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

Wang, X.[1], Li, B.[1], Gerada, D.[2], Huang, K.[1], Stone, I.[3], Worrall, S.[3], Yan, Y. [1*]

[1] Fluids and Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, UK

[2] Power Electronics and Machine Research Group, Faculty of Engineering, University of Nottingham, UK

[3] GKN Innovation Centre, Abingdon, Oxford

Abstract:

The development of electric cars has well been regarded as a major solution for tackling the challenges of carbon-neutrality faced by the modern communities. Electric motor is certainly the core and most important components of an electric car, and the thermal management for electric motors has drawn increasing attention from both industry and academic society. This is because electric motors in modern electric cars are required to be more powerful and competitive with higher torque, higher speed and higher power density, therefore the efficient thermal management has become essential to maintain the motors efficiency, durability and safety. The failure of thermal management will result in demagnetization of magnets, aging of the insulation materials, decrease of efficiency, shorter lifetime and even burnout of motors. To enlighten the future research, 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,

* Corresponding author: Prof. Yuying Yan, E-mail: Yuying.Yan@nottingham.ac.uk.

some suggestions are given for future possible research and applications. The paper is expected to be a good reference and inspiration for the development of new thermal management concepts of electric motors.

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 a carbon-neutrality society by reducing the carbon emission have drawn wide attention from all over the world, as the climate change and global warming are emerging as big threats [1]. Against this background, the transportation sector, which consumes a great amount of primary energy, is undergoing a significantly important updating through electrifications [2, 3]. It is reported that with the development of electric vehicles, greenhouse gas emissions can be reduced by 20% and by a further 40% if the electricity is produced by renewable energy [4]. Some remarkable policies and initiatives have been proposed by many countries and organizations, especially in Asia-Pacific regions [5, 6]. Therefore, the market share of electric vehicles is growing sharply. According to predictions, 35% of global new cars for sale by 2040 [7] will be electrified. For the sake of saving energy and achieving a carbon-neural society, motor-drive systems are drawing much attention from academic, engineering, and investment communities [8]. To increase the market proliferation of electric vehicles, electric motors need to be more powerful and provide higher power densities, higher torque densities, and higher speeds [9-11]. In general, as motors are designed to be higher power densities, the loss-density in motors will increase rapidly, which makes the thermal management to be more challenging, and become the main factor of limitation for the performance metrics. Therefore, advanced thermal management technologies has become very necessary and essential.

High speed motors for electric cars are complex thermal systems [12, 13]. The components are made of different materials, and these materials have different optimal range of operating temperatures and temperature limits for safety. As the heat sources are distributed in different components, various mechanisms may have to be applied [14]. The heat inside of the motor is transferred by heat conduction, convection, and radiation in a very compact space. Heat conduction occurs between the housing and stator, winding and stator, and housing and end plate, as well as shaft and bearings, etc. The convective heat transfer involves airflow or other liquid coolants and solid components, which usually includes both laminar flow and turbulent flow. The failure of thermal management for electric motors can cause a series of problems. For example, the temperature higher than an expected value will cause excessive thermal stress in solid components; and the excessive stress may cause the deformation of the components, leading to the failure of assembly of them. Such unexpected high temperature will often result in problems of insulation as the change of thermal conductivities of the insulation materials. Thus, under higher temperature loads, the insulation lifespan will be significantly decreased, also accelerate aging of the materials. According to a recent study, the life span of the commonly used insulation materials will be halved if the temperature increases to an additional 10 ℃ [15]. The temperature limitation of the insulation materials greatly limits the current density of winding and the output power of the motor [16]. The failure of insulation materials may also cause an electric short circuit and lead to catastrophic burnout of components. Permanent magnet motors are currently predominantly used in electric cars. The magnet contains rare-earth elements and is very sensitive to temperature rise. The overheating of the motor will also cause irreversible demagnetization of the magnets [17, 18]. The technology for designing and developing high-efficient heat dissipations from the components of electric motors (e-motors) has become very crucial [19].

To date key investigations in both theoretical modeling and experimental validations of developing thermal management technologies for high speed electric car motors are reported. The theoretical modeling mainly refers to numerical analysis methods [20, 21] and lumped parameter thermal network (LPTN) methods [22]. Numerical analysis can provide more detailed information about heat flux, temperature and pressure distributions in e-motor domain under given conditions, and the lumped parameter thermal network method is able to conduct a quick prediction of temperatures on thermal nodes with relatively lower accuracy. Both numerical analysis and lumped parameter thermal network (LPTN) methods can be carried out under steady-state and transient-state conditions [23]. Some general key factors in theoretical modeling, such as equivalent thermal conductivity between winding and stator, air heat transfer coefficient at end space, contact thermal resistance, can directly identify the characteristics of models; and this has been extensively addressed. Meanwhile, various thermal management technologies are proposed to address the cooling of e-motors with different heat density requirements. The heat transfer performances of air cooling (including natural air convection, forced air convection, air impingement cooling) and liquid cooling (including jacket cooling using different liquid coolants, spray cooling, jet impingement cooling, etc.) were comprehensively studied for the purpose of cooling the stator, winding and rotor. In addition to the cooling methods by fluids mentioned above, the enhancement of heat conduction between solid components has also been studied and reported. Such prospective methods include, but not limited to, thermal paste, potting materials, heat guides, PCMs and heat pipes. To pursue better cooling effects, some combinations of these methods have been proposed and validated by experimental studies, as will be presented in the following section.

Several review papers have provided important assessment on thermal management technologies and given valuable suggestions for future studies. In 2015, Shazly et al [12] reviewed the works on thermal modeling of axial-flux permanent-magnet synchronous motors. The numerical schemes, such as LPTN, finite element (FE) and computational fluid dynamics (CFD) applied to e-motors were thoroughly examined. Gai et al [24] reviewed a few investigations on traction e-motor cooling, which covers both theoretical modeling and experimental testing; and some commercial applications 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. With the popularity of electric vehicles, thermal management of e-motors used in this scenario has drawn wide and increasing attentions. The e-motors used for electric vehicles have specific profile of performance, assembly requirements, and technical challenges. The evaluation of current thermal management technologies and discussions of further research have become ever important and critical. However, there are still no exclusive state-of-the-art assessments available.

In this paper, a comprehensive review of the latest development of thermal management technologies for e-motors used for electric cars are presented. The review covers recent research progress in not only theoretical modelling but also experimental testing. Although the cooling strategies discussed in this paper are for e-motors under certain operating conditions, the cooling effect and such strategies are also useful for other motors. The paper is expected to be a valuable reference for future research and boosting the application of electric vehicles.

2. Heat generation of motors in electric cars

For thermal management, the first step is to identify the power losses of motors under given conditions. Most motors used in electric cars are alternating current induction motors, switched reluctance motors, and permanent magnet synchronous motors and they are with typical power range of (100~200) KW. They have different operating profiles and characteristics [26]. 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.

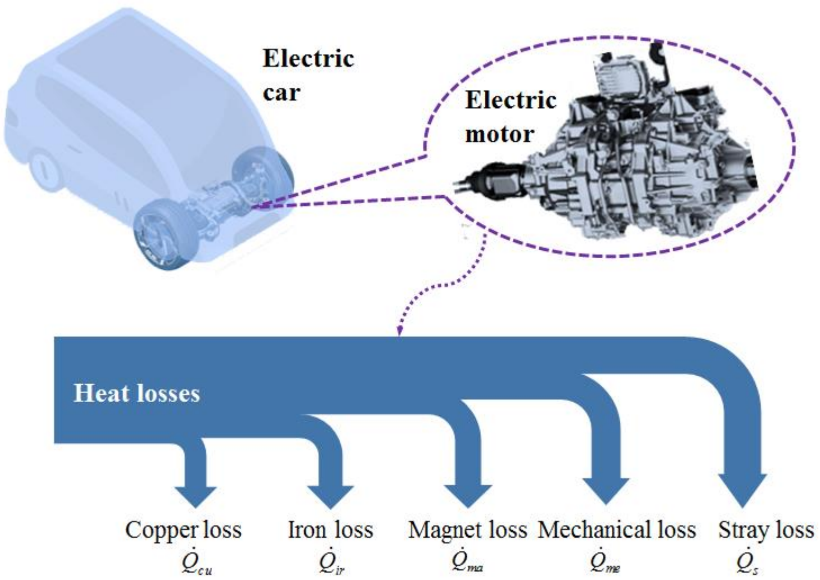


Fig. 1 various heat losses of electric motors

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 operating conditions, type of laminations and their dimensions. 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 occurs 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 copper conductor given same current. From this point of view, keeping the winding temperature at a lower level significantly benefits the decreasing of copper losses and increasing the motor efficiency.

- Mechanical losses

The mechanical losses are commonly caused by friction between different solid components, such as the rotor and bearings, shaft and end rings. It is highly dependent on the rotor speed, lubricant properties, 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 result from axial and tangential velocity of the air flow in the air gap. With the increase of the rotor speed, the windage loss becomes more and more significant. For a simple cylindrical geometry, the windage can be calculated by analytical or empirical correlations.

- Magnet Losses

Permanent Magnet motors 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 and 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 into stray no-load losses due to main flux variations and stray load losses due to leakage flux [34]. The stray losses are 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 with the on-site experimental thermal testing of electric motors, thermal modeling has proven to be a more economical way, and a more suitable way to combine electromagnetic and mechanical modeling for the optimization of motor. The commonly used thermal modeling methods are numerical models and lumped parameter thermal network (LPTN) models. In this section, the characteristics of the two methods will be highlighted and discussed.

3.1 Finite-element and computational fluid dynamics

The finite-element (FE) and computational fluid dynamics (CFD) are two main numerical models. Both 2D and 3D FE models 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, CFD method is required. The CFD has a widespread reputation for its excellent ability to analyze heat transfer performance over the natural/forced convection heat transfer, impingement heat transfer and spray heat transfer in various scenarios. The temperature, pressure, and flow fields can well be addressed and visualized by CFD models, making it gain popularity. Furthermore, CFD has also been used to optimize the parameters of the electric motors, especially for the geometric dimensions as indicated in literature [38, 39].

The FE and CFD are capable to provide very accurate simulation results for the heat transfer process even being used to analyze motors with complex structures. Another advantage of numerical analyses is that it can be easily combined with electro-magnetic-mechanical analytical models, making multi-physical analysis possible [40]. Nevertheless, the calculation time of numerical 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 heat transfer environments, 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 materials and heat transfer characteristics. When trying to simulate the transient temperature response, thermal capacitances of the nodes are also needed [42]. The heat generation in different components are commonly considered uniformly-distributed and in the center of the represented nodes [43, 44]. Given the operating conditions, the thermal network can be determined by solving the governing energy balance equations in steady and transient states, respectively [45]. Meanwhile, there are also 2D and 3D LPTN models. An LPTN model with more nodes is expected to have a better accuracy. Nevertheless, models with fewer nodes can also provide satisfactory results. A typical LPTN model is shown in Fig. 2.

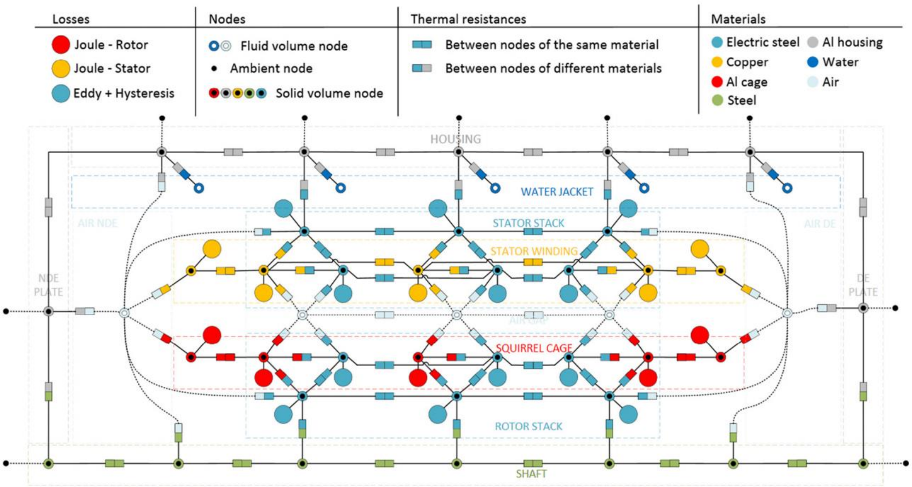


Fig. 2 A typical LPTN model for the electric motor [46]

LPTN is a proven efficient method to analyze the cooling performance of electric motors. Compared with the numerical methods presented before, the calculation of LPTN is by far faster as well as accurate. Therefore, LPTN models play an important role in parameter sensitivity analysis [47, 48], and LPTN models have remarkable flexibility for both steady-state and transient analyses. Investigations have revealed that even with very small number of thermal nodes, the LPTN can still 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 typical numerical and LPTN methods, a combination of CFD and LPTN is another possible method. The hybrid method is introduced to balance the accuracy and calculation resource 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 modeling option in the future. More such models are still on the way.

Both numerical and LPTN models efficiently support the design of electric motors as well as provide guidelines to optimize related parameters. Nevertheless, the design of the motor is a multi-physical process, in which many disciplines are involved. Currently, 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 practical scenarios [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 certain tested motors as these correlations are case-sensitive [56]. Another aspect is the evaluation of component thermal properties, especially for 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 evaluation of anisotropic thermal conductivity of winding is of great importance to build accurate models [57]. In addition, attention should also be paid to the influence of components deformation, uneven distribution of heat and the radiation heat transfer as they are also essential in some cases [58, 59].

3.3 Key challenges and solutions for modeling

To achieve a successful thermal modeling, there are some key aspects need to be carefully addressed for both LPTN and numerical analyses. As above-mentioned, most heat in the motor is dissipated through heat conduction and convection heat transfer of liquid. For heat conduction, accurate models to calculate the thermal transport properties 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 interests [61, 62]. They are main factors that greatly influence the accuracy of models built.

3.3.1 Equivalent thermal conductivity (ETC) of winding

The heat transfer between the slot winding and iron core is very complex and poses a great challenges. In a fairly limited space, there are hundreds of conductors, insulation materials, residual air, and impregnation, and they are all randomly distributed spatially [63, 64]. It is very difficult to simulate the heat conduction of each conductor and this is also not necessary in most cases. A more practical way to obtain the ETC of winding for thermal modeling [65].

The area-weighted method has proven an effective way to obtain theETC of winding [66, 67]. The methods predict the ETC by the area ratio of conductors, air and insulation materials [68]. Based on experimental results, Boglietti et al [69] concluded that the ETC of winding could be regressed by the following simple correlation,

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

Similarly, Tang et al [70] 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 [71] proposed another thermodynamic model to predict the ETC of winding by,

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

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 predicted 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 are expected to benefit the accuracy of modeling. Nategh et al [73] proposed a multi-layer elliptical cylinder model to predict the ETC of the winding. The thermal conductivity of the winding was evaluated by analyzing the heat conduction of each layer. The overall thermal resistance was finally given as,

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

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

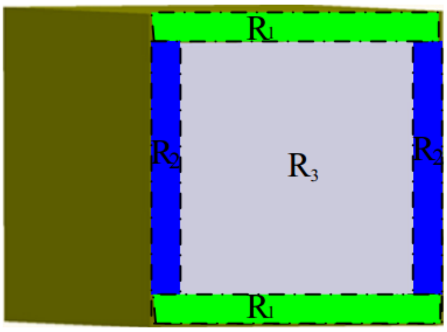


Fig. 3 Porous metal model for equivalent thermal conductivity of winding [74]

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

Some more methods to estimate the ETC of winding are listed in Table. 1. Generally, for typical winding layout, the area-weighted evaluation method is expected to provide reasonable results and of good accuarcy. Nevertheless, the evaluation of area ratios of each componments (air, winding, impingation, and insulation material) in the domain needs carefully attention. As for some special winding configurations, the analytical models (multi-layer model, etc.) is recommended.

3.3.2 Air gap heat transfer

The heat transfer in the air gap is very important in thermal analysis, 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 descript as it is influenced by geometrical dimensions, rotor velocity, air properties, etc. Generally, for the small annulus area between the stator and 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 simultaosly or not. Taylor number and modified Taylor number are defined to characterize the flow in air gap and are given by [76, 77],

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

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

For the air flow with low Taylor number, the flow is laminar shear flow and the heat transfer process is predominantly dominated by 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 influence of axial flow should also be considered and 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 predict the air gap heat transfer under different conditions. More details of these correlations and their physical mechanisms are comprehensively reviewed [82, 83]. The correlations to evaluate the air gap heat transfer in the motors are further presented in Table. 1. The heat transfer correlations discussed can provide good accuracies for the heat transfer of the air gap. When the air flow in the gap is two-dimensional, the equations of (10, 11) are suggested.

3.3.3 Heat transfer in end space

Generally, the end winding heat transfer refers to the heat transfer process 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, especially for high-speed motors [84]. Furthermore, the end winding is usually the hottest spot of electric motors. As a result, the heat transfer in end space has drawn wide attention.

The heat transfer in the end space is very complex considering the intricate geometry of components and heat transfer mechanisms involved in such 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 on 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 geometry configuration of the end winding 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. Meanwhile, 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 directly introduced 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 end winding in end space is considered as a boundary condition with appropriate choice of heat transfer correlations. For the air near the shaft, the flow can be turbulent due to the fast rotation movement, while the air is almost stagnant near the housing and end-cap surface. With this concept, the heat transfer in end space is usually presented in two parts- contributions of natural convection and forced convection. To quantify the air flow near the end winding surface, 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 vary 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 heat transfer were determined by LPTN and CFD model, respectively. The following correlation was suggested,

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

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

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

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

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

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 between the winding and ambient air,

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

More presented correlations and evaluation methods are given in Table 1. For most cases, the heat transfer coefficient correlation presented can successfully address the heat transfer prediction of end space, and some of them have been validated or correlated by experimental data. The Nusselt correlations are based on heat transfer research, the prediction accuracy highly depends on the characteristic temperature and properties evaluated.

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. For example, the cavities in the end winding provided additional heat transfer paths and small variations of cavities 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 special attention should also be paid to the applicability of chosen correlations. Besides, evaluation of the heat transfer area of the end winding surface 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 in end space 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 in certain conditions. 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	$Nu = \begin{cases} 2, T_a \leq 41, \\ 0.212T_a^{0.63}Pr^{0.27}, 41 < T_a < 100 \\ 0.386T_a^{0.5}Pr^{0.27}, T_a > 100 \end{cases}$	$Nu = 0.153Re^{0.618}Pr^{0.33}$
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	$\lambda_{eq}=0.069\eta^{-2.9048}Re^{0.4614\ln(3.33361\eta)}$	$Nu_t=0.456Re_t^{0.6};\ \alpha_c=15+6.5\omega_r^{0.7}$ $Nu_r=1.67Re_t^{0.385};\ Nu_{rf}=0.456Re_{rf}^{0.6}$
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	$Nu=\begin{cases}2, T_a\le 41,\\ 0.212T_a^{0.63}Pr^{0.27}, 41<T_a<100\\ 0.386T_a^{0.5}Pr^{0.27}, T_a>100\end{cases}$	$h=k_1(1+k_2u_r^{k_3})$
Li et al [105]		$Nu=0.023Re^{0.8}Pr^{0.4}c_l$	$Nu=0.15Re^{0.8}-100(r_c/r_r)^2$	
Nategh et al [106]		$Nu=7.49-17.02\frac{h}{w}+22.43(\frac{h}{w})^2-9.94(\frac{h}{w})^3+\frac{0.065RePrd_h/l_{ch}}{1+0.04(RePrd_h/l_{ch})^{2/3}}$	$Nu=0.409T_a^{0.241}-137T_a^{-0.75}$	$Nu=0.664Re^{0.5}Pr^{1/3}$
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]	$\lambda_{eq} = \sum_{i=1}^{n} \delta_i / \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i}$	$Nu = 0.012(Re^{0.87} - 280)Pr^{0.4} [1 + (\frac{d_e}{L})^{0.67}](\frac{Pr_f}{Pr_s})^{0.11}, \ Re > 2300$ $Nu = 7.49 - 17.02\frac{h}{w} + 22.43(\frac{h}{w})^2 - 9.94(\frac{h}{w})^3 + \frac{0.065RePrd_h / l_{ch}}{1 + 0.04(RePrd_h / l_{ch})^{2/3}}, Re < 2300$	$\lambda_{eq} = 0.069\eta^{-2.9048} Re^{0.4614\ln(3.33361\eta)}$	$Nu_t = 0.456Re_t^{0.6}; \ h_c = 15 + 6.5\omega_r^{0.7}$ $Nu_r = 1.67Re_t^{0.385}; \ Nu_{rf} = 0.456Re_{rf}^{0.6}$
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	$Nu = 0.386T_a^{0.5}Pr^{0.27}$	$h = k_1(1 + k_2 u_r^{k_3})$
Staton et al [79]		$Nu = 7.49 - 17.02\frac{h}{w} + 22.43(\frac{h}{w})^2 - 9.94(\frac{h}{w})^3 + \frac{0.065RePrd_h / l_{ch}}{1 + 0.04(RePrd_h / l_{ch})^{2/3}}, Re < 2300$ $Nu = \frac{(f/8)(Re - 1000)Pr)}{1 + 12.7(f/8)^{0.5}(Pr^{2/3} - 1)}, Re > 2300$	$Nu = 0.386T_a^{0.5}Pr^{0.27}$	$h = k_1(1 + k_2 u_r^{k_3})$

4. Thermal management technics for electric motors

The thermal management of motors should be considered at the very beginning of the motor design, as the motor size, power, and efficiency are directly linked to the heat dissipation capability. The current thermal management concepts available are generalized in Fig. 4. Broadly they can be divided into convection cooling and heat conduction enhancement. For the convection cooling, the air cooling (natural convection, forced convection, jet impingement) and liquid cooling (jacket cooling, immersion cooling, spray cooling, jet cooling, etc.) for the stator, winding, and rotor are available to meet the cooling 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 of these individual methods proposed to tackle extreme conditions. All the technologies will be presented and discussed in details in this section.

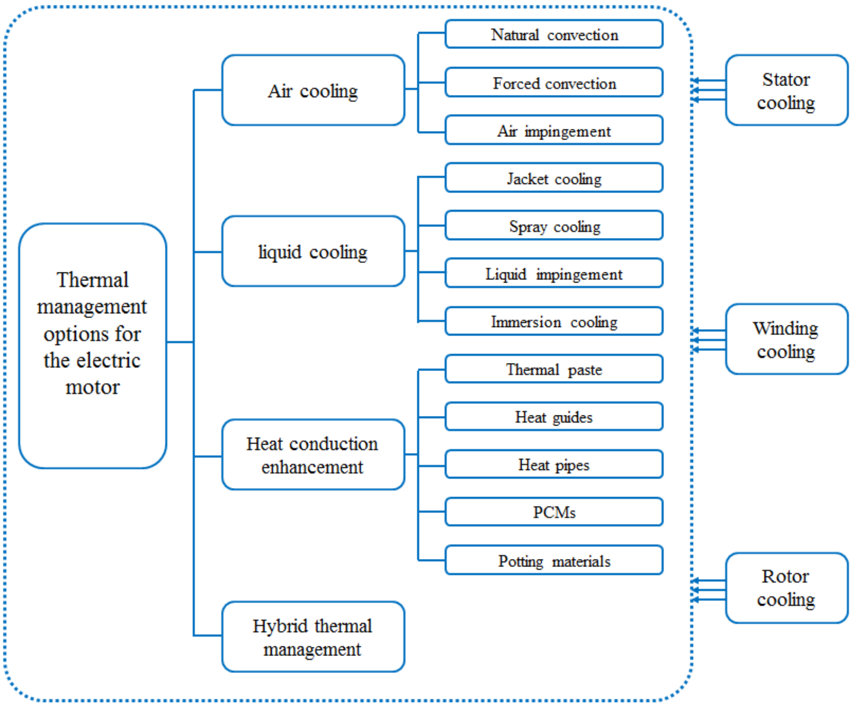


Fig. 4 thermal management options for electric motors

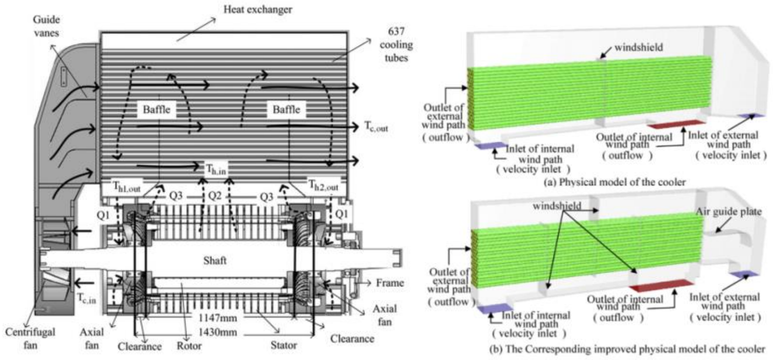
4.1 Stator cooling

4.1.1 Air cooling

Air cooling is a basic cooling method for motors. It is commonly implemented 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 rate between the housing and ambient air. The existence of these fin structures efficiently extends the heat transfer area of the outer surface of the housing [114]. How to maximize the cooling effect by optimization the fin geometric dimensions is the most important consideration in this regards. 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. Meanwhile, better heat dissipation performances were obtained by increasing the average and total hydraulic diameters. Kuria et al [116, 117] indicated up to 15% decrease of end winding temperature was achieved by optimizing the casing height and width. It was also presented that the orientation of fin presented no significant effects on the end winding temperature. Chen et al [118] developed a model to simulate the cooling performance of a 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 had a more significant influence on the temperature of winding, despite that the temperature of winding also decreased with the fin pitch ratio, fin thickness and 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 arranged. 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 effects.

For air-cooled motors, the air flow and heat transfer inside of the motor are more critical. The internal air flow in compact space 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. Generally, centrifugal, axial and piezoelectric fans have been used or tested for motors cooling [123, 124]. The selection and optimization of the fans' structure are important factors to enhance the cooling effect, as indicated by the contribution of Chen et al [125], Nakahama et al [39], and Kim et al [126]. Meanwhile, both the interior air path geometries and fan parameters have 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, and the structure was 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 through 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 also optimized, in which scenario 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 a fan cover, frame and end shield by adopting an air-guide plate, a 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 enhanced with the existence of extra cooling ducts in the stator and the teeth, despite at the cost of increasing iron loss to some extent.



(a) (b)

Fig. 5 the flow paths 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 flow. Nevertheless, the increase of the fin geometries will also increase the volume and weight of the motor, which may lead to other problems, such as difficulties of motor integration and assembly 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 and increase the air flow velocity. 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 process. 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 power 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 in jacket [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 introduce 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 positions 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 of 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 good performance of the proposed water jacket configuration. Pechanek et al [142] studied the cooling performances of 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 requirement of heat transfer coefficient and pressure drop were balanced by the optimization of channel shape, locations and numbers. Satrustegui et al [46] analyzed different designs of water jackets, as shown in Fig. 6. It was suggested that the axial water jacket presented a higher pressure drop than spiral water jacket given the same heat transfer area. Based on studied results, three design criteria were further presented to meet the requirements of turbulent flow, pressure drop and erosion. Wu et al [144] designed and studied the performance of 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 increased. Meanwhile, it was also indicated that the twisted channel water jacket 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 larger 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 exactly 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 impacts on the cooling 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 an electric motor. It was suggested that the cooling performance of the motor was better with smaller height and width of the channel but at the cost of higher pressure drop.

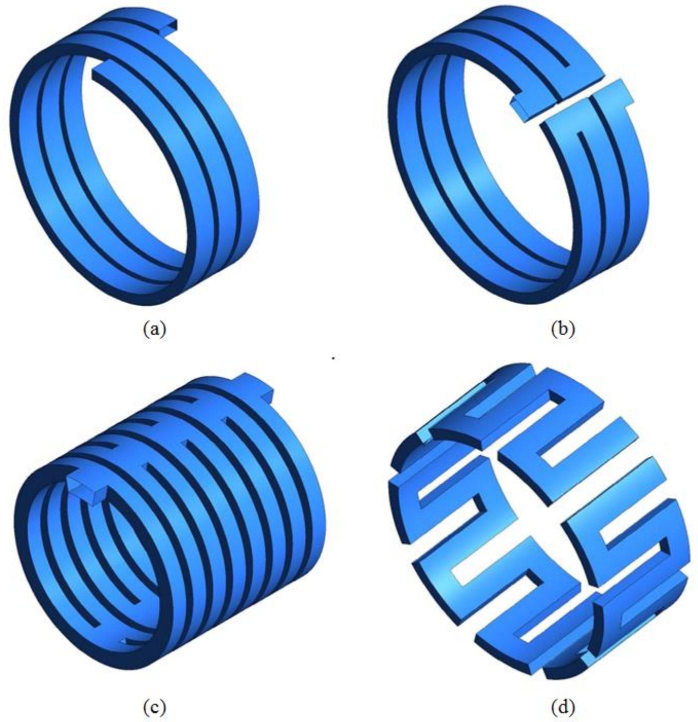


Fig. 6 different configurations of water jacket [46] (a) spiral; (b) U-shaped; (c) U-shaped (bifurcated); (d) axial

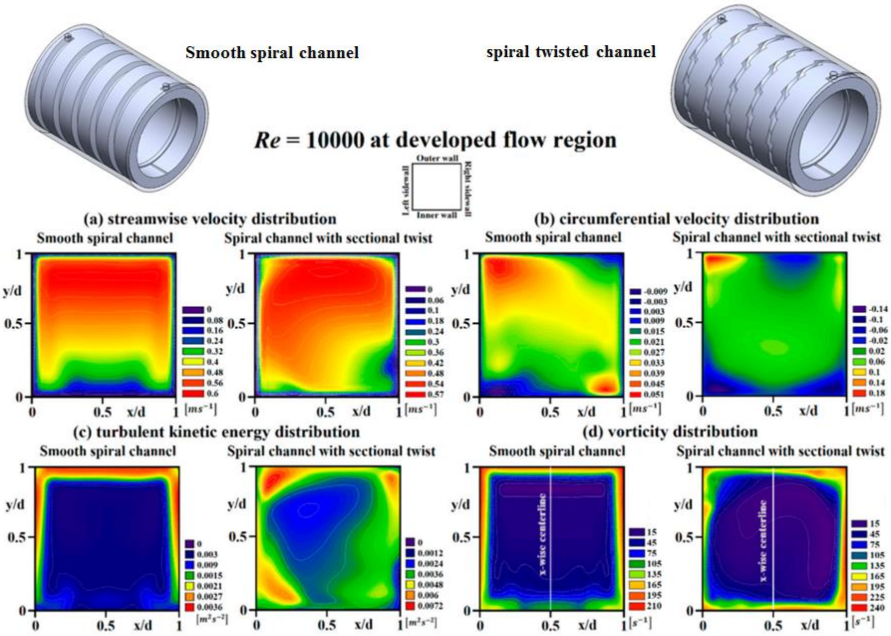


Fig.7 The structure of the water jacket channel [144]

To summarize, 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, covering higher heat density, low noise, and a totally separated system [142]. Generally, the cooling channels are located in the housing. Nevertheless, placing the channels located nearer the winding will surely benefit the temperature decrease [150], but may cause an increase of iron losses. The most common coolant is water, while the oil, water/glycol, and even dielectric fluid, thermomagnetic fluid have also been tested 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 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 are needed to consider 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 opertating at higher power densities, most heat is generated in the winding. As a result, direct cooling for the winding provides greater efficiency compared with the stator cooling [155] methods mentioned in the previous section. Based on the winding location, the winding is divided into slot winding and end winding. They have different heat transfer environments and different cooling technics are needed accordingly. The cooling methods of them 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 environment of the slot winding is the harshest because of 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 inside of 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 cooling method was tested with a permanent magnet motor, and the motor operated 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 with the indirectly cooling methods. 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 cooling 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.

Another efficient layout for cooling channels is at the top of the slot. Schiefer et al [161] developed a cooling structure. The fluids flowed through the serpentine cooling channels at the top of the motor slots. The results indicated the temperature of the slot winding significantly decreased from 223.5 °C to 85 °C. 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 °C 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 to maximize current density and corresponding 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 of the coolant, and there are no necessities 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 tested conditions. Chen et al [164] modeled and tested the slot direct cooling for a hollow conductor winding. The results indicated 86.8% heat of the conductor was dissipated by the forced convection in the channel. The modeling results were in good accordance with the experimental testing results. Other special-profiled windings have also been studied. Wohlers et al [165] tested two special types of winding. 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.

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 accordingly, and the pressure drop of the flow in small channels can be very considerable. The situation is even worse for the motor with many slots. The big pressure drop will increase the power and size of coolant feed pump. 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 to provide the same torqur output. 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 spot is usually in the end winding. Therefore, the cooling of the end winding is very important [88]. For the motor cooled by air or liquid coolant jacket, the end winding mainly dissipate 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 for the end-winding are still needed to contribute to the cooling of 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 direct 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 the oil left the motor section at the bottom of the stator. It was indicated that with the oil cooling, the temperature of the end winding was decreased by down to about 50 ℃. Meanwhile, Marcolini et al [172] concluded that with the oil cooling for the end winding, the oil extracted 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 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 with the cooling by water jacket only when two ends of end winding were immersed by still oil.

Other cooling methods which have shown exceptional potential 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. It was indicated that with the use of oil, the temperature of end winding was decreased by about 20%. Meanwhile, the time required to achieve 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 2.5~5 times. Furthermore, a larger flow rate is expected to benefitthe winding cooling. With respect to the rotor rotation cases, the rotation resulted in increasing the temperature disparities between the different winding locations, while this effect could be offseted 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. It was reported that with the oil spray on end winding surface, the current density roughly doubled as well as the output torque, at the cost of fractional increase of pump 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 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.

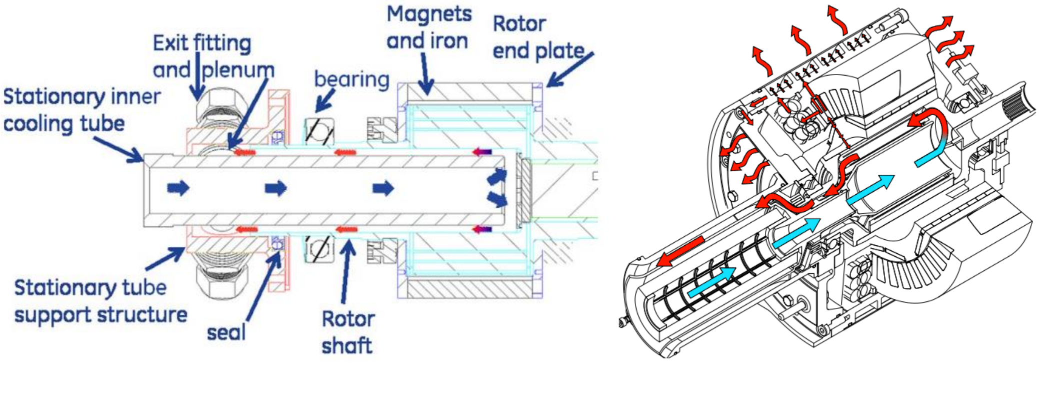
From the foregoing discussion, the temperature of the end winding can be impressively decreased when using liquid cooling methods. The liquid not only dissipates the heat from the end winding but also the winding portion inside the slot, providing an efficient axial heat transfer path for the motors. The available space for the cooling of end winding is relative larger than that of the slot winding. 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 still has drawbacks 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-structured manifolds, while complex manifold structures will decrease the reliability of the cooling loop.

4.3 Rotor cooling

The rotor in motors is often characterized by having a poor heat transfer 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 than the stator winding due to harsh thermal environment [182]. The implement of rotor cooling methods is needed to ascertain the rotor operates within a safe temperature range. This section will focus on new technologies which provide improved rotor cooling.

Generally, the current rotor cooling techniques are based on hollow shafts, in 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. 8 (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·K) to 2900 W/(m^2·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 enhanced 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 to be a liquid, even can be 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. 8 (b). In this arrangement air intake and discharge are on the same side. With the proposed rotor cooling, the temperature of the magnet was decreased by 40 ℃ 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 ℃ to 70.53 ℃ at the studied heat 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 ranges.



(a) (b)

Fig.8 the hollow shaft cooled by different media (a) oil [143] (b) air [185]

Despite that the importance of rotor cooling has been recognized, the technical 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 is expected to address the rotor temperature better. Meanwhile, the integration of rotor cooling with stator cooling is also very crucial.

4.4 Heat conduction enhancement

In a typical motor, the axial thermal conductivity of the stator lamination is very small due to poor properties of lamination as well as to avoid iron losses, 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 redistribute the heat and accelerate the heat transfer process.

4.4.1 Potting materials

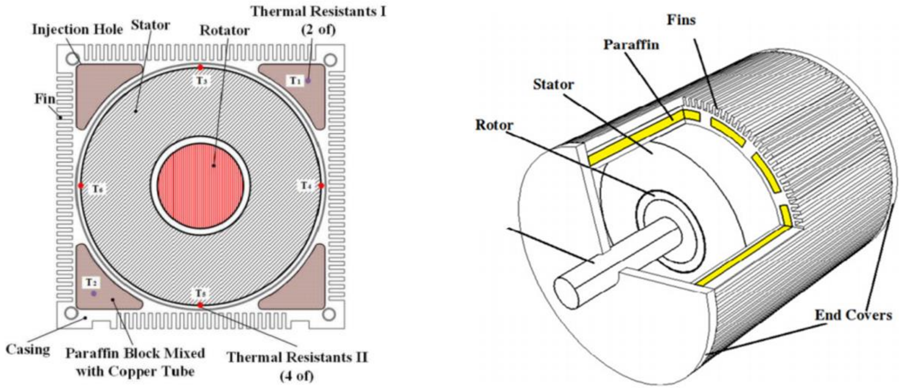
Some potting materials are available to enhance the heat conduction process in motors. They are used to fill in the air pockets between the solid components. Sun et al [187] tested the potting material as a heat transfer bridge between the end winding and casing. It was suggested that the temperature was lowered by 23.6% with the application of the potting materials. Furthermore, it was capable to significantly delay the temperature increase of the motor. Yao et al [188] concluded that the temperature of the end winding was decreased by 20.27 °C 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 °C and 6 °C, respectively. Polikarpova et al [189] also used the potting material to connect the water-cooled frame and the end winding, and a 10% temperature drop was 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 in enhancement of heat conduction.

4.4.2 Heat guide plates

Heat guide (HG) plates have also being used to provide an extra heat transfer path to dissipate the heat in motors. They are mostly used with 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-spots. 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 the presence of 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 analyses. Apart from the presented heat guides, the back-iron can also be used to support heat transfer. 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. 9 (a). It was revealed that in the steady 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 times. The same research team also proposed another structure, as illustrated in Fig. 9 (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 with the solid-phase conductivity. Furthermore, the sensitivity analysis showed that the temperature decreased with the increase of thermal conductivity, melting latent heat and decrease 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 presence of PCMs. The incorporation of PCMs led to 8% and 18% reduction in temperature rise of winding and winding weight, respectively. All of this research indicates a good prospect of PCMs in motor thermal management.

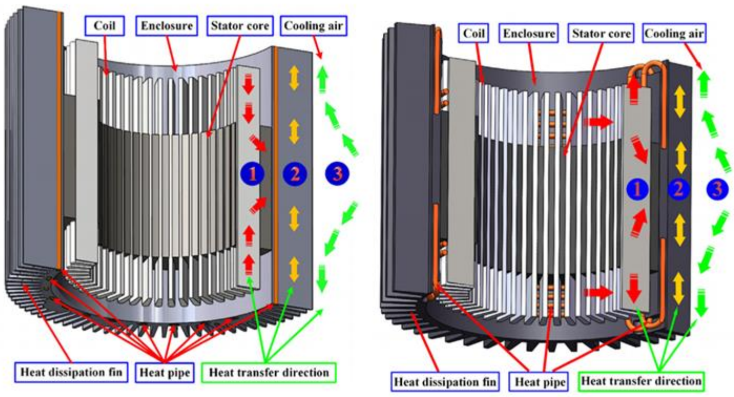


(a) (b)

Fig.9 the utilization of PCMs (a) [193] (b) [195]

4.4.4 Heat pipes

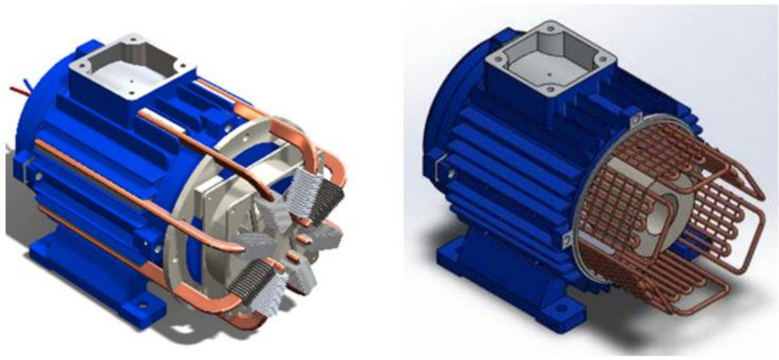
Heat pipes are well-known heat transfer devices of high equivilent thermal conductivity. They have been used by researchers to enhance the heat conduction between components in the motor. Groll et al [198] reported a pioneering design that used 28 heat pipes in the rotor and 36 heat pipes in the stator. 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. 10(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. 10 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. 11(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 overall structure is presented in Fig. 11(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 surfaces were decreased by 81.35 °C and 84.05 °C, respectively.



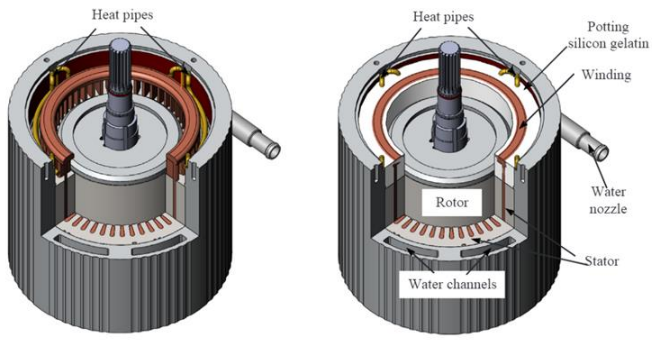
(a) (b)

Fig. 11 heat pipes used in motors (a) [200]; (b) [201]

In summary, the applications 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 fluctuation of the motors. Therefore, 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 heat dissipation. Some methods combining heat conduction enhancement with cooling technologies were also explored. Along with 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. 12. 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 requirements and greatly decreased energy consumption. Polikarpova et al [204] proposed another hybrid thermal management method for a motor. 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 that the number of copper bars had an apparent influence on motor efficiency [205].



(a) (b)

Fig. 12 the heat pