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A critical review on thermal management technologies for motors in electric cars

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Abstract:

Electric cars are recognized playing a key role to achieve a low-carbon or even net-zero emission society, in which one of the core components is electric motors. Thermal management technologies of electric motors in electric cars are significantly important considering the motors are being designed to be more powerful and competitive with higher torque, higher speed and higher power density. The failure of thermal management will result in demagnetization of magnets, ageing of the insulation materials, decrease of efficiency, shorter lifetime and even burnout of motors. In this paper, both the theoretical modeling and experimental investigations of the latest thermal management methods are reviewed. The state-of-the-art of various thermal management techniques, including air cooling (natural and forced air cooling, air impingement cooling) and liquid cooling (water/oil jacket cooling, jet impingement cooling, spray cooling, immersion cooling, slot channel forced convection cooling) for the stator, winding and rotor are critically presented. Meanwhile, heat transfer enhancement methods by conduction based on potting materials, thermal paste, heat guides, PCMs and heat pipes are highlighted. Following that, hybrid thermal management technologies to address extreme conditions are also discussed. In the last section, some suggestions are given for future possible research and application. The paper is expected to be a good reference and inspiration for the development of new thermal management concepts for electric motors.

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Key words: electric motor; advanced cooling; thermal management; lumped parameter thermal network; critical review; electric cars

Contents

Nomenclature

A	area (m^2)	Greek symbols	
B	flux density (T)	α	coefficient
B_m	maximum flux density (T)	β	coefficient
ΔB	local amplitude of flux (T)	δ	thickness of lamination (m)
C_f	friction coefficient	η	radius ratio
c_l	geometric modification parameter	λ	thermal conductivity (W/(m· K))
Cp	heat capacity (J/(kg· K))	ν	kinematic viscosity (m^2/s)
d	diameter (m)	ξ_c	three-point parameter
f	friction factor	ρ	Density (kg/m^3)
Fg	geometric factor	φ	fill factor
Gr	Grashof number	χ	parameter
h	heat transfer coefficient (W/(m^2· K))	ω	angular speed
H	height (m)	subscript	

i	index	a	air
I_{rms}	phase current RMS (A)	al	axial layer
j	index	ag	air gap
k	coefficient	c	critical
L	length (m)	ch	coil channel
m	phase number	cu	copper
N	number	ed	eddy
Nu	Nusselt number	eq	equivalent
p	Power loss (W/m^3)	ew	end winding
pf	wire packing factor	ex	excess
Pr	Prandtl number	f,ag	windage loss of air gap
Q	heat (J)	f,end	windage loss of rotor end
r	radius (m)	h	channel
r_m	mean radius (m)	hy	hysteresis
r_c	velocity modification parameter	in	insulation
Δr	difference of radius (m)	im	impregnation
R	resistance (Ω)	ir	iron
R_s	armature winding resistance (Ω)	r	rotor
R_{s0}	reference armature winding resistance (Ω)	re	rotor end
Re	Reynolds number	$s0$	reference
T	temperature (K)	sl	slot
Ta	Taylor number	t	thrust collar

Ta_m	modified Taylor number	w	winding
T_0	period (s)	z	axial direction
u	velocity (m/s)	ϕ	peripheral direction
V	volume (m^3)	superscript	
w	width (m)	i	time step i
		$i+1$	time step i+1

1. Introduction

Technologies contribute to carbon-neutrality by reducing the carbon emission have drawn wide attention all over the world, as the climate change and global warming are emerging as big threats to our society [1]. Against this background, the transportation sector, which consumes a great amount of primary energy, is undergoing a significantly important updating through electrifying [2, 3]. It was reported that with the application of electric vehicles, the greenhouse gas emissions reduce by 20% and by a further 40% if the electricity is produced by renewable energy [4]. A lot of remarkable policies and initiatives have been proposed by many countries and organizations, especially in the Asia-Pacific regions [5, 6]. Therefore, the market share of electric vehicles is growing very sharply. According to predictions, 35% of global new car sales by 2040 [7] will be electric. For the sake of energy saving and achieving a carbon-neural society, motor-drive systems are drawing the attention of academic, engineering, and investment communities [8]. To increase the market proliferation of electric vehicles, electric motors in the near future need to be more powerful and provide higher power densities, higher torque densities, and higher speeds [9-11]. Generally, it has shown that as the motor design is pushed for higher power densities, the loss-density in the motor increases rapidly which makes the thermal management more challenging, and often the main limiting factor on the performance metrics that can be attained. Therefore, advanced thermal management technologies are critically needed.

An electric motor is a very complex system from a thermal point of view [12, 13]. It has different components made of different materials, and these materials have different optimal temperature ranges as well as temperature withstand limits. Furthermore, the heat sources also distributed in different components and relate to various mechanisms [14]. The heat inside of the motor is transferred by heat conduction, convection and radiation in quite a limited space. Heat conduction occurs between the housing and stator, winding and stator, housing and end plate, shaft and bearings, etc. The convection heat transfer involves airflow or other liquid coolants and solid components, which usually includes both laminar flow as well as turbulent flow. The failure of thermal management for electric motors causes a series of problems. Firstly, the high temperature will cause excessive thermal stress in solid components. The excessive stress may cause the deformation of the components, leading to the failure of assembly of the motor. Furthermore, higher temperatures are also problematic for insulation materials. The insulation lifespan will significantly decrease and age faster under higher temperature loads. According to research, the life span of the commonly used insulation materials will be halved for an additional 10 ℃ [15] in temperature. The limitation of the insulation material greatly limits the current density of winding and the output power of the motor [16]. The failure of insulation material may also cause an electric short circuit and lead to catastrophic burnout of components. Permanent magnet motors are predominantly used in electric cars. The magnet contains rare-earth elements and is very sensitive to temperature rise. The overheating of the motor will cause irreversible demagnetization of the magnets [17, 18]. The techniques for the design of high-efficiency heat dissipation mechanisms for motors have been and will continue to be a very important research topic [19].

To date key research has been published to investigate the performance of various thermal management technologies for the motors, including both theoretical modeling as well as experimental testing in the past decades. The theoretical modeling mainly refers to numerical analysis methods [20, 21] and lumped parameter thermal network (LPTN) methods [22]. While the numerical analysis is capable to provide more detailed information about the temperature, heat flux, pressure fields in the motor under given conditions, the lumped parameter thermal network method is characterized by a quick prediction for the temperature of thermal nodes with relatively lower accuracy. Both numerical analysis and lumped parameter methods (LPTN) can be used under steady-state and transient-state conditions [23]. Some general key factors in theoretical modeling, such as equivalent thermal conductivity between winding and stator, end space heat transfer coefficient, contact thermal resistance, directly identify the characteristics of models and have been extensively addressed. Meanwhile, various thermal management technologies are proposed to address the cooling of motors with different heat density requirements. The heat transfer performances of air cooling (including natural air convection, forced air convection, air impingement) and liquid cooling (including jacket cooling with different liquid coolants, spray cooling, jet impingement cooling, etc.) were comprehensively studied to cool the stator, winding and rotor. In addition to the cooling methods by fluids mentioned above, methods that can enhance the heat conduction between solid components have also been presented. Prospective methods include but are not limited to thermal paste, potting materials, heat guides, PCMs and heat pipes. To pursue an extremely good cooling effect, some combination of these methods has also been proposed and validated by experimental studies.

It is accepted that review papers contain important assessment on thermal management technologies and provide valuable suggestions for future studies. In 2015, Shazly et al [12] presented a review on thermal modeling of axial-flux permanent-magnet synchronous motors. The LPTN, finite element (FE) and computational Fluid Dynamics (CFD) modeling for the motors were thoroughly examined. Gai et al [24] reviewed the investigations on traction motor cooling covering both theoretical modeling and experimental testing. Some commercial application examples were also introduced. Carriero et al [25] presented another excellent review paper, in which the novel cooling methods and designs proposed in patents and commercial traction motors were highlighted, while the corresponding theoretical modeling was not discussed. With the popularity of electric vehicles, thermal management of the motors used in this scenario is drawing wide attention. The motors used in electric vehicles have specific performance profile, assembly requirements. The estimation of current thermal management technologies is crucially important. However, there are still no exclusive state-of-the-art assessments available.

In this paper, a comprehensive review of the latest thermal management technologies for electric motors in the transportation sector are presented from both a theoretical as well as experimental point of view. Despite the cooling strategies are performed for motors in certain operating conditions, their cooling effect can also be identified or inspired accordingly strategies for other motors [26]. The paper is expected to be a valuable reference for future research, boosting the application of electric vehicles.

2. Heat generation of motors in electric cars

Most motors used in electric cars are alternating current induction motors, switched reluctance motors, and permanent magnet synchronous motors and with typical power range of (100~200) KW. For thermal management, the first step is to identify the power losses of motors under certain operating conditions. In general, the heat losses of the motors are caused by different mechanisms and generated in different components, as shown in Fig. 1. The losses can in general be tailored according to the electromagnetic design choices, for example, magnetic loading, electrical loading, materials recipe, geometrical optimizations etc. In this section, the key heat losses are briefly discussed – a detailed discussion on calculation and modeling for different kinds of motors goes far beyond the scope of this work.

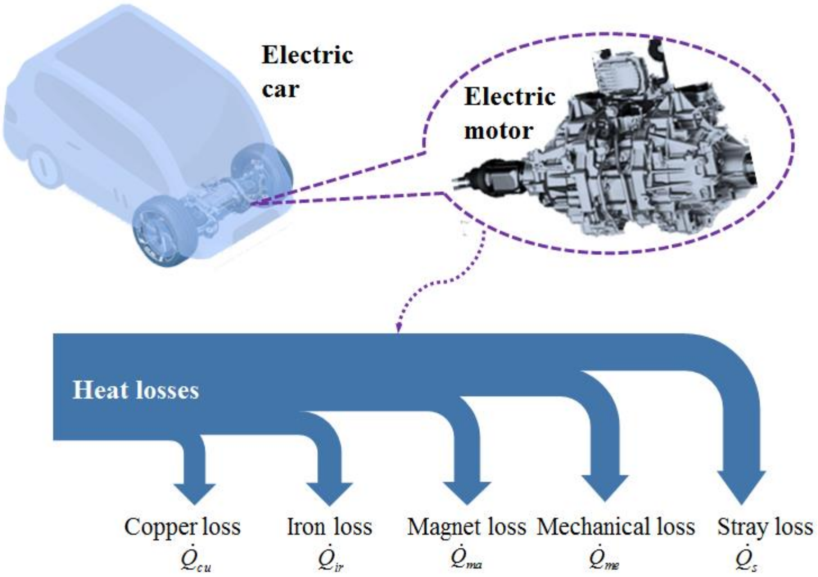


Fig. 1 Various heat losses of electric motors

According to the mechanism, the heat losses of the motor are classified into,

- Iron losses

Iron losses occur in both the stator and rotor laminations under alternating magnetic flux. Iron losses change with the operating conditions, type of lamination and thickness. It generally consists of three components, namely the eddy loss, hysteresis loss and excess loss [27, 28].

As the magnetic field distribution varies within motors and often the tips are under heavier saturation, the FE method is typically employed to accurately calculate the iron losses.

- Copper losses

Copper losses usually contribute the most of motor losses, especially in high power density motors. It happens in the winding either in the stator or rotor depending on the motor type. The losses are caused by the Joule effect [29]. As the electric resistance changes with the temperature [30, 31], higher resistance means more heat generated in the conductor. From this point of view, keeping the winding temperature at a lower level significantly benefits the decreasing of copper losses as well as increasing the motor efficiency.

- Mechanical losses

The mechanical losses are caused by friction between components, such as the rotor and bearings, shaft and end rings. It is highly dependent on the rotor speed, lubricant, torque load and manufacturing factors. It is generally higher with high rotor speed, poor lubrication and higher surface roughness [32]. Another typical component of mechanical losses is the friction between the air and the rotating rotor defined by windage losses [33]. The losses can result from axial and tangential velocity of the air. With the increase of the rotor speed, the windage loss becomes more and more significant. For simple cylindrical geometry, the windage can be calculated by analytical or empirical correlations.

