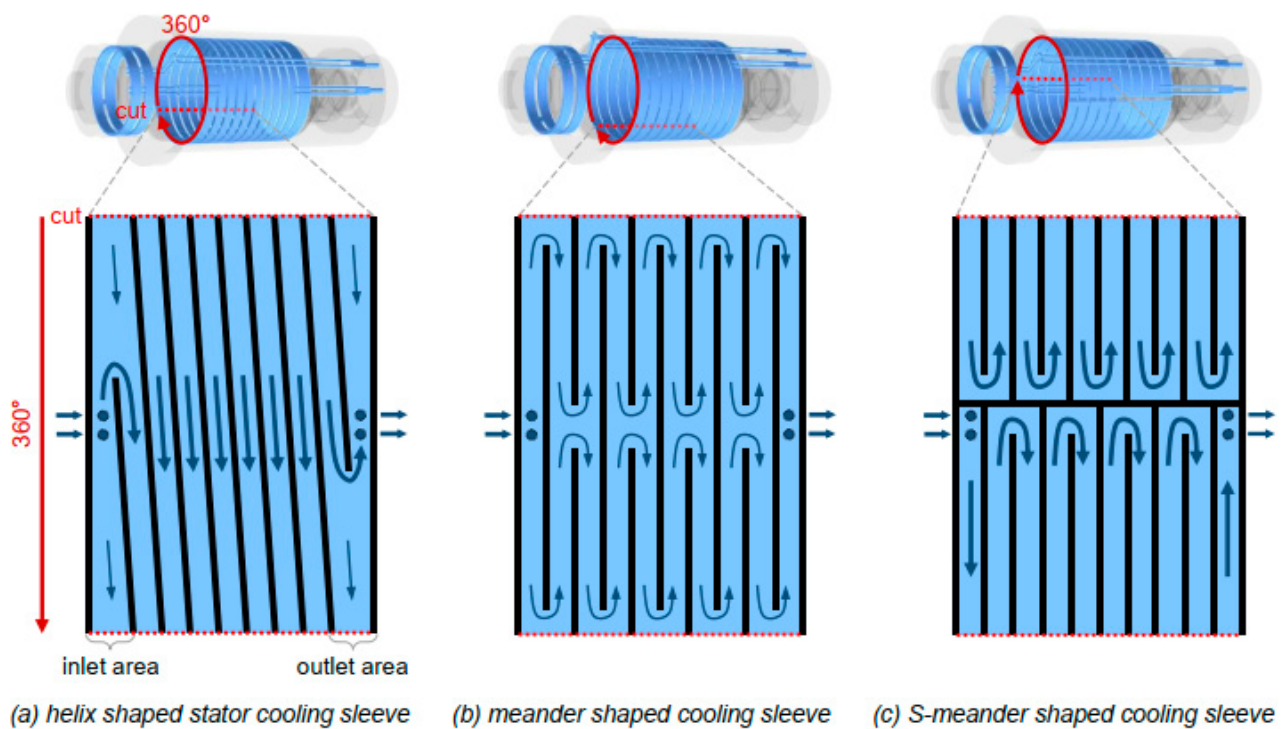


Figure 7. Expansion diagram of different cooling water channels [28].

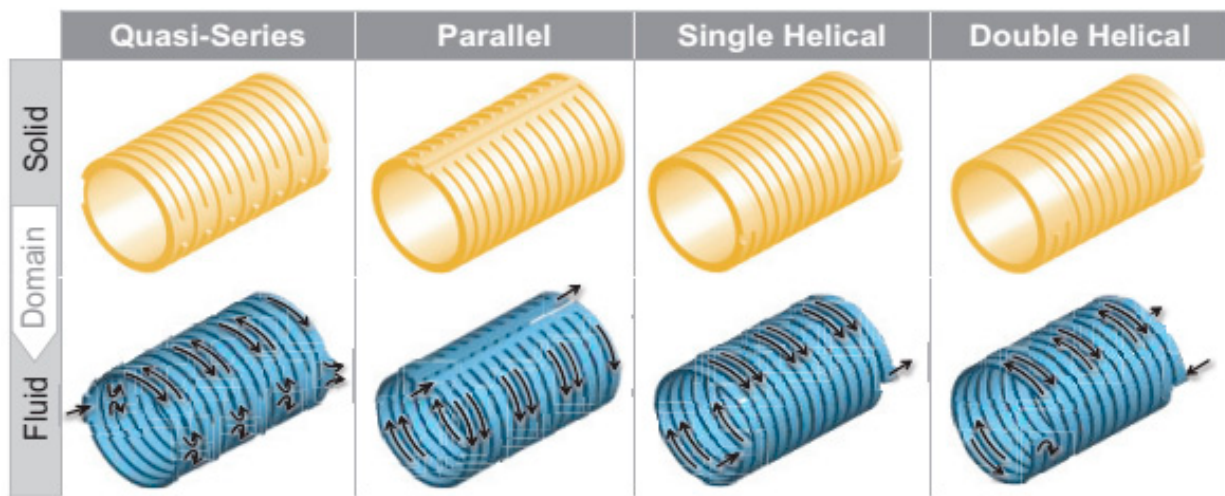


Figure 8. Typical designs of stator cooling sleeves and resulting flow paths in the fluid domain [21].

In addition to thermal efficiency, temperature uniformity of the motor is also a key research direction. Fan et al. [29] have proposed a water-cooled housing with balanced cooling capacity, which is optimized for the purpose of temperature uniformity and cooling efficiency. The contact surfaces of the thermal conduction casing are optimized so that the cooling output and heating input in different areas can be balanced, as shown in Figure 9. The results show that this structure can minimize the shell temperature difference with good heat dissipation efficiency.

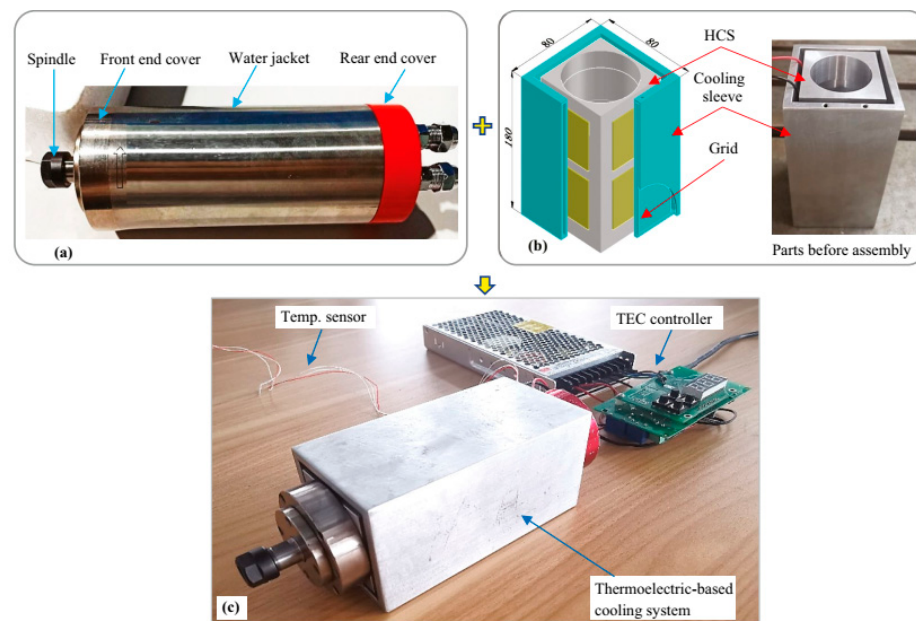


Figure 9. An optimization method to equalize cooling capacity based on energy saving [29]. (a) Structure before application; (b) Uniformly cooled water-cooled housing; (c) Overall structure of the motor spindle after assembly.

3.1.2. Coolant Flow Status

The velocity and temperature of coolant are important for heat transmission. Moreover, the latent heat of phase transitions in the coolant can also be utilized. Zhang et al. [30] conducted experiments on the relationship between the parameters of a water-cooled structure and its spindle temperature. The spindle temperature decreased as the cooling water velocity increased. Changing the initial cooling water temperature was more effective in suppression of the spindle temperature. Spindle temperature gradually tended to stable as cooling water flow increases [31]. Zhang et al. [32] investigated the effect of water runner diameter and flow rate on spindle cooling during the cooling process. In a certain area, larger flow channel diameter and flow rate can reduce the temperature and radial heat elongation effectively.

To improve cooling efficiency, Liu et al. [33] exploited the latent heat of coolant for motor cooling, as shown in Figure 10. The liquid coolant entered via the housing and subsequently exchanged heat in the spiral grooves of the housing. The coolant was then sprayed into the motor for a secondary heat exchange while the coolant underwent a vaporized phase change and the latent heat of the coolant was used for cooling. The results showed that by utilizing the latent heat of the coolant, the same mass flow rate of coolant could provide more cooling capacity.

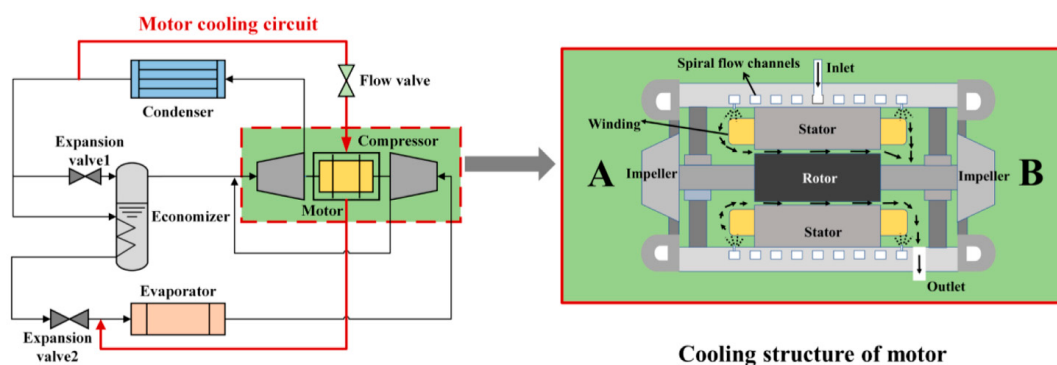


Figure 10. Schematic structure of gas–liquid phase change cooling in the motor [33].

Proper mating of cooling input power and heat evacuation can improve cooling efficiency. To ensure motor cooling efficiency and reduce spindle thermal errors, Liu et al. [34] controlled circulating coolant supply power by matching the power difference between heat generation and heat evacuation. To generate different temperature coolant supplies and reduce thermal errors in the motorized spindle, Zhang et al. [35] equipped spindle coolant channels with a differentiated water-cooling circulation system and real-time spindle temperature detection.

3.2. Stator

Copper loss in the stator is the main source of heat generation inside a motor. Since the stator is fixed, it is relatively efficient, and it is convenient to cool it separately. To achieve efficient cooling of the stator, Fang et al. [36] studied heat pipe cooling structures, as shown in Figure 11. Evaporation cooling was achieved by winding miniature heat pipes on the stator and cooling the heat pipes via air-cooling. This method can extend the effective time of temperature control by about 21%. The highest motor temperature under nominal conditions may be substantially decreased by 22.3%. Zhang et al. [37] found that a proper increase in the number of stator slots resulted in lower torque ripple and rotor eddy current losses and less heat generation.

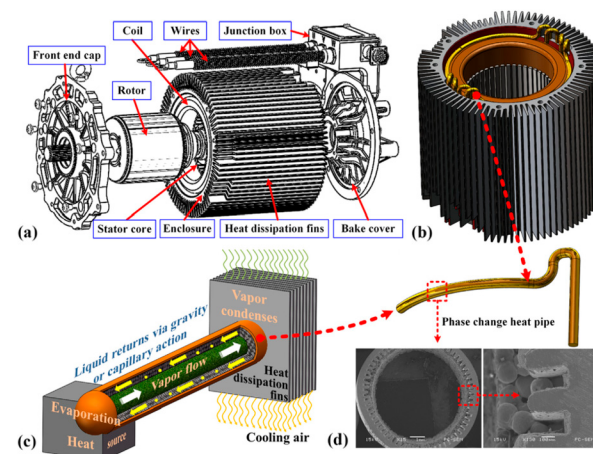


Figure 11. Schematics of (a) air-cooled permanent magnet synchronous motor; (b) motor; (c) a single heat pipe; (d) heat pipe structure [36].

3.3. Air Gap Convection

Exhausting hot gases inside a motor is another common route for cooling the motor. In order to improve cooling efficiency, Anderson et al. [38] designed an air inlet and outlet to achieve internal air cooling and to reduce thermal resistance to heat evacuation. Abubakar et al. [39] added a circulating air-cooled cooling structure for the application of external air supply to the motor of a high-speed centrifugal blower, as shown in Figure 12. The results show that forced ventilation-cooling of the motor gap can improve motor cooling efficiency.

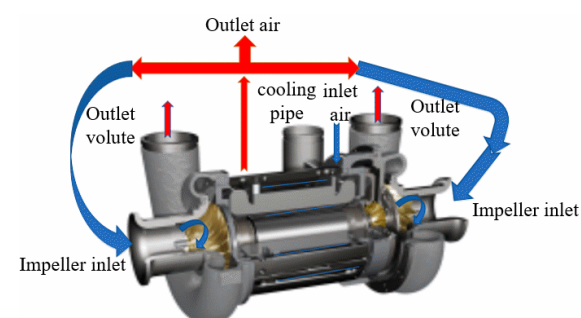


Figure 12. Schematic diagram of open-type air cooling for motor [39].

For convective heat transfer in the motor gap, improving the gas flow state in the gap is a very important parameter, which is affected by the flow rate, gap size, etc. Ding et al. [40] exploited the homogeneity of a motor and its driven compressor rotor to enhance axial convection heat evacuation. Zhang et al. [41] studied the effect of gap size for air convection heat transfer efficiency and explored the cooling effect of a 0.18–0.24 mm gap. It was found that as the air-cooled motor gap decreased, the flow velocity of the fluid on the stator and rotor surfaces increased for more effective heat dissipation. Wan et al. [42] enlarged the internal slots of a stator core for ventilation ducts to improve stator convective heat evacuation efficiency. Husain et al. [43] found that a single U-shaped arrangement of permanent magnets was more effective in cooling the rotor. For improving the convection transfer efficiency of a stator and rotor, Yan et al. [44] added a fan to the main shaft and enlarged the grille area, as illustrated in Figure 13.

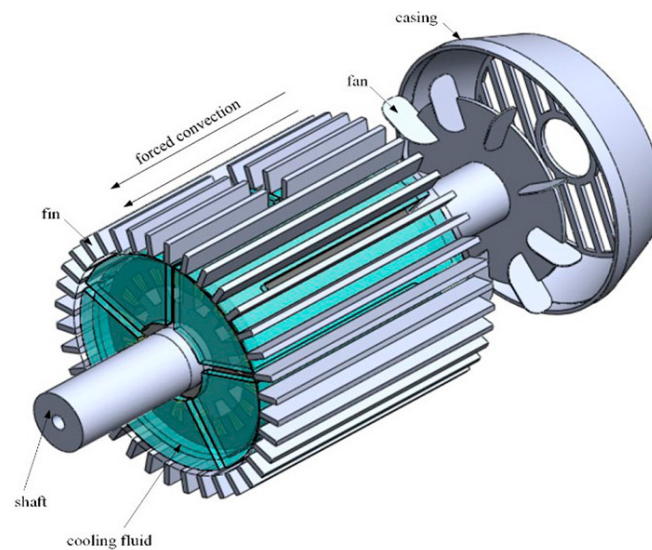


Figure 13. Stator and rotor reinforced heat dissipation structure [44].

3.4. Motorized Spindle Cooling

Most of the heat generated from iron loss is conducted to the motor spindle. There will be heat deformation that affects the mechanical properties. To improve spindle heat evacuation, shaft core cooling is applied. Through the tiny channels in the center of the spindle, fluid is introduced for higher heat transfer and heat evacuation. Shi et al. [45] analyzed the thermal problems of motorized spindles with spindle cooling, as shown in Figure 14. A cooling runner was machined into the spindle core and circulated through the oil for cooling. Cui et al. [46] simulated the temperature distribution and thermal deformation of the spindle when the core was cooled by air. The method indicates that core cooling can actively reduce the temperature rise of the spindle.

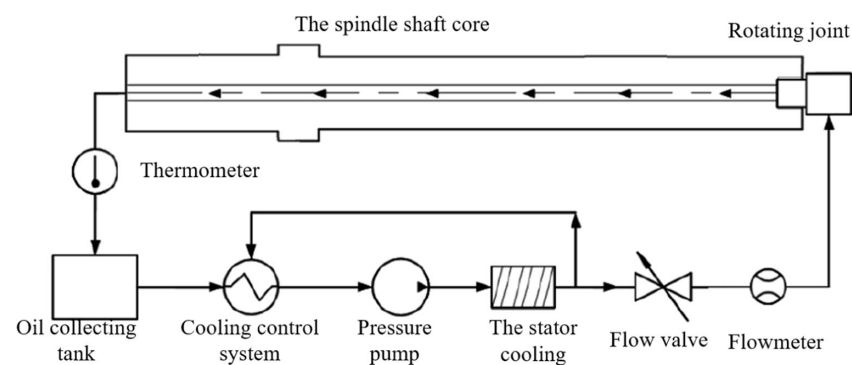


Figure 14. Schematic diagram of motor core oil-cooling system [45].

The utilization of heat pipe structures is a relatively new and efficient means of cooling. Liang et al. [47] investigated a motor center cooling method based on a heat pipe model, as shown in Figure 15. This structure reduces the amount of thermal resistance and dissipates heat from the rotor using heat pipes embedded in the motorized spindle while retaining the water-cooling of the housing. A heat pipe structure can be evaporated at the stator and rotor for cooling purposes and later condensed at the shaft end using impulse jet flow. Compared with the traditional water-cooled form, this new cooling structure reduces the maximum shaft temperature by 35%. Li et al. [48] designed a central annular spindle core heat pipe cooling system, as shown in Figure 16. This cavity is connected axially to the external cavity to form an annular hydrothermal structure. The heat evacuation characteristics of the circulating heat pipe in the rotating state were investigated.

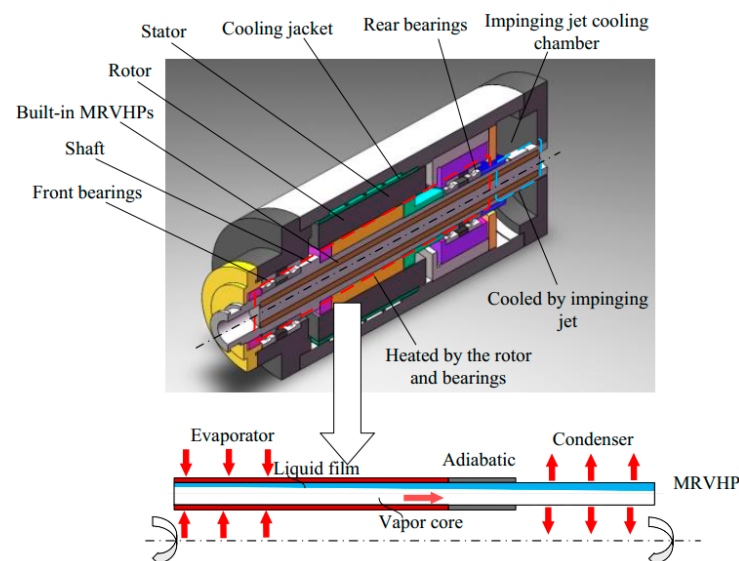


Figure 15. Central heat pipe cooling structure for motorized spindles [47].

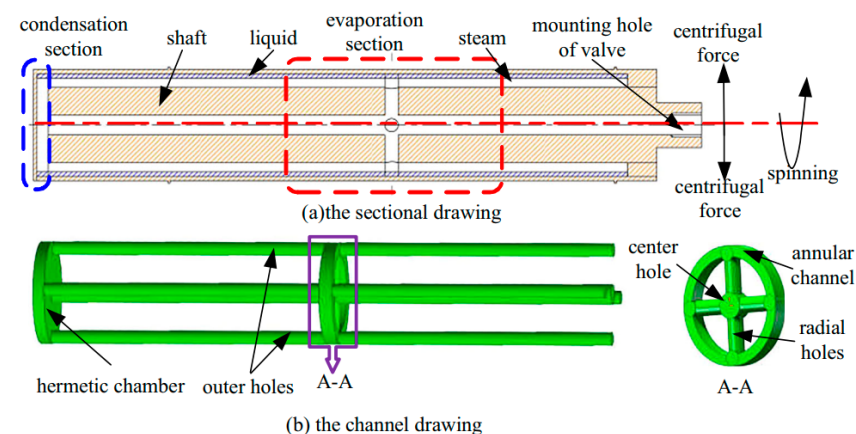


Figure 16. Schematic diagram of the heat pipe cooling system for the central annular spindle core in the motor [48].

Shi et al. [49] performed numerical simulations of an annular rotating heat pipe featuring a bent structure to cool a motorized spindle, as shown in Figure 17. The variation of flow and thermal performance of the inner tube was investigated for different power and rotational speed. The data shows that the thermal performance of the annular rotating heat pipe improves with the increase of rotational speed and heating power. The overall thermal resistance decreased by 30.0% and 36.8% when the speed was increased from 2000 rpm to 6000 rpm and 10,000 rpm, respectively. When the heating power was increased

from 30 watts to 120 watts and 200 watts, the overall thermal resistance decreased by 31.0% and 37.0%, respectively. However, the temperature difference increased with increase in heating power and decreased with increase in speed.

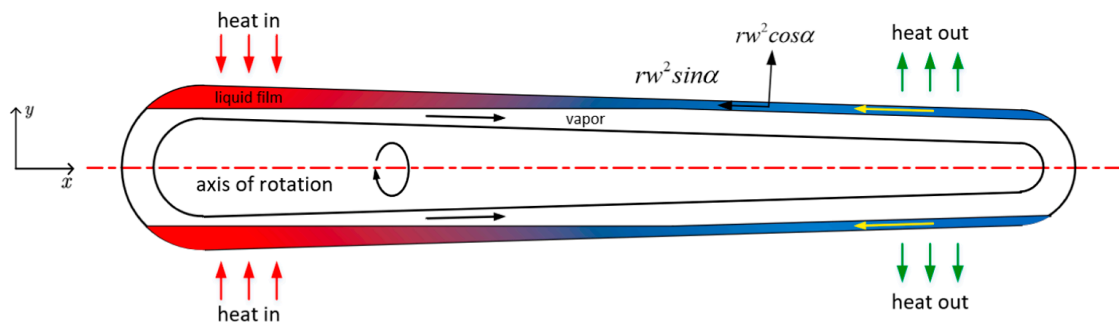


Figure 17. Schematic of the loop rotating heat pipe [49].

3.5. Common Cooling Methods and Coolants

In current applications of motor cooling, liquid cooling through the housing and forced ventilation cooling in the axial gap are two common cooling methods; sometimes both are used.

For the rotor with small thermal loads, gas cooling is a direct, effective, and economical cooling method. Gaseous coolants are usually used for convection-enhanced cooling in the gap, mostly using air. Cao et al. [50] created an air-cooled structure for a 600-kW motor, as presented in Figure 18. The motor had a radial air inlet on one side and an axial air outlet on the other side. This allowed airflow to circulate inside the motor for forced convection cooling.

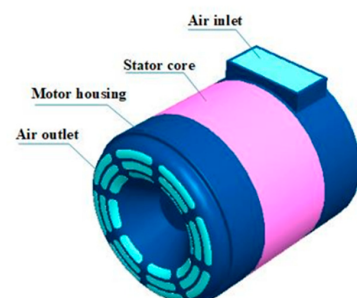


Figure 18. Single air-cooled structure motor [50].

In motors that generate a large internal heat load, liquid cooling is required for heat evacuation and cooling [51]. The liquid coolant normally used for convection cooling of the housing is applied with oil and other refrigerants in addition to the commonly used water. Compared with air-cooling, its cooling effect improves, but it is necessary to design airtight water-cooled housing. The water-cooled motor is shown in Figure 19, with cooling water channels and water inlet and outlet openings in the motor housing [52].

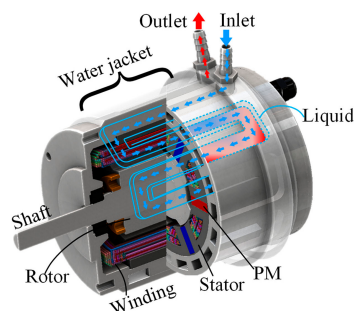


Figure 19. Liquid-cooled construction motor [52].

When the motor power and speed requirements are higher, a combination of the air and liquid cooling methods need to be considered. Wang et al. [53] investigated high-speed motors for compressors with a combined air–liquid cooling form, as illustrated in Figure 20. Cooling air is drawn into the motor from the left side, flows into the gap, and subsequently exits on the right side. Cooling water is then convected into the motor housing for heat evacuation.

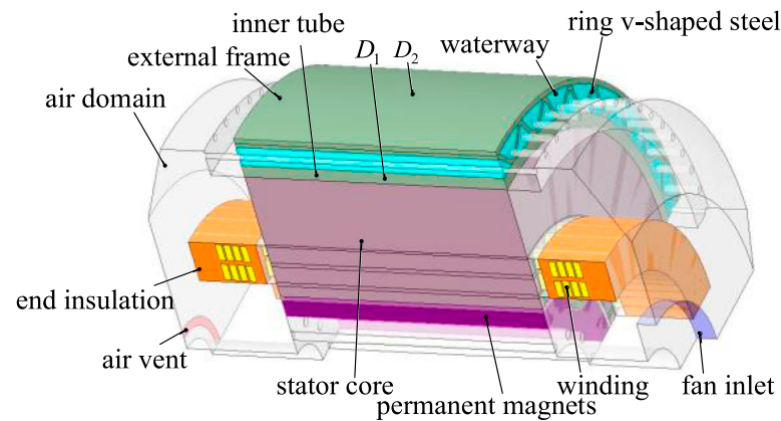


Figure 20. Air–liquid composite motor cooling structure [53].

Based on the requirements of the application environment, other coolants have also been applied. Sasa et al. [54] studied a 1 kW high-speed motor cooled using passing liquid nitrogen. This is a motor used for low-temperature superconductivity to increase power for aircraft propulsion. Du et al. [55] studied the use of R245 as a refrigerant for cooling high-speed motors, as shown in Figure 21. Lee et al. [56] demonstrated a cooling system for unmanned aircraft drive motors. The system utilizes a spiral grooved self-cooling enclosure and internal oil cooling to reduce maximum temperature of the motor spindle by approximately 30 °C.

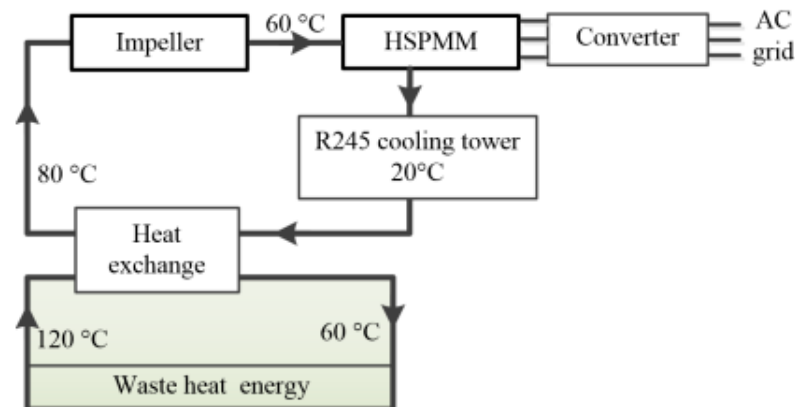


Figure 21. Motor cooling systems with R245 [55].

Most motor cooling forms are air-cooled, liquid-cooled, or a combination of both. Table 1 lists the different forms of motor cooling published in the literature. Air-cooled motors have relatively large axis diameters and relatively low rotational speeds. Liquid-cooled motors tend to rotate at higher speeds than air-cooled motors. When ultra-high speeds are demanded, motors are typically equipped with air–liquid composite cooling.

Table 1. Cooling method of the motor.

Reference	Rotor Diameter (mm)	Power (kW)	Rotational Speed (rpm)	Cooling Method
[57]	2660	630	37.5	Air
[58]	110	20	15,000	Air
[19]	/	10	5000	Air
[37]	92	225	35,000	Air
[12]	380	520	4700	Air
[18]	92	225	34,500	Air
[59]	54	0.264	12,600	Air
[14]	1960	480	6000	Air
[60]	330	600	4636	Air
[61]	65	105	36,000	Air
[62]	220	70	4000	Air
[63]	228.6	110	1500	Liquid
[64]	350	350	15,000	Liquid
[65]	38	8	100,000	Liquid
[66]	38.9	9.6	8700	Liquid
[67]	200	15	1000	Liquid
[68]	/	30	12,000	Liquid
[69]	/	25	5000	Liquid
[70]	300	100	3000	Liquid
[71]	185	305	10,000	Liquid
[72]	/	7.5	24,000	Liquid
[73]	204	800	15,000	Liquid
[74]	100	80	30,000	Liquid
[75]	60	11	12,000	Liquid
[76]	70	15	30,000	Air and liquid
[77]	36.3	22	90,000	Air and liquid
[78]	200	100	50,000	Air and liquid
[79]	55	30	60,000	Air and liquid
[80]	50.2	40	14,000	Air and liquid
[81]	5	0.138	1,200,000	Air and liquid
[21]	42	30	30,000	Air and liquid
[82]	69.5	223	60,000	Air and liquid

4. Future Development of High-Speed Motor Cooling

Lower losses, higher efficiency, higher lifetime and less cost are the objectives of the evolution of high-speed motors. Expectations for ultra-high speeds and high power are increasing as the requirements for high-speed motor applications improve. Desired characteristics of current motors suitable for electric vehicles include high efficiency, wide speed range, high starting torque, and wide constant power range power factor. These properties are highly dependent on the motor's core length, rotor and stator slots, and air gap [83]. In addition, the high-speed motor for the Mars Exploration Rover requires a supply voltage of 40 V, an output power of 50 W, and a weight of 25 g, which means high efficiency and high-power density [84], which can be used in outer space to minimize core losses and reduce the heat generated by the motor. Zhang et al. found that motor power density has become a major concern in electric motor research, as shown in Figure 22. The application direction thus shifted to power systems for electric propulsion, fuel cell systems, robotic actuators and other small high-speed motors [6]. Heat dissipation and evacuation in the motor is still a challenge that needs to be improved urgently.

For machine tools, the purpose of enhanced heat evacuation is to improve machining accuracy, and the focus is on spindle thermal elongation. In other applications, high-speed motors are required to maintain rated performance and pursue overall small temperature drop. On the basis of the evaluation of heat evacuation paths for high-speed motors, the following research directions for motor heat evacuation are summarized.

1. Reduction of heat sources: Explore ways to decrease motor losses by approaching the source of heat. Reduce heat generation by optimizing stator and rotor materials as well as slot patterns to lower motor losses during operation. Achieve the purpose of reducing the overall temperature rise of the motor.
2. Utilization of latent heat of coolant: Motor casing cooling generally uses liquid convection heat transfer. Considering the two-phase heat transfer of the coolant and fully utilizing the phase change latent heat of the coolant, the cooling capacity and heat dissipation efficiency of the motor can be improved.
3. Optimization of the design of the shell cooling channels. According to the motor's actual structure, the cooling channel design is optimized to reduce flow resistance and ensure uniformity of flow and temperature distribution.
4. Establishment of air-cooling runners. Convection heat transfer efficiency is improved by methods such as built-in fans and enlarged leaf grilles. An external circulating air system can also be installed.
5. Strengthen motorized spindle heat evacuation. Establish motorized spindle axial core cooling or heat pipe runner to reduce heat transfer thermal resistance and effectively decrease spindle temperature rise and thermal deformation.

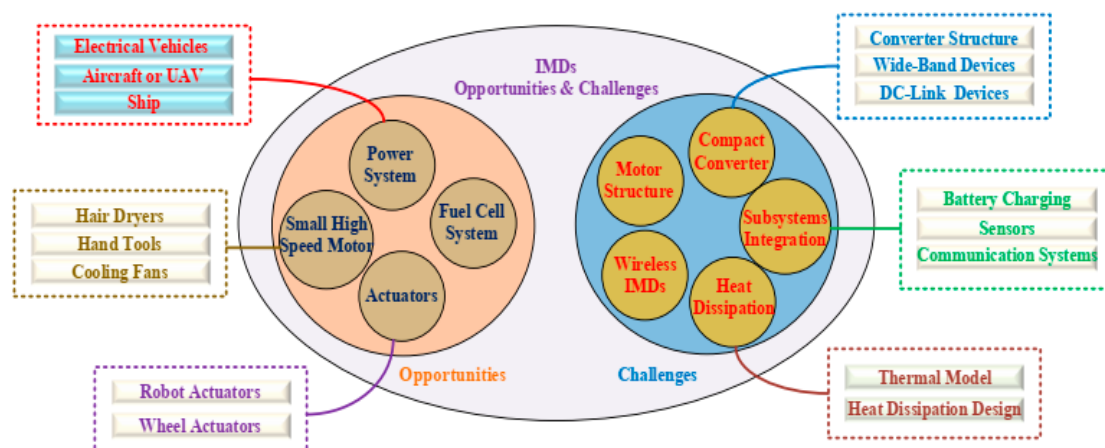


Figure 22. Opportunities and challenges for motor drive systems [6].

5. Summary

As high-speed motors develop rapidly, the requirements for their performance have been pushed to a new level. Cooling efficiency seriously affects motor operating performance, and research on cooling systems has received extensive attention. Effective cooling of high-speed motors is essential to decrease thermal errors and thermal deformations. In this paper, the following work has been done to summarize the enhanced cooling of high-speed motors.

1. A summary of different applications and cooling requirements of high-speed motors is presented. High-speed motors are mainly used in electric devices, turbo-machinery, and high-speed machine tools. Among them, high-speed machines are more concerned with temperature rise and thermal elongation of the spindle.
2. Heat evacuation paths and main thermal resistance in the motor are discussed. An overview of current research on optimizing thermal resistance is also presented. Liquid-cooling in the rotor housing is the main cooling method. Secondly, air-cooling is also used, sometimes in combination with liquid-cooling. Axial cooling of motorized spindle cores is also being investigated, among which heat pipe structures is one of the key applications.
3. Future development of high-speed motor cooling is predicted. Reduction of heat generation from heat sources, utilization of latent heat from coolant, optimization of

housing cooling flow paths, designing of axial air-cooling circulation systems and strengthening of spindle heat evacuation can be mainly considered.

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