- Magnet Losses

Permanent Magnet Machines typically employ magnets in the rotor. Eddy currents are generated within the magnets mostly due to the armature field. These losses can be significant and are difficult to quantify analytically due to the 3D effects, and hence FE is used for their calculation. These losses can be reduced by segmenting the magnets radially/circumferentially.

- Stray losses caused by other factors

Apart from the losses discussed above, the stray losses are also important, especially in high-frequency motors. The stray losses can be divided by stray no-load losses due to main flux variations and stray load losses due to leakage flux [34]. The stray losses were described by “portion of the total loss in an electric machine not accounted for by the sum of the friction and windage loss, the copper loss, and the core loss” in IEEE Std 112 [35]. The stray loss can account for more than 10% of the total losses.

3. Thermal Modeling of electric motors

Compared to the on-site experimental thermal testing of electric motors, thermal modeling is proven to be a more economical way, and more suitable way to combine with electromagnetic and mechanical modeling to conduct motor design optimization. The commonly used thermal modeling methods are numerical models and lumped parameter thermal network (LPTN) models. In this section, the characteristics of the two aforementioned methods are highlighted and discussed.

3.1 Finite-element and finite volume models

The finite-element (FE) and computational fluid dynamics (CFD) are two main numerical models. Both 2D and 3D FE are used to simulate the heat transfer in electric motors [36]. The convection heat transfer is approximated by boundary conditions based on empirical correlations or analytical algorithms [37]. To achieve more accurate modeling of convective heat transfer, CFD modeling is required. The CFD has got a widespread reputation for its excellent ability to analyze convection heat transfer over the natural/forced convection heat transfer, impingement heat transfer and spray heat transfer existing for the cooling of the motors. The temperature, pressure, and flow field can well be addressed and visualized by CFD models, making them very important methods. Furthermore, CFD has also been used to optimize the parameters of the electric motors, especially for the geometric parameters [38, 39].

The FE and CFD are capable to provide very accurate simulation results for the heat transfer process even used to analyze motors with complex structures. Another advantage of numerical analysis is that it can be easily combined with electro-magnetic analytical models, making multi-physical analysis possible [40]. Nevertheless, the calculation time of numerical analyzing models is much larger than the LPTN models, and the calculation consumption significantly increases when the model turns from 2D to 3D.

3.2 Lumped parameter thermal network (LPTN) models

LPTN models are generally more popular thermal modeling methods for electric motors. In LPTN models, motors are divided into several sections according to their thermal environment, and each section is represented by a thermal node [41]. Thermal resistances, of heat conduction, convection and radiation are used to connect these thermal nodes. They are determined by geometric dimensions of motors, thermal properties of material and heat transfer characteristics. When trying to simulate the transient temperature response, thermal capacitances also need to be included [42]. The heat generation in different components are commonly considered uniform and in the center of the represented nodes [43, 44]. Given the operating conditions, the thermal network can be solved by the governing energy balance equations in steady state and transient state, respectively [45]. As with CFD models, there are also 2D and 3D LPTN models. An LPTN model with more nodes is expected to have better accuracy. Nevertheless, models with fewer nodes can also provide satisfactory results. A typical LPTN model is shown in Fig. 2.

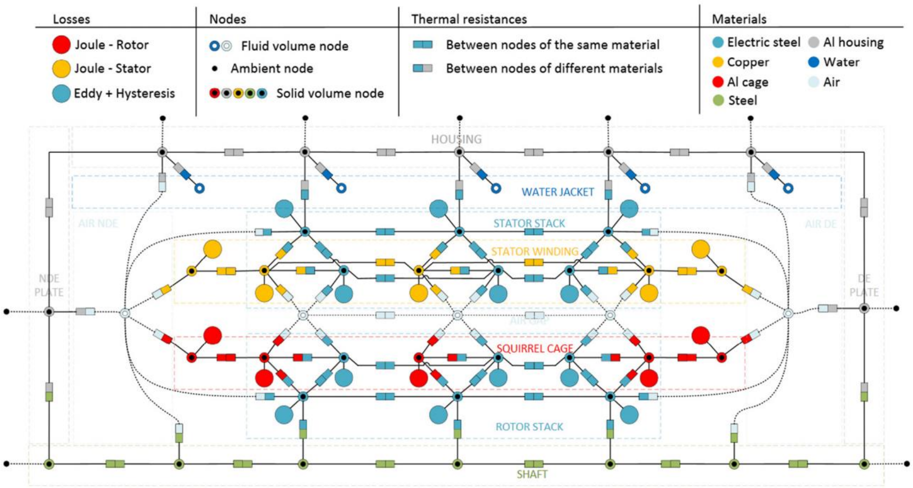


Fig. 2 A typical LPTN model for the electric motor [46]

LPTN is a proven very efficient method to analyze the cooling performance of electric motors. Compared to the numerical methods presented before, the calculation of LPTN is by far faster as well as accurate. Therefore, the LPTN model plays an important role in parameter sensitivity analysis [47, 48]. The LPTN model has remarkable flexibility for both steady-state and transient analysis, making it useful for almost all types of motors in their design process. Investigations have revealed that even very small number of thermal nodes can predict the temperature distribution quite well. Nevertheless, the calculation of LPTN incorporates a lot of empirical heat transfer correlations and anisotropic properties evaluation methods [49]. The appropriate selection of these correlations needs superior experience in heat transfer and thermal modeling. Furthermore, the assumptions for LPTN modeling may also put its accuracy at risk.

Apart from the typical numerical methods and LPTN methods, a combination of CFD and LPTN is another possible method to analyze the thermal management of motors. The hybrid method is introduced to balance the accuracy and calculation time of the models [50, 51]. Furthermore, artificial neural network (ANN) has great advantages to solve complex non-linear problems and has been widely used in heat transfer prediction, pattern control and fault detection of electric machines [52, 53]. Jiang et al [54] presented an ANN model to simulate the electromagnetic and thermal optimization of electric machines, suggesting the ANN could be a possible option in the future. More such models are still on the way.

Both numerical models and LPTN models efficiently support the design of electric motors as well as provide important guidelines to optimize the related parameters. Nevertheless, the design of the motor is a multi-physical process, during which many disciplines are involved. The heat losses input to the thermal modeling is usually obtained from electromagnetic analysis separately. However, the electromagnetic characteristics of motor are highly dependent on the thermal management technologies used. From this point of view, trying to analyze the cooling of motor without electromagnetic analysis will inevitably introduce deviations from the real scenario [55]. Regarding the thermal models themselves, there are also some concerns. The boundary conditions are very difficult to accurately describe, like the convection heat transfer of air gap and end space. The heat transfer correlations used may not be suitable for the tested motor as the correlations are case-sensitive [56]. Another aspect is the evaluation of component thermal properties, especially the winding. This is more critical for LPTN models as the winding is just represented by several thermal nodes. As discussed in the next section, the anisotropic thermal conductivity of winding is of great importance to build accurate models [57]. In addition, attention should also be paid to the deformation of the components, uneven distribution of heat, the radiation heat transfer as they are also essential in some cases [58, 59].

3.3 Key challenges and solutions of modeling

To achieve a successful thermal model, there are some key aspects need to be well addressed for both LPTN and numerical analysis. As mentioned before, most heat in the motor is dissipated by heat conduction and convection heat transfer process. For heat conduction, accurate models to calculate the thermal conductivities of solid components, especially the winding are very important [60]. For convection heat transfer, the heat transfer coefficient evaluations in air gap and end space are most influential and of great interest [61, 62]. They are main factors that greatly influence the accuracy of models.

3.3.1 Equivalent thermal conductivity (ETC) of winding

The heat transfer between the slot winding and iron core is very complex and presents one of the key challenges. In a fairly limited space, there are hundreds of conductors, insulation materials, residual air, and impregnation, and these are all randomly distributed [63, 64]. It is very difficult to simulate the heat conduction of each conductor and this is also not necessary. A more practical way to simulate the heat transfer of the winding is using the ETC of winding [65].

One of the most popular ways to consider is using the area-weighted method [66, 67]. The methods predict the ETC by the area ratio of conductors, area and insulation materials [68]. Based on experimental results, Boglietti et al [69] concluded that the ETC of winding could be regressed by following simple correlation,

$$\lambda_{eq} = 0.2425[(1-\varphi)A_{sl}L_w]^{-0.4269} \tag{1}$$

Similarly, Tang et al [71] suggested the following correlation,

$$\lambda_{eq} = \frac{A_a}{A_r}\lambda_a + \frac{A_{in}}{A_r}\lambda_{in} + \frac{A_{im}}{A_r}\lambda_{im} \tag{2}$$

Huang et al [70] proposed another thermodynamic model to predict the ETC of winding,

$$\lambda_{eq} = \frac{\lambda_{cu}\lambda_{in}}{\lambda_{in} + 2\lambda_{cu}\ln(r_{in}/r_{cu})} \tag{3}$$

The model was furthermore extended to consider the influence of fill factor and void ratio.

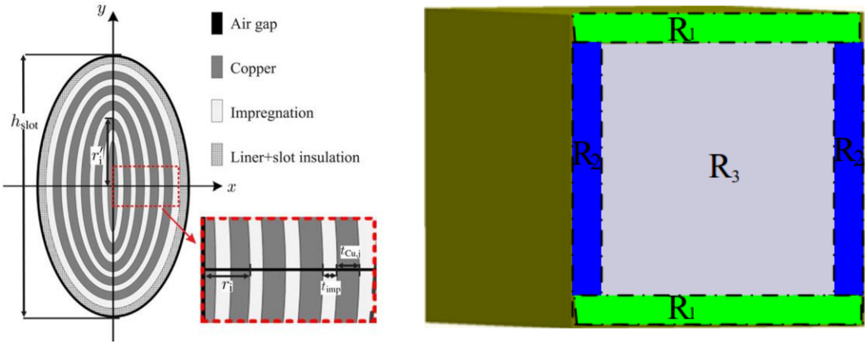
Liu et al [72] developed a new analytical method according to the double-homogenization approach and presented a two-step correlation to get the ETC of winding. The ETC of winding was given by,

$$\lambda_{eq} = \lambda_{im} \frac{(1+pf)\lambda_{cu,in} + (1-pf)\lambda_{im}}{(1-pf)\lambda_{cu,in} + (1+pf)\lambda_{im}} \tag{4}$$

Meanwhile, analytical models that consider the influence of layout of the conductors, the conductor, air, insulation and impregnation thermal properties as well as geometric dimensions will surely benefit the accuracy of modeling. Nategh et al [73] proposed a multi-layer elliptical cylinder model to predict the ETC of the winding domain, with the concept shown in Fig. 3(a). The thermal conductivity of the winding was evaluated by analyzing the heat transfer of each layer. The thermal resistance was given as,

$$\begin{aligned} R = \frac{N_{al}}{2\pi L_w \lambda_{in} N_{sl}} \{ &\ln[4(r_i+\delta_{in}) + 2\Delta r + 4\sqrt{(r_i+\delta_{in})^2 + \Delta r(r_i+\delta_{in}) + \Delta r^2/2}] \\ &- \ln[4r_i + 2\Delta r + 4\sqrt{r_i^2 + \Delta r r_i + \Delta r^2/2}]\} \end{aligned} \tag{5}$$

Inspired by porous metal material, Liu et al [74] presented a remarkable model to calculate the thermal conductivity of winding, as shown in Fig. 3(b). The heat transfer was divided into three parallel paths. According to the thermal network, the equivalent thermal conductivity was presented,



(a) (b)

Fig. 3 Equivalent thermal conductivity of winding models (a) Multi-layer elliptical cylinder model [73] (b)

Porous metal model [74]

$$\lambda_{eq} = \frac{\lambda_{in}(H_w - w_{cu})}{H_w} + \frac{w_{cu}H_w\lambda_{cu}\lambda_{in}}{[\lambda_{cu}(H_w - w_{cu}) + w_{cu}\lambda_{in}]H_w} \tag{6}$$

Some more methods to estimate the ETC of winding are listed in Table. 1.

3.3.2 Air gap heat transfer

The heat transfer in the air gap is of great importance, especially for air-cooled electric motors. The heat transfer direction in air-gaps is dependent on the relative temperature of stator and rotor [75]. Nevertheless, it is very difficult to accurately model as it is influenced by geometrical dimensions, rotor velocity, air properties, etc. Generally, for the small annulus area between the stator and the cylindrical rotor, the Taylor-Couette flow and Taylor-Couette-Poiseuille flow are used to distinguish the air flow in the air gap depending on whether there is axial flow or not. Taylor number and modified Taylor number are defined to characterize the flow in air gap and are given by [76, 77],

$$Ta = \frac{\omega^2 r_m \delta_{ag}{}^3}{v^2} \tag{7}$$

$$Ta_m = \frac{\omega^3 r_m \delta_{ag}{}^3}{v^2}\frac{1}{F_g} \tag{8}$$

For the air flow with low Taylor number, the flow is laminar shear flow and the heat transfer process is predominantly heat conduction. In this scenario, researchers recommended the heat transfer *Nu* by a constant value [78, 79]. With the increase of Ta_m, many pairs of vertices will appear in the axial direction and the critical angular velocity of the rotor can be calculated by $Ta_m = 1697$. With a further increase of Ta_m, turbulent flow heat transfer will dominate the heat transfer process. The following correlations were recommended to calculate the heat transfer coefficients [77],

$$Nu = \begin{cases} 0.064 Ta_m{}^{0.367} \; Ta_c < Ta_m < 10^4 \\ 0.205 Ta_m{}^{0.241}, 10^4 < Ta_m < 10^6 \end{cases} \tag{9}$$

In the case of Taylor- Couette-Poiseuille flow, the velocity of axial flow should also be considered. There are different flow patterns [80]. For the turbulent flow, the following correlation proposed by Kuzay et al [81] are suggested,

$$Nu = 0.022[1 + (1 + \frac{2\delta_{ag} u_{\phi}}{\pi r_r u_z})^2]^{0.8714} {Re_z}^{0.8} Pr^{0.5} \tag{10}$$

Gazley et al [82] also proposed a correlation which covered the axial and radial Reynolds number up to $1.2e^4$ and$1.1e^5$, respectively.

$$Nu = 0.03(\frac{2\delta_{ag}\sqrt{{u_z}^2 + {u_{\phi}}^2}}{\nu})^{0.8} \tag{11}$$

Another possible method to evaluate the heat transfer of air gap is by treating the air gap as a solid domain with equivalent heat conductivity. The equivalent heat conductivity can be presented by [57],

$$\lambda_{eq} = 0.069\eta^{-2.9048} Re^{0.4614\ln(3.33361\eta)} \tag{12}$$

In addition to the correlations presented here, there are also many other notable correlations proposed in the literature. They can be selected to simulate the air gap heat transfer under different conditions. More details of these correlations were comprehensively reviewed [82, 83]. The correlations to evaluate the air gap heat transfer in the motors are further presented in Table. 1.

3.3.3 End winding heat transfer

Generally, the end winding heat transfer refers to the heat transfer between the end winding and the air in end space. The end space heat transfer plays a notable role in the cooling of electric motors [84]. Furthermore, the end winding is usually the hottest spot of the electric motors. As a result, the cooling of the end winding has drawn wide attention.

The heat transfer in the end space is very complex considering the intricate geometry of components heat transfer mechanisms involved in a compact space. Some pioneering research has been published trying to unveil its heat transfer characteristics. Boglietti et al [85] concluded that the presence of the end ring had a direct influence of the end winding temperature. It was also suggested the over-temperature of the end winding was decreased with the rotation of the rotor [86]. The methods dealing with the end winding geometry also matter significantly. Rocca et al [87] presented that the difference of geometries affected the heat dissipation through the housing and end winding by up to 45.6% and 62.26%, respectively. It is no doubt that the air flow at the surface of end winding significantly affects the heat transfer of end winding, and in respect to this Micallef et al [88] concluded that increased air flow provided a better cooling performance, while directing the air to the tip of the end winding was more efficient. These conclusions definitely help to enhance our understanding and inspire possible optimization methods.

For LPTN and FE models, the heat transfer of the end winding is considered as a boundary condition with appropriately chosen of heat transfer correlations. For the air near the shaft, the flow can be turbulent due to the fast rotation, while the air is stagnant near the housing and end-cap surface. In this concept, the heat transfer contribution is usually presented in two parts- natural convection and forced convection. To quantify the air flow near the end winding, the velocity of rotor surface is normally used as the characteristic velocity. A typical heat transfer correlation generalized and mostly used by the scholars was given by [57, 79],

$$h = k_1(1 + k_2 {u_r}^{k_3}) \tag{13}$$

The coefficients k_1, k_2, and k_3 varied with the tested conditions and motor types. There are different sets of coefficients and can be found in related literature [89, 90]. Another method to evaluate the heat transfer coefficient is given by Nusselt number. Ahemd et al [91] studied the convection heat transfer by a hybrid CFD and LPTN model. The contributions of natural convection and forced convection were determined by LPTN and CFD model, respectively. The following correlation was suggested,

$$Nu = 4.69 Re^{0.27} Pr^{0.21} Gr^{0.07} (\frac{d}{L_{ew}})^{0.36} \tag{14}$$

The correlation was also regressed in the presence of rotor speed,

$$h = 13.633 + 0.4072 u_r \tag{15}$$

Basso et al [92] proposed a series of correlations with a general form to predict the heat transfer in the end space

$$Nu = k_1 Re_{\theta}^{k_2} \tag{16}$$

Where k_1 and k_2 were determined by CFD analysis and varied with the locations of end winding. Li et al [93] also proposed the following correlation to evaluate the heat transfer of the winding and ambient air.

$$Nu = 0.456\,\mathrm{Re}_t^{0.6} \tag{17}$$

More presented correlations and evaluations are given in Table 1.

Despite the research presented here, the heat transfer characteristics of convection heat transfer of end winding in end space have not been fully revealed, and further effort is still needed. It was suggested that the cavities in the end winding provided additional heat transfer paths and small variations of cavities could cause significant variations of the heat transfer coefficients [94, 95]. Nevertheless, the cavities are difficult to accurately model even with CFD methods, not to mention LPTN models. The selection of empirical correlations is a realistic and fast method to obtain the heat transfer coefficient, but careful attention should also be paid to the applicability of the chosen correlations. Besides, evaluation of the heat transfer area of the end winding is also a complex task [96].

In this section, the modeling methods for ETC of winding, air gap heat transfer and end winding heat transfer are presented in detail. In general, there are already plenty of correlations that can be used to address them in either LPTN or FE models and successful cases were also reported. The correlations are generalized based on experimental as well as CFD simulation results. Nevertheless, careful checking of the tested conditions should be done before applying these correlations as they are very case-sensitive. Apart from key concerns discussed here, the equivalent density and heat capacity of winding [66], contact thermal resistance [63] between solid walls may also need to be examined for certain motors. A possible way to identify as well as validate these parameters is by an inverse approach from the experimental data [97, 98].

Table 1. Heat transfer models used in simulation

References	Sub-models			
	equivalent slot winding thermal conductivity	Jacket heat transfer	Air gap heat transfer	End space heat transfer
Karnavas et al [99]	401/401/401	$Nu=\frac{(f/8)(Re-1000)Pr}{1+12.7(f/8)^{0.5}(Pr^{2/3}-1)}$	$Nu=0.409T_a^{0.241}$	
Anderson et al [100]			$Nu=1.5975Ta^{0.3282}, Ta>10^8$	
Montonen et al [101]	0.5/0.5/400	NA	$Nu=\begin{cases}2, T_a\le 41,\\ 0.212T_a^{0.63}Pr^{0.27}, 41<T_a<100\\ 0.386T_a^{0.5}Pr^{0.27}, T_a>100\end{cases}$	$Nu=0.153Re^{0.618}Pr^{0.33}$
Jiang et al [102]		NA	$Nu=\begin{cases}2,\ T_a<1700\\ 0.128T_a^{0.367}, 1700<T_a<10^4\\ 0.409T_a^{0.241}, 10^4<T_a<10^7\end{cases}$	$h=15.5(0.29u_r+1)$
Li et al [103]		NA	$Nu=\begin{cases}2,\ T_a<1700\\ 0.128T_a^{0.367}, 1700<T_a<10^4\\ 0.409T_a^{0.241}, 10^4<T_a<10^7\end{cases}$	

Rehman et al [57]	$\lambda_{eq} = \sum_{i=1}^{n} \delta_i / \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i}$	NA	$\lambda_{eq} = 0.069\eta^{-2.9048} Re^{0.4614\ln(3.33361\eta)}$	$Nu_t = 0.456 Re_{\mathrm{t}}{}^{0.6};\ \alpha_c = 15 + 6.5\omega_r^{0.7}$ $Nu_r = 1.67 Re_{\mathrm{t}}{}^{0.385};\ Nu_{rf} = 0.456 Re_{rf}{}^{0.6}$
Sciascera et al [23]	0.6	NA	10.5	
Boglietti et al [86]		NA		$h_1 = 6.32u_r + 39.2$ $h_2 = 6.86u_r + 46.728$ $h_3 = 5.49u_r + 38.209$
Acquaviva et al [104]	$\lambda_{eq} = \frac{f_1(\lambda_{in}, \varphi, \xi_c, \lambda_w)}{f_2(\lambda_{in}, \varphi, \xi_c, \lambda_w)}$	NA	$Nu = \begin{cases} 2, T_a \le 41, \\ 0.212 T_a{}^{0.63} Pr^{0.27}, 41 < T_a < 100 \\ 0.386 T_a{}^{0.5} Pr^{0.27}, T_a > 100 \end{cases}$	$h = k_1(1 + k_2 u_r{}^{k_3})$
Li et al [105]		$Nu = 0.023 Re^{0.8} Pr^{0.4} c_l$	$Nu = 0.15 Re^{0.8} - 100(r_c / r_r)^2$	
Nategh et al [106]		$Nu = 7.49 - 17.02\frac{h}{w} + 22.43(\frac{h}{w})^2 - 9.94(\frac{h}{w})^3 + \frac{0.065 RePrd_h / l_{ch}}{1 + 0.04(RePrd_h / l_{ch})^{2/3}}$	$Nu = 0.409 T_a^{0.241} - 137 T_a^{-0.75}$	$Nu = 0.664 Re^{0.5} Pr^{1/3}$
Wrobel et al [107]	3.5/3.5/229.3	NA	NA	NA

Nategh et al [50]		$Nu = 7.49 - 17.02\frac{h}{w} + 22.43(\frac{h}{w})^2 - 9.94(\frac{h}{w})^3 + \frac{0.065RePrd_h / l_{ch}}{1+0.04(RePrd_h / l_{ch})^{2/3}}$	$Nu = 0.409T_a^{0.241} - 137T_a^{-0.75}$	$h = 15(1+0.4u_r^{0.9})$
Bogietti et al [108]	$\lambda_{eq} = 400.925 - 0.058T$	NA	$Nu = \begin{cases} 2, Re < Re_{cr} \\ 0.386Pr^{0.27} / \sqrt{R_r\delta_{ag}}, Re > Re_{cr} \end{cases}$	$h = 15.5(0.29u_r + 1)$
	386/0.8/0.8	$Nu = \frac{(f/8)(Re-1000)Pr)}{1+12.7(f/8)^{0.5}(Pr^{2/3}-1)}$		N/A
Xjpteras et al [109]	$\lambda_{eq} = \sum_{i=1}^{n}\delta_i / \sum_{i=1}^{n}\frac{\delta_i}{\lambda_i}$	NA	$\lambda_{eq} = 0.069\eta^{-2.9048}Re^{0.4614\ln(3.33361\eta)}$	
Aglen et al [110]		3500	$Nu = 0.409T_a^{0.241} - 137T_a^{-0.75}$	50
Michael et al [67]	$\lambda_{eq} = \frac{\lambda_{cu}\lambda_{in}}{\lambda_{in}\varphi + (1-\varphi)\lambda_{cu}}$	$Nu = 0.012\left(Re^{0.87} - 280\right)Pr^{0.4}$ $(1+\sqrt[3]{(d_h / l_{ch})^2})$		N/A
Polikarpova et al [111]	0.58/0.58/386	$Nu = \frac{(f/8)(Re-1000)Pr)}{1+12.7(f/8)0.5(Pr^{2/3}-1)}$		NA
Zhang et al	$\lambda_{eq} = 0.2749[(1-\varphi)A_sL_c]^{-0.4471}$	$Nu = \frac{(f/8)(Re-1000)Pr)}{1+12.7(f/8)0.5(Pr^{2/3}-1)}$	$h = 0.386\lambda T_a^{0.5}Pr^{0.27} / (2\delta)$	$h = 15(1+0.15u_r)$

[112]				
Li et al [93]	$\lambda_{eq} = \sum_{i=1}^{n} \delta_i / \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i}$	$Nu = 0.012(Re^{0.87} - 280)Pr^{0.4}$ $[1 + (\frac{d_e}{L})^{0.67}](\frac{Pr_f}{Pr_s})^{0.11}, \quad Re > 2300$ $Nu = 7.49 - 17.02\frac{h}{w} + 22.43(\frac{h}{w})^2$ $-9.94(\frac{h}{w})^3 + \frac{0.065RePrd_h / l_{ch}}{1 + 0.04(RePrd_h / l_{ch})^{2/3}}$ $, Re < 2300$	$\lambda_{eq} = 0.069\eta^{-2.9048}Re^{0.4614\ln(3.33361\eta)}$	$Nu_t = 0.456Re_{\mathrm{t}}^{0.6}; \ h_c = 15 + 6.5\omega_r^{0.7}$ $Nu_r = 1.67Re_{\mathrm{t}}^{0.385}; \ Nu_{rf} = 0.456Re_{rf}^{0.6}$
Li et al [113]		$Nu = 0.023Re^{0.8}Pr^{0.4}c_l$	$Nu = 240.72(0.001366G^{-1.26} + 0.675)$ $(3.983 \times 10^{-6}Re + 0.4822)$	
Jiang et al [54]	$\lambda_{eq} = \varphi\lambda_{cu} + (1-\varphi)\lambda_{in}$			$h = 41.1 + 6.22u_r$
Staton et al [63]	$\lambda_{cu} = 0.1076\varphi + 0.029967$	NA	$Nu = 0.386T_a^{0.5}Pr^{0.27}$	$h = k_1(1 + k_2u_r^{k_3})$
Staton et al [79]		$Nu = 7.49 - 17.02\frac{h}{w} + 22.43(\frac{h}{w})^2$ $-9.94(\frac{h}{w})^3 + \frac{0.065RePrd_h / l_{ch}}{1 + 0.04(RePrd_h / l_{ch})^{2/3}},$ $Re < 2300$ $Nu = \frac{(f/8)(Re - 1000)Pr)}{1 + 12.7(f/8)^{0.5}(Pr^{2/3} - 1)}, Re > 2300$	$Nu = 0.386T_a^{0.5}Pr^{0.27}$	$h = k_1(1 + k_2u_r^{k_3})$

4. Thermal management technics for electric motors

The thermal management of motors should be considered at the very first stages of the motor design, as the sizing is directly linked to the heat dissipation capability. The current thermal management concepts are generalized in Fig. 4. Broadly these can be divided into convection cooling and heat conduction enhancement. For the convection cooling, the air cooling (natural convection, forced convection, jet impingement), liquid cooling (jacket cooling, immersion cooling, spray cooling, jet cooling, etc.) for the stator, winding, and rotor are available to meet the requirements of different motors. In addition, heat transfer in the motor can also be enhanced by implementing some high thermal conductivity materials/components, like potting materials, heat guides, PCMs, and heat pipes. There are also notable combinations between these single methods to tackle extreme conditions. All the technologies are presented and discussed in detail in this section.

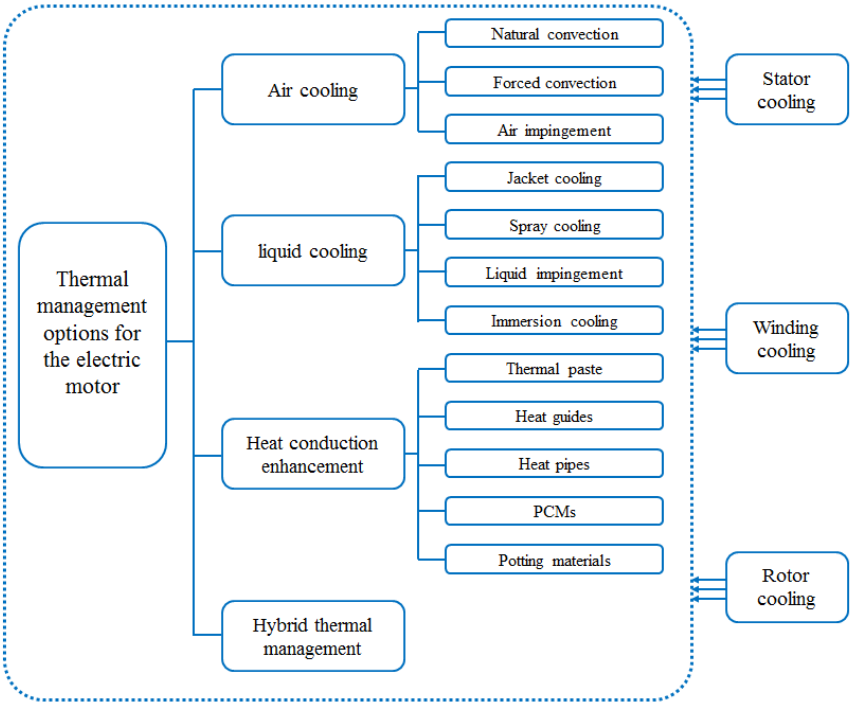


Fig. 4 thermal management options for electric motors

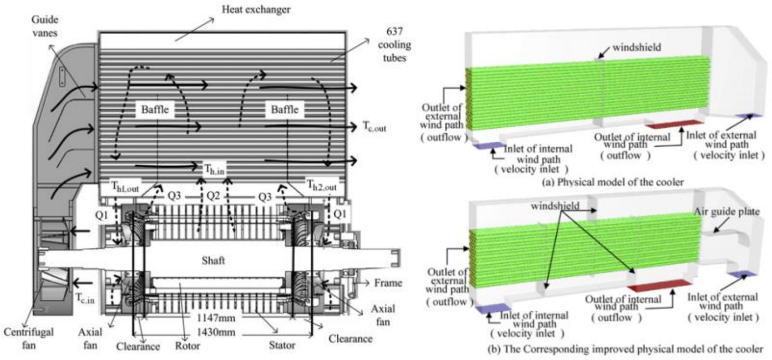
4.1 Stator cooling

4.1.1 Air cooling

Air cooling is a basic cooling method for motors. It is commonly employed to cool motors with a relatively low heat density. The air cooling can be natural air cooling on the outside surface and forced air cooling inside of the motor.

On the outside surface of the housing, there are commonly some fins to increase the heat transfer between the housing and ambient air. The existence of the fin structures can efficiently extend the heat transfer area of the outer surface of the housing [114]. How to maximize the cooling effect by optimization of the fin geometric dimensions is a continuous research topic. Ulbrich et al [115] conducted an analysis and found that for the studied cases, the housing with nine fins was generally better than those with 6~8 fins, while a further increase to 10 fins didn't have a significant positive effect. Better heat dissipation performances were obtained by increasing the average and total hydraulic diameters. Kuria et al [116, 117] indicated a decrease of up to 15% was achievable for end winding temperature by optimizing the casing height and width. It was also presented that the orientation of fin presented no significant effect on the end winding temperature. Chen et al [118] developed a model to simulate the cooling performance of the fin structure. It was shown that the cooling performance was better with higher fin geometry, lower fin pitch and higher airflow velocity in the array of fins. According to Peng et al [119], the fin pitch ratio has a more significant influence on the temperature of winding, despite that the temperature of winding decreased also with the fin pitch ratio, fin thickness and fin height. Meanwhile, the fin efficiency decreased with the fin height. Kim et al [120] developed groove-structured housings for an in-wheel motor and proved that the cooling capacity was increased when the direction of groove structures was the same with the air and densely arranging. The importance of fin orientation was also highlighted by Xu et al [121], who suggested that the wrongly arranged fin orientation may have no positive effect.

For air-cooled motors, the air flow and heat transfer inside the motor are more critical. The internal air flow dominates the heat transfer process [122]. To enhance air cooling, fans are commonly used to force the air to circulate in the interior path to cool the motor components as well as optimize the temperature distribution. Generally, centrifugal, axial fans and piezoelectric fan have been used or tested for motors [123, 124]. The selection and optimization of the fans' structure are important factors to enhance the cooling, as indicated by the contribution of Chen et al [125], Nakahama et al [39], and Kim et al [126]. Both the interior air path geometries and fan parameters have a great influence on the pressure drop and heat transfer performance of the air flow [127, 128]. Chang et al [129] studied the three-dimensional air flow to cool a large-capacity motor, as shown in Fig. 5(a). The temperatures of the stator and rotor were both decreased by up to 6 ℃ by increasing the flow rate and uniformity of air, updating the structure along the air flow path. Wen et al [130] introduced an air guide plate and modified the shield in the air path to eliminate the vortex energy loss, as shown in Fig. 5(b). With the new flow path, the temperature at the outlet was decreased by 3.3 ℃. Kim et al [131] suggested that providing direct flow was more important than increasing flow rate. Furthermore, the root inlet location, inlet length and groove threshold were optimized, at which point the performance of the motor was 24.3% better than the baseline. To reduce the negative influence of reverse flow and flow separation, Moon et al [132] improved the structure of the fan cover, frame and end shield by adopting an air-guide plate, flattened sub-structure, and a 45° chamfer, respectively. The temperature rise of the stator winding was decreased by 7.5%, from 97.4 ℃ to 90.1 ℃. Nakahama et al [133] optimized the air flow path for the motor by a new dual-path structure. The structure helped decrease the stator temperature and in turn downsize the motor geometry as well. Li et al [134] studied the temperature characteristics of a motor with a centrifugal impeller. It was found that with optimizing the structure of the diffuser profile, the increased air flow rate reduced the air temperature rise and thus lowered the temperature of the motor. Besides, Sun et al [135] and Asef et al [136] also indicted that the cooling of motors could be better with the existence of extra cooling ducts in the stator and the teeth, at the cost of increasing iron loss to some extent.



(a) (b)

Fig. 5 the flow path of the air cooling (a) [129] (b) [130]

To summarize, external natural air cooling can be improved by optimizing the fin structures. Generally, the increase of heat transfer area is helpful for the cooling of motors, if there is no significant negative impact on the air velocity. Nevertheless, the increase of the fin geometries will also increase the volume and weight of the motor, which may lead to other problems in some cases, such as for motor integration and for in-wheel motors. Regarding the internal air flow heat transfer, reduction of the flow resistance along the air path will surely decrease the pressure drop, increase the flow velocity, and enhance the forced convection heat transfer. The air flow in the motor involves the rotation in the end space, the air gap flow, and possible small duct flow which creates very complicated fluid dynamics coupled with heat transfer. The windage loss is closely related to the flow path and flow dynamics of the air [100]. A better air path is characterized by high flow velocity, low-pressure drop and excellent heat transfer performance [137]. It is also noteworthy that if big changes are made to optimize the air flow path, a corresponding mechanical stress analysis should also be conducted to ensure the motor's structural integrity. Meanwhile, it can be concluded that the improvement of fan parameters is another efficient method to enhance motor cooling. Apart from the air natural cooling and forced convection cooling, air impingement cooling is another very good choice on some occasions as suggested by Xu et al [138]. Overall, air cooling is used in lower heat density of motors due to the poor thermodynamic properties of air. For motors with higher heat density, liquid cooling is more favorable.

4.1.2 Liquid jacket cooling

Liquid jacket cooling is another popular cooling method used for commercial motors especially for those in automotive applications. The heat is dissipated by liquid coolant mainly through the convection heat transfer [139, 140].

Water is the coolant in most cases. There are plenty of studies which have investigated the influence of channel dimensions, cross-section shape and the flow rate on the performance of the coolant jacket. Rehman et al [57] concluded that with the increasing of cooling passages from 4 to 8, the maximum temperature of the stator decreased, while a further increase of passage number wouldn’t make too much improvement. It was also found increasing the flow rate of the coolant was a more effective method to enhance the cooling performance. Huang et al [37] compared three cooling methods regarding the position of the cooling ducts, including in the stator back-iron, in the interface of housing-to-stator and in the housing. It was suggested that both the direct cooling methods showed a smaller temperature rise for the stator. With more cooling ducts, better performance was achieved. Unlike the traditional water jacket, Li et al [141] placed the water loop at the bottom of the teeth with two parallel flow paths. The experimental results showed that the temperature of the end winding was the highest with a temperature rise of 60 ℃, indicating the good capacity of the proposed water jacket layout. Pechanek et al [142] studied two-channel layouts with the same cross-sectional area. It was suggested that the axial partitioning structure has a higher heat transfer coefficient, while the tangential case has a lower pressure drop. For the former one, the local hot spots were generally in the “U” bends caused by local water turbulence, while for the latter one, the only presented local hot spots occur near the water outlet. Refaie et al [143] developed a novel water jacket structure consisting of several circumferential cooling passages. It was suggested that the heat transfer coefficient and pressure drop requirement were balanced with the optimization of channel shape, locations and numbers. Satrustegui et al [46] analyzed different design of water jackets, as shown in Fig. 6. It was suggested that the axial water jacket proposed a higher pressure drop than spiral water jacket given the same heat transfer area. Based on the studied results, three design criteria were presented to meet the typical requirements of turbulent flow, pressure drop and erosion. Wu et al [144] designed and studied two different water jacket channels. One was smooth while the other one was twisted, as shown in Fig. 7. The twisted channel jacket changed the flow characteristics of water by intensively enhancing the circumferential velocity, turbulence energy and vorticity distribution. As a result, the heat transfer coefficient was also increased. Meanwhile, a further study indicated that the twisted channel water jacket also considerably improved the uniformity of heat transfer. Li et al [145] presented that the greater width of channel would lead to better heat dissipation capacity as well as large flow resistance. The height had a greater influence on the pressure distribution rather than the temperature. When trying to optimize the water jacket cooling performance, the roles of various parameters were not the same. According to the work of Bennion et al [146], given the heat transfer correlation of the water jacket, the stator radial conductivity, stator casing contact resistance and slot-winding axial conductivity have the most sensitive impact on the performance.

Water is not the only coolant that has been studied. Some studies use other liquids for heat dissipation, such as water/ethylene glycol [99] and oil [147]. Deriszadeh et al [148] indicated that with the increase of the ethylene glycol concentration and number of turns, the heat transfer coefficient increased. Furthermore, the increase of the heat transfer coefficient was more significant than the increase of the pressure drop. Yang et al [149] tested and simulated the oil jacket cooling for a motor. It was suggested that the cooling performance of the motor was better with lower height and width of the channel but at the cost of higher pressure drop.

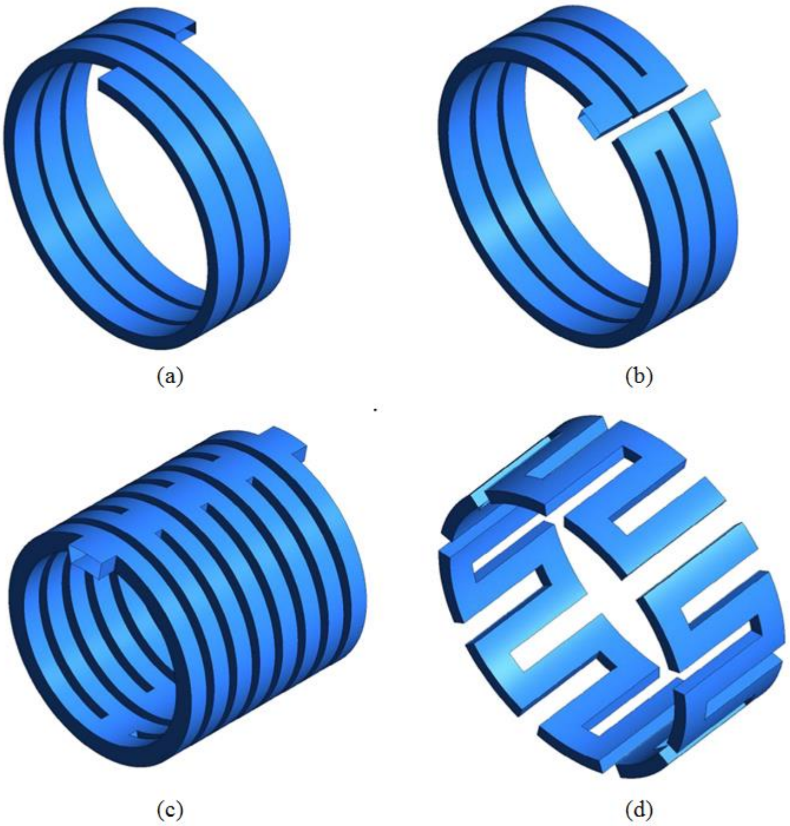


Fig. 6 different configurations of water jacket [46] (a) spiral; (b) U-shaped; (c) U-shaped (bifurcated); (d) axial

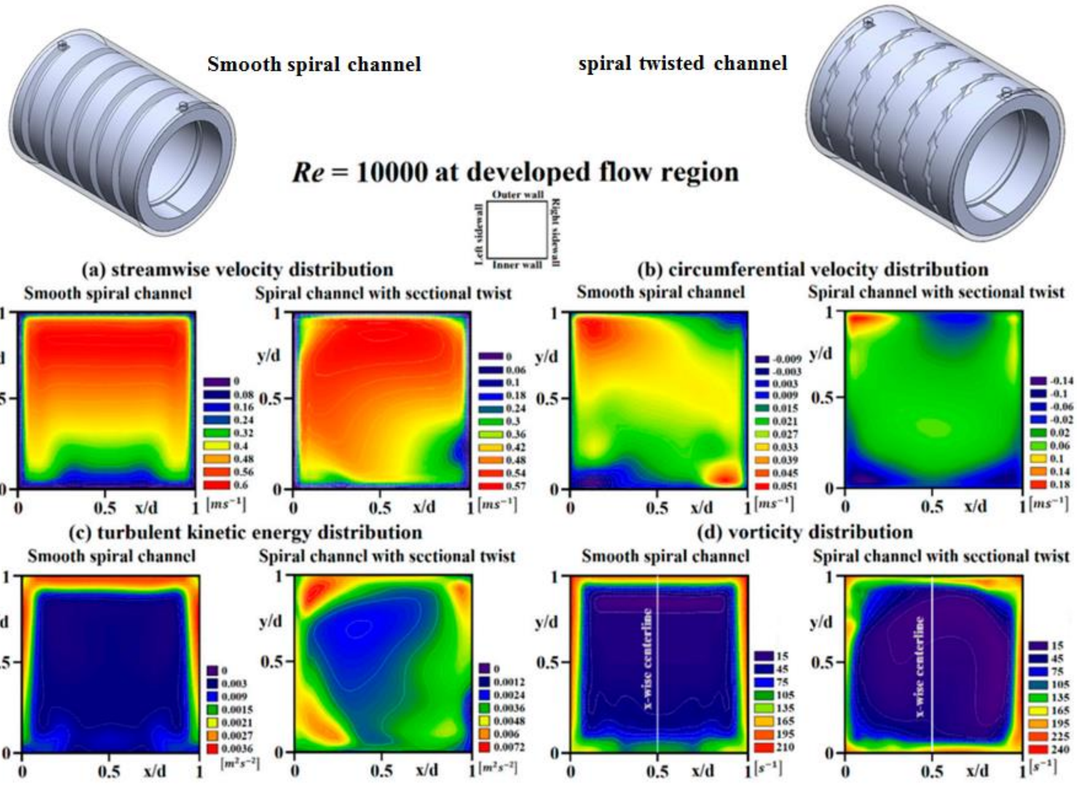


Fig.7 The structure of the water jacket channel [144]

To summarize, for the cases show liquid cooling for the stator has been widely used in the medium-level heat density motors, the liquid circulates in the axial or spiral serpentine jacket channels to dissipate the heat. It has obvious advantages over air cooling, like higher heat density, low noise, and a totally separate system [142]. Generally, the channels are located in the housing. Nevertheless, placing the channel located nearer the winding will surely benefit the temperature decrease [150], but may cause an increase of losses. The most common working fluid is water, while the oil, water/glycol, and even dielectric fluid, thermomagnetic fluid are also available to cool the motor [151, 152]. No matter what coolant is used, the optimizations of the channel dimensions and flow rate are proved efficient ways to improve the heat transfer ability of jacket cooling. A lot of novel structures have been proposed and thoroughly investigated. Overall, methods that can increase the flow velocity of the coolant are expected to present better performance. However, some of them may also introduce a larger pressure drop along the channels. For jacket cooling, air cooling also plays an important role in heat transfer process, especially for the rotor. The optimization of air flow path is also recommended for the motor with jacket cooling [104, 153]. In addition, some concerns need to be considered for the motor with jacket cooling. The inlet temperature is recommended within a certain range. Otherwise, the coolant may cause thermal shock to the insulation material or not be capable to dissipate the heat [154]. Furthermore, attention should also be paid to the water quality to avoid corrosion-related problems.

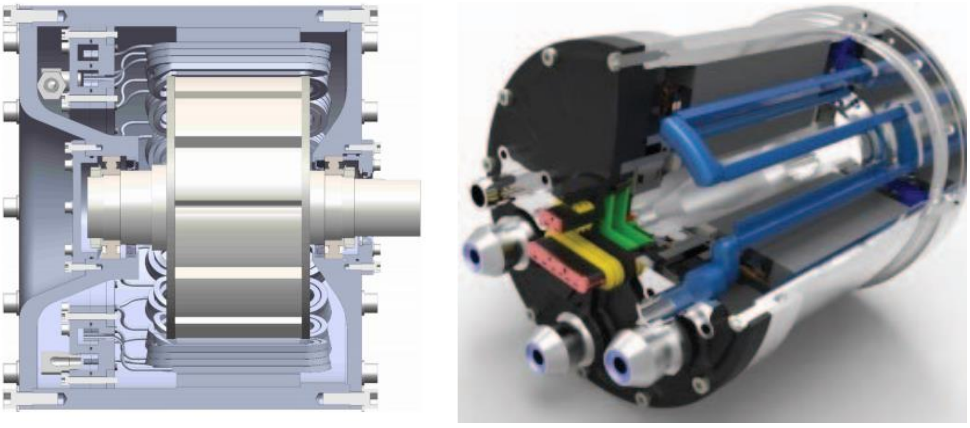
4.2 Winding cooling

In an electric motor, especially those aiming for higher power densities, most heat is generated in the winding. As a result, direct cooling for the winding provides greater efficiency compared to the stator cooling [155] of the previous section. Based on the winding location, the winding is divided into slot winding and end winding. The cooling methods of the aforesaid are separately considered and presented in this section.

4.2.1 Slot winding cooling

The slot winding refers to the conductors (or part of the winding) lying within the slots. Generally, the heat transfer scenario of the slot winding is the harshest because of the limited spaces that can be implemented for thermal management. Nevertheless, some ingenious cooling methods have been developed to cool the slot winding.

One robust method is by embedding the cooling channels along with the winding in the slot. In this circumstance, the coolant directly dissipates the heat generated in the slot winding [156, 157]. Lindh et al [158] tested a slot winding cooling with cooling ducts. The structure of the cooling ducts is as shown in Fig. 8(a). The cooling method was tested with a permanent magnet motor, and the motor worked well with temperature well below 80 °C. In another work, Lindh et al [159] further concluded the direct cooling method significantly lowered the temperature of the winding by more than 50 °C comparing to the indirectly cooling method. Reinap et al [160] also confirmed the significant decrease of the temperature through cooling of slot winding. In some certain conditions, more cooling ducts may provide a better performance, as indicated by Xu et al [121]. Three cooling ducts were located with the slot winding. It was reported that the temperature of the slot winding was decreased by more than 50%. Tuysuz et al [22] also studied the cooling of slot winding with several axial ducts, and showed that the cooling method presented a superior cooling effect than the standard water jacket cooling given the same flow rate.

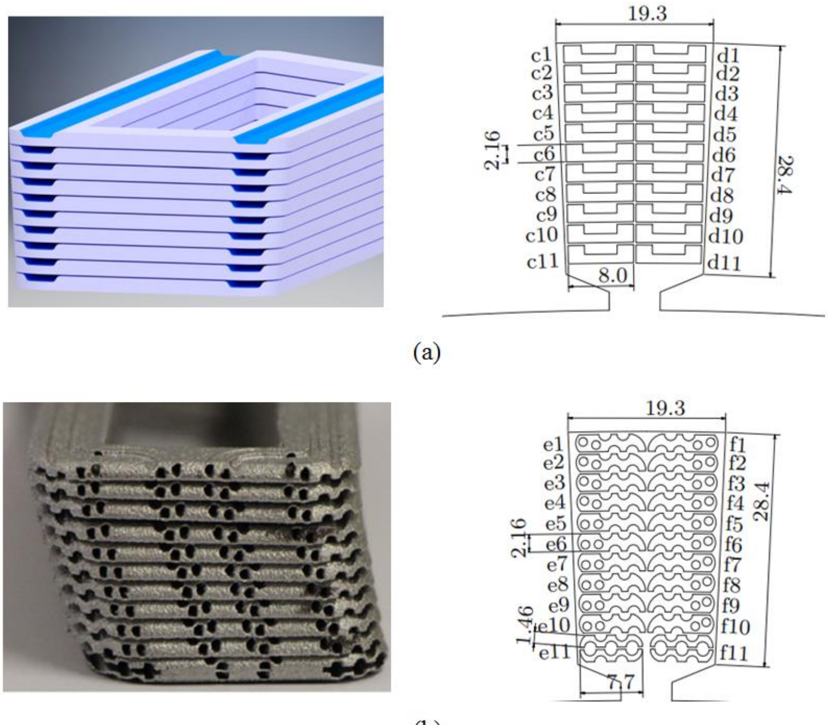


(a) (b)

Fig. 8 The layout of channels for slot winding cooling (a) [158]; (b) [161]

Another efficient layout for the cooling channels is at the top of the slot. Schiefer et al [161] developed a cooling structure as shown in Fig. 8(b). The fluids flowed through the serpentine cooling channels at the top of the motor slots. The results indicated the temperature of the slot winding decreased from 223.5 ℃ to 85 ℃. Tuysuz et al [22] introduced the coolant to the designed pipe between the rotor and slot winding. The temperature of the winding was decreased by 20 ℃ and the power density of the motor doubled. Liu et al [162] also observed the excellent positive effect of slot winding cooling. All of the research shows excellent prospects of direct slot cooling in the goal to maximize current density and correspondingly power density. There are also other spaces near the winding available to introduce the cooling channels, as indicated by Refaie et al [143] and Sixel et al [163].

For some motors, the windings of which are made of hollow conductors, the winding itself does provide cooling paths, and there is no necessity to introduce extra cooling channels as presented above. Alexandrova et al [154] tested a motor with rectangular hollow winding. The coolant cooled the winding from the bottom of the inner winding to the outer layer winding. The oil cooling efficiently dissipated 2.9 kW out of 3 kW in the tested condition. Chen et al [164] modeled and tested the slot direct cooling for a hollow conductor winding. The results indicated 86.8% heat energy of the conductor was dissipated by the forced convection in the channel. The modeling results were in good accordance with the experimental test results. Other special-profiled windings have been studied. Wohlers et al [165] tested two special types of winding, and their layouts are shown in Fig. 9. One of them had partial concave cross-section and the other one was characterized by small holes and channels. It was found that the direct winding cooling raised the possible current density of the coil by about fivefold for the studied cases.



(a)

(b)

Fig. 9 two types of winding and their layouts [165]

To summarize, compared with the water jacket cooling, the slot winding cooling is more efficient as the winding, which is the main heat source, is directly cooled. It significantly increases the output of the motor, efficiency and is capable to address higher current density levels. The slot cooling channels can be placed in or on one lateral side of the winding according to the winding topologies. With the use of hollow or profiled conductors, the direct contact between the coolant and winding is achievable along with the profile of conductors, providing a closer and more efficient cooling [166]. Specially, researchers also suggested that apart from convection flow cooling, the evaporative cooling for the hollow copper winding [167, 168] can also be an option. Nevertheless, when using cooling channels for the slot winding, attention should be paid to the following considerations. The slot area is commonly very limited, and therefore, the dimension of cooling channels is very small, too. As a result, the pressure drop of the flow in the small channels can be very considerable. The situation is even worse for the motor with many slots. The big pressure drop may put the coolant feed pump at a risk. Furthermore, the presence of the cooling channels in the slot will also occupy the effective area of the slot [169]. A larger current density will be needed in some circumstances. The material of the pipe is another concern. While the materials that cause extra magnetic losses or safety concerns are not recommended, some plastic and ceramic materials may suffer from their poorer thermal properties.

4.2.2 End winding cooling

For typical jacket-cooling motors, the highest temperature is usually in the end winding. Therefore, the cooling of the end winding is very important [88]. For the motor cooled by air or coolant-jacket, the end winding mainly transfer the heat by forced-air convection in the end space, the research on which had been presented in the earlier section. Although there are some literature shows that the end winding could be efficiently cooled by the air cooling, efficient liquid cooling at the end-winding may contribute more for high-density motors. The advanced end winding cooling strategies by liquid is presented in this section.

Liquid convection heat transfer has been proposed to cool the end winding directly due to its high heat transfer coefficient. Madonna et al [170, 171] tested a noninvasive cooling method for the end winding. It was experimentally proved that the temperature of the end winding was dropped from 172 ℃ to 130 ℃, and also with a decrease of slot winding. Montonen et al [101] pumped the oil to the end winding surface through four holes and left the motor section at the bottom of the stator. The conclusions indicated that with the oil cooling method, the temperature of the winding was decreased by down to about 50 ℃. Following that, Marcolini et al [172] concluded that with the oil cooling for the end winding, the oil could extract about 3.3 times more heat compared to the water jacket cooling. Twofold torque and power density improvements were predicted in the investigated condition. Oil immersion cooling has also been proven to be another effective option for end winding. Li et al [173] investigated the end winding oil cooling under stagnant and flowing states by separating the rotor and stator through a well-sealed glass fiber sleeve. It was found that the temperature of the end winding was reduced by 43.6 ℃ compared to the cooling with water jacket only when two ends of end winding are immersed by still oil.

Other cooling methods which have shown exceptional promise for the end winding is jet impingement cooling [174] and spray cooling [175]. Li et al [176] sprayed the oil to the end winding through the holes in the end cover, and the structure is shown in Fig. 10(a). It was indicated that with the use of the oil, the temperature of the end winding was decreased by about 20%. Meanwhile, the time required to be at steady state was reduced by 30%~60%. Davin et al [177] comprehensively tested the lubricating oil to cool the end winding of a motor with different nozzle configurations and flow patterns. It was suggested that even with a small amount of oil, the winding temperature was significantly decreased, and the dissipation power was improved by around 2.5~5 times. Furthermore, a larger flow rate always benefited the winding cooling. In respect to the rotor rotation cases, the rotation resulted in increasing the thermal disparities between the different winding locations, while this effect could be offset by increasing the flow rate. Liu et al [178] tested the cooling performance of the recently popular hairpin winding with oil cooling under different oil flow rates, spray pressures, outlet velocities and nozzle types, as shown in Fig. 10 (b). It was reported that with the oil spray at end winding, the current density roughly doubled as well as the output torque, at the cost of fractional increase of pumping power. Meanwhile, the temperature uniformity was better with higher oil flow rate and more nozzles. A CFD model was presented by Guechi et al [179] to study the spray cooling on the end winding. It was concluded that with the spray cooling, the temperature of the winding was obviously lowered. Refaie et al [143] also developed a spray cooling for the end winding to pursue the better cooling performance of the winding.

(a) (b)

Fig. 10 Oil spray cooling for end winding (a) [176] (b) [178]

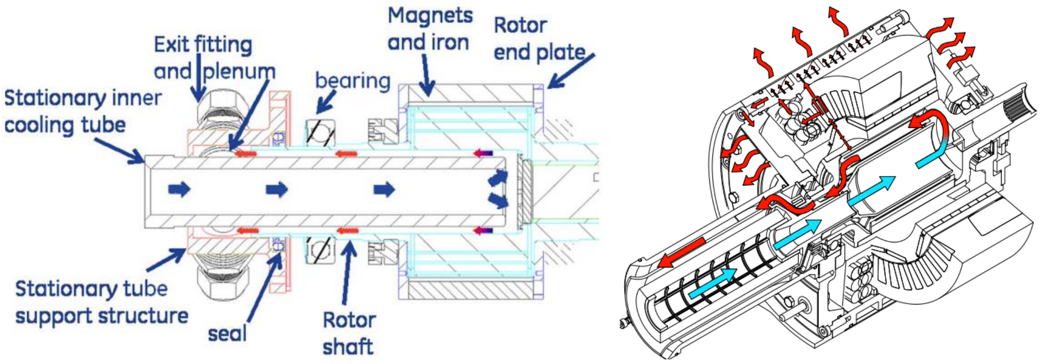
From the foregoing discussion, the temperature of the end winding can be impressively decreased when using liquid cooling methods. The liquid not only dissipates the heat from the end winding but also the winding portion inside the slot, providing an efficient axial heat transfer path for the motors. The available space for the cooling of end winding is larger than that within the slot. Therefore, more efficient liquid cooling methods are possible, like spray cooling, splash cooling and even thermoelectric cooling [180]. However, despite that end winding cooling seems to be a very impressive cooling method to cool the armature conductors it has the main drawback when applied to large length/diameter motor cooling, in which cases the cooling performance for the middle part may not be enough. Another axial cooling method may also be needed in this scenario [181]. Furthermore, due to the annulus shape of the end winding, good temperature uniformity is not easily achieved by simple manifolds, while complex manifold structures will decrease the reliability of the cooling loop to some extent.

4.3 Rotor cooling

The rotor is often characterized by a poor thermal path to the stator cooling medium. With the increase of electric motor energy density, the cooling of the rotor is drawing attention. In an induction motor, the temperature of the rotor may be at the same level as or even higher level than the stator winding [182]. The implementation of rotor cooling methods is needed to ascertain that the rotor operates in a safe temperature range. This section will focus on new technologies which provide improved rotor cooling.

Generally, the modern rotor cooling techniques are based on hollow shafts, through which the coolant path is provided. Refaie et al [143] proposed a rotor cooling strategy for an interior permanent magnet motor, as shown in Fig. 11 (a). The oil was introduced to the hollow shaft by the stationary tube and then flowed into the annulus formed in the hollow shaft. After optimization, it was reported that the heat transfer coefficient achieved ranged from 800 $W/(m^2 \cdot K)$ to 2900 $W/(m^2 \cdot K)$ corresponding to different rotor speeds. Chuan et al [183] investigated another rotor liquid cooling for a permanent motor. It was concluded that the rotor liquid cooling considerably decreased the temperature of the magnets. A CFD model was developed by Gai et al [184] to study the influence of shaft cooling on the performance of motors. The liquid was introduced to the shaft by holes. It was suggested that the rotation of the rotor significantly increased the convection heat transfer of the liquid. The temperatures of the rotor were decreased by 15 ℃ and 50 ℃ when the shaft speeds were 3000 rpm and 10000 rpm, respectively.

The coolant is not necessary a liquid, and even by air, the cooling performance is also very remarkable. Jaeger et al [185] developed a fin-structure air cooling method to cool the rotor with a hollow shaft, as shown in Fig. 11 (b). In this arrangement air intake and discharge are on the same side. With the rotor cooling, the temperature of the magnet was decreased by 40 °C when the rotor speed was 10000 rpm. In this scenario, the output torque was increased by about 50%. Wu et al [144] used air flow to cool the rotor with a hollow rotor structure. It was presented that the hot spots of temperature moved to the external surface of the shaft while the temperature dropped from 80.1 °C to 70.53 °C at the studied load. In addition, the oil immersion was also tested to cool the rotor. Ponomarev et al [186] concluded that with the oil immersion cooling, the highest temperature was in the middle of the slot winding, and all the components operated well within the safety temperature range.



(a) (b)

Fig. 11 the hollow shaft cooled by different medium (a) oil [143] (b) air [185]

Despite that the importance of rotor cooling has been recognized, the options for the rotor cooling are still very limited. Their performances, characteristics, and following optimizations are yet extensively studied. More related research in the future will help to address the rotor temperature better.

4.4 Heat conduction enhancement

In a typical motor, the axial thermal conductivity of the stator lamination is very small, and it behaves as a thermal barrier for axial heat transfer. Meanwhile, the contact thermal resistances caused by small air gaps and surface roughness between different solid components are not negligible. From this point of view, the methods of increasing heat conduction are also very important to relocate the heat and accelerate the heat transfer process.

4.4.1 Potting materials

Some potting materials are available to enhance the heat conduction process. They are used to fill in the air pockets between the solid components. Sun et al [187] tested the potting material as a heat transfer bridge between the end winding and casing. It was suggested that the temperature was lowered by 23.6% with the application of the potting material. Furthermore, it was capable to significantly slow down the temperature increase of the motor. Yao et al [188] concluded that the temperature of the end winding was decreased by 20.27 ℃ with the potting materials. Polikarvopa et al [111] investigated the influence of potting materials for the end winding, and it was found that the temperatures of the end winding and rotor decreased by 7 ℃ and 6 ℃, respectively. Polikarpova et al [189] also used the potting material to connect the water-cooled frame and the end winding, with a 10% temperature drop reported. Similar to the investigations with the potting material, the impact of thermal paste was also validated by Kulan et al [190, 191], who observed a clear temperature drop with the paste at the end region. All of the aforementioned studies suggested the positive effect of potting materials.

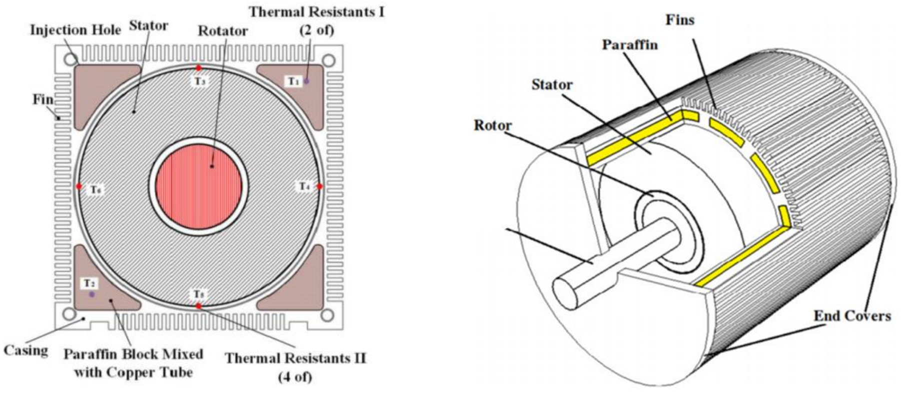
4.4.2 Heat guide plates

Heat guide plates are also used to provide an extra heat transfer path to dissipate the heat. They are mostly used in slot winding. Michael et al [67] placed a heat path into the slot to enhance the heat transfer among the slot conductors. An approximately 40% reduction of temperature was reported for the hot-spot temperature.

Wrobel et al [107] performed a study to improve heat extraction from the winding with heat guides (HGs) integrated into the slot. It was shown that the temperature rise of winding was reduced by approximate 30% with laminated HG, and two-thirds of improvement associated with the heat transfer enhancement in the radial direction. Further experimental testing verified the results very well. Xu et al [192] used a T-type copper plate to enhance the heat transfer in the slot. Its effect was further confirmed by CFD analysis. Apart from the presented heat guides, the back-iron can also be used to play its role. Zhang et al [112] presented research to extend back-iron to the slot along the centerline. This novel method provided a significant winding temperature drop of 26.7% after optimization and was verified experimentally.

4.4.3 Phase-change materials (PCMs)

Due to excellent thermal storage characteristics, phase change materials are another alternative solution for thermal management of motors. Wang et al [193] applied PCMs in the motor, with the position of the PCMs is illustrated in Fig. 12 (a). It was revealed that in the constant heating condition, the use of PCM increased the operating time by up to 50%. For the case of the intermittent heating condition, the use of the material reduced the peak temperature of the casing by 12.8%. Wang et al [194] designed a hollow casing with some cavities to store phase change materials. The performance was investigated with different types of paraffin under various operating conditions. It was found that the temperature control of the casing temperature can be achievable with different melting temperatures and re-solidification time. The same research team also proposed another structure, as illustrated in Fig. 12 (b) [195]. The continuous operating time prolonged and the peak temperature was decreased by about 32.7% and 7.82 ℃ in the tested condition, respectively. Bellettre et al [196] implemented several PCMs to test the cooling of an induction motor. It was suggested that the liquid-phase thermal conductivity had a greater influence on reducing end winding temperature and latent heat storage compared to the solid-phase conductivity. Furthermore, the sensitivity analysis showed that the temperature decrease with the increase of thermal conductivity, melting latent heat and decreasing of melting temperature. The PCMs can also be placed in hollow conductors, as reported by Ayat et al [197]. The decreasing of the temperature was observed with the PCMs. The incorporating of PCMs led to 8% and 18% reduction in temperature rise of winding and winding weight, respectively. All of this research indicated a good prospect of PCMs in motor thermal management.

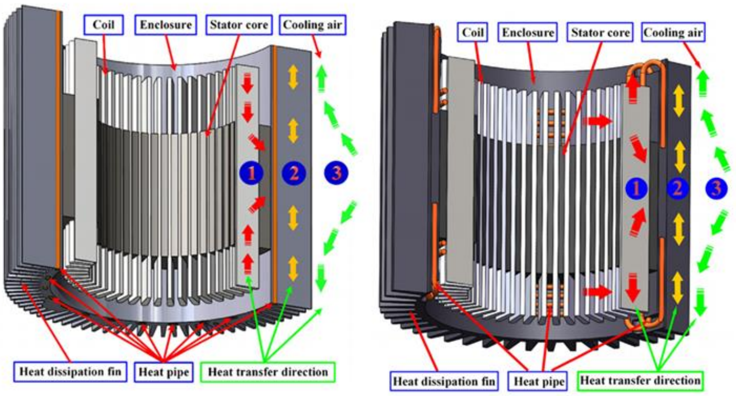


(a) (b)

Fig.12 the utilization of PCMs (a) [193] (b) [195]

4.4.4 Heat pipes

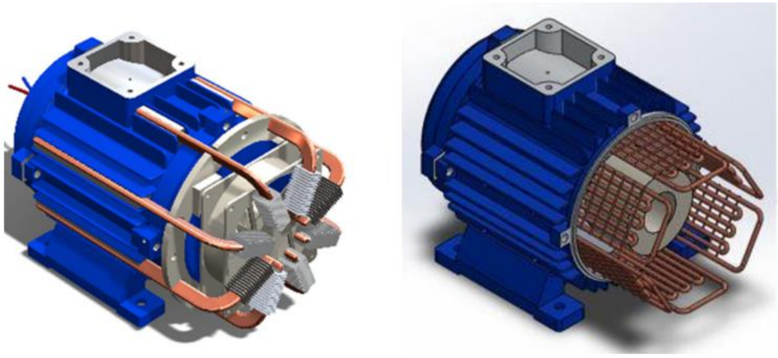
Heat pipes are well-known heat transfer devices of high thermal conductivity. They have been used by researchers to enhance the heat conduction between components in the motor. Groll et al [198] reported a pioneering design that used 28 heat pipes in the rotor and 36 heat pipes in the stator. It was revealed that with the heat pipes, the peak temperature was reduced by 60 °C. The pipes dissipated about 75% of the generated heat. The results proved that the heat pipe could be a good choice for thermal management of motors. Fang et al [199] developed two interesting enclosure structures with heat pipes for a motor, and the structures were presented in Fig. 13(a) and (b). It was found that the new structures successfully decreased the temperature gradients in the enclosure and the stator. The effective time for temperature control was also prolonged with the new structures by up to 21.4%.



(a) (b)

Fig. 13 two different enclosure structures with heat pipes [199] (a) straightly embedded heat pipe; (b) 3D rounding heat pipe

Nandy et al [200] experimentally investigated the temperature of an electric motor with eight L-type sintered heat pipes, as shown in Fig. 14(a). It was found that the surface temperature of the motor was significantly decreased from 102.2 °C to 68.4 °C. Pulsating heat pipe was also used by Aprianingsih et al [201] to cool an electric motor, and the structure is presented in Fig. 14(b). Acetone was used as the working fluid with a filling ratio of 0.5. The experimental results indicated that with the use of the pulsating heat pipe, the temperatures of inner and outer surface were decreased by 81.35 °C and 84.05 °C, respectively.



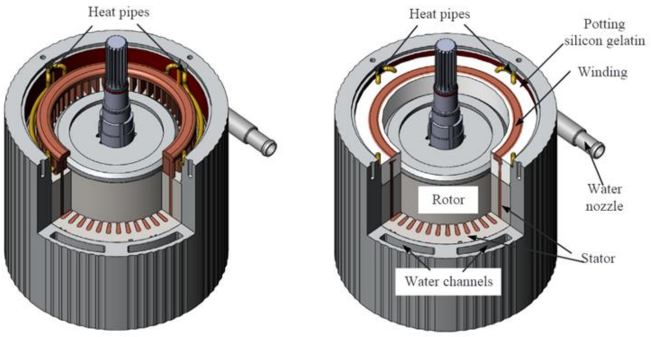
(a) (b)

Fig. 14 heat pipes used in motors (a) [200]; (b) [201]

In summary, the application of potting materials, heat pipes, PCMs, and heat guides extend choices for thermal management of motors. Their existence greatly enhances the heat conduction between the components. Furthermore, they also contribute to alleviating the temperature variations of the motors. Considering some theoretical models are available to analyze the temperature of the motor with them, they have a great prospect in thermal management of motors. Nevertheless, the using of the heat pipe, heat guides may cause magnetic problems and additional eddy losses within which should be carefully calculated and considered.

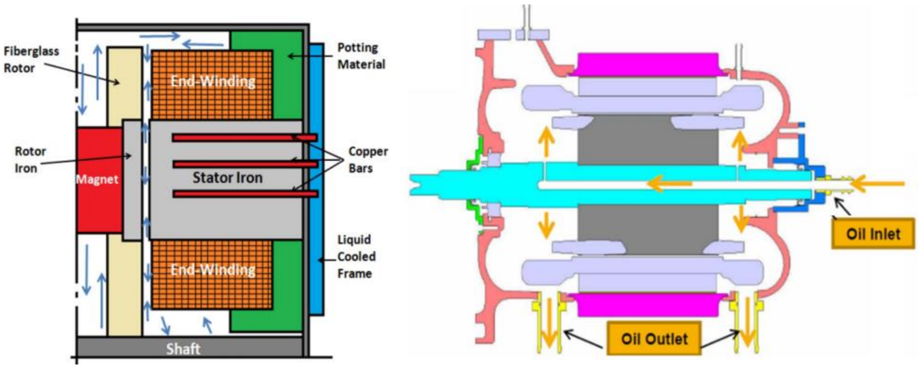
4.5 hybrid thermal management

Despite the above-mentioned thermal management technologies have already provided plausible methods to meet the temperature requirements of different electric motors, their combination may be needed in some extreme conditions. The simplest hybrid cooling involves both the water jacket cooling and forced air cooling [55], in which both the water jacket and air cooling contributed to the motor cooling. Some methods combining heat conduction enhancement with cooling were also explored. Apart from water jacket cooling, Sun et al [202] combined the potting material and heat pipes in the end region of the motor, as shown in Fig. 15. With both the presence of potting material and heat pipe, the temperature decreased by 22.9 ℃. Furthermore, the temperature of the casing was more uniform. Huang et al [203] developed a novel hybrid thermal management system with heat pipes, fan and water jacket. The results indicated that the new cooling system well satisfied the cooling requirement and greatly decreased energy consumption. Polikarpova et al [204] proposed another hybrid thermal management method for a motor. The cooling structure is illustrated in Fig. 16 (a). The method consisted of water jacket in the housing, copper bars in the teeth and potting material around the end winding. It was concluded that the system outperformed the water jacket cooling, and the slot winding temperature was reduced by 20 ℃ and (25~35) ℃ in the case of copper bars and copper bars/potting material. It was also suggested the number of copper bars had an apparent influence on motor efficiency [205].



(a) (b)

Fig. 15 the heat pipe and potting material hybrid thermal management [202] (a) heat pipe; (b) heat pipe and potting material



(a) (b)

Fig. 16 The hybrid cooling for the motors (a) [204] (b) [206]

Regarding a higher level of thermal management integration, rotor cooling is also actively involved [207]. Park et al [208] tested a hybrid cooling system for a motor. The oil was introduced to the hollow shaft by an oil pump and was sprayed to the winding, bearing, gear, and stator through the designed channels in the cooling channels. The results confirmed the excellent cooling ability of oil spray from the rotor, with a maximum temperature decrease of 24.95%, 11.63%, 15.76% comparing with stagnant, circulating and simple channel cooling, respectively. Assaad et al [206] developed a cooling structure that introduced the oil to the hollow shaft, and through the holes at the surface of the shaft to achieve the oil projection on stator, end winding and end rings, as shown in Fig. 16 (b). It was found that continuous power significantly increased from 19 kW to 37 kW. Another hybrid method was developed by Lim et al [209] with an oil spray cooling system to cool the rotor, bearing, stator winding and gearbox for an in-wheel motor. The structure is given in Fig. 17 (a). The temperatures of the motor of different parts were well within the safety range. It was also presented that oil spray cooling in this manner provided better cooling capacity and more uniform temperature distribution for the motor. Lee et al [210] developed a coolant flow path included the upper housing, housing jacket, lower housing and hollow shaft, as shown in Fig. 17(b). The new cooling structure provided excellent cooling performance with a 50% and 38% decrease of the winding temperature when compared with the air cooling and water jacket cooling, respectively.

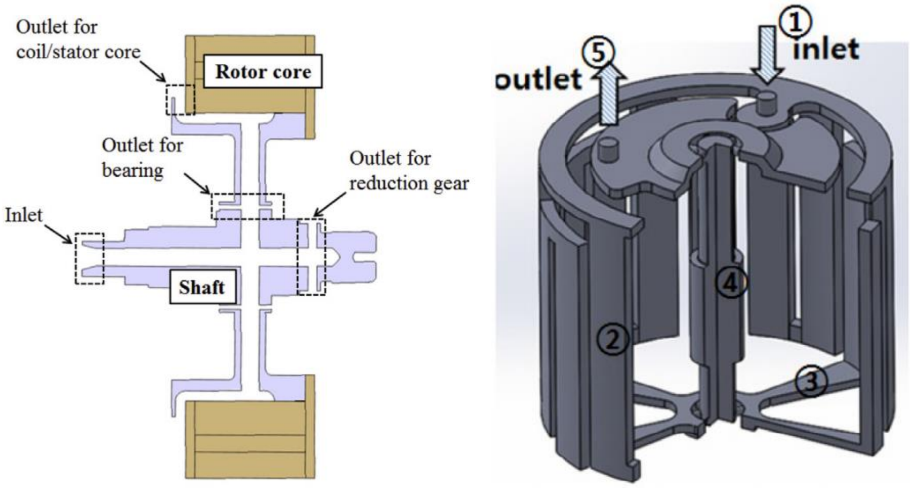


Fig. 17 hybrid cooling structures (a) [209] (b) [210]

The hybrid thermal management is expected to be more efficient than single cooling methods. It can satisfactorily address the different cooling requirements of the winding, iron, and even the mechanical components of the motor. Nevertheless, the system is also very intricate, and the flow path of the coolant is subject to elaborate designs. For cool paths with small holes, it is very sensitive to the impurity in the coolant, which should be avoided. Meanwhile, the hybrid system also increases the cost and decreases the reliability of the motors. A good cooling system will be a balance among the cooling efficiency, cost and reliability.

5. Conclusions and future challenges

In this paper, the latest thermal management technologies for electric motors are comprehensively reviewed. Generally, the theoretical models provide reliable and economical ways to analyze the temperature distribution, while the experimental investigations validate many thermal management technologies. The air convection cooling (including natural convection, forced cooling and air impingement cooling) and liquid cooling (including jacket cooling with water, oil, glycol, spray cooling, immersion cooling, jet impingement cooling) have been investigated and optimized to cool the motor with various temperature requirements, as shown in Fig. 18. In addition, some methods to enhance the heat conduction between the solid domains by the thermal paste, potting materials, heat pipes and heat guides were also presented. The main conclusions of this paper are:

- The numerical models and lumped parameter thermal network (LPTN) models have been used to predict the temperature distribution of the motors. Numerical models are generally able to provide accurate results and easily integrated with multi-physical simulation. The LPTN models deliver fast results and the accuracy is highly influenced by the modeling of the contact thermal resistance between solid interfaces, heat transfer correlations for end space, and equivalent thermal properties (especially the thermal conductivity and thermal capacity) of winding. Furthermore, the evaluation of heat transfer area of end winding is also very important. The concentric shape-model and porous media model are expected as initial approximation.
- For typical motors used in electric cars, like induction motor and permanent motor, most heat generates in

the winding either in the stator or the rotor. Therefore, the cooling of the winding is of most importance, and indirect cooling and direct cooling methods are available. Basically, current thermal management technologies address well for the cooling of motors from low to high heat density. For low heat density motors (< ~7 A/mm^2), air cooling is desirable, including natural cooling and forced air cooling with a fan. For the motor with medium-high heat density (~12 A/mm^2), liquid cooling is more advisable to cool the motor. The jacket cooling with water, water/glycol, slot and end winding cooling (immersion cooling, convection cooling, jet and spray) are among effective choices. Besides, the heat pipe, paste, PCM, and potting material can also be used to enhance the heat conduction among different components. For motors with even higher heat density (> 15 A/mm^2), hybrid cooling technologies are recommended. For induction motors, the consideration of rotor cooling is strongly recommended.

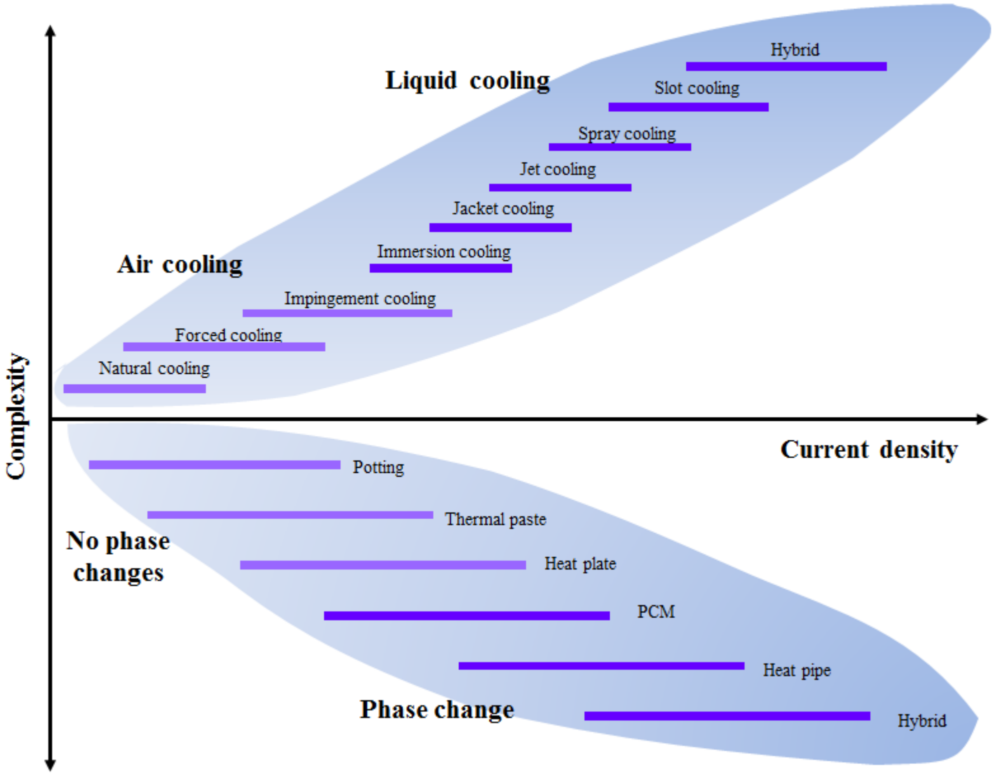


Fig. 18 Overall estimates on thermal management technologies for electric motors.

Nevertheless, even with these outstanding thermal management technologies presented above, there are still some issues. The following bullets highlight future challenges that need to be further addressed.

- For theoretical models of the motors, some key issues, like equivalent thermal conductivity of winding, convection heat transfer in the air gap and end space and contact thermal resistance should be thoroughly addressed as they are closely related to the accuracy of the models. Both theoretical modeling and extensive experimental validations in various conditions are still needed.
- The hybrid thermal management solutions are desirable for a higher heat density, but also increase the complexity and decrease the reliability of motors, as well as the economic and control cost. General evaluation models covering cooling performance, economy and reliability will surely benefit the decision-making process. Furthermore, advanced control, safety evaluation and diagnostic models are also needed.
- Despite cooling methods play a very important role, the optimization of electric motors involves many disciplines. Some improvement in thermal management may not coincide with mechanical and electromagnetic considerations. A multi-physical analysis is thus essential to evaluate the overall effectiveness of thermal management technologies.
- In actual automotive drivelines, the motor is highly integrated with the inverter and even the gearbox. The cooling loop dissipates the heat of the whole systems. Furthermore, in electric cars, there is integration even with the battery cooling system and HVAC system. In this practical scenario, thermal management is a more complex system-level issue. More integration research and exploration will be very helpful.

The paper hopes to provide valuable information and to inspire more remarkable innovative electrical motor thermal management concepts in the future.

Declare of Interest

None

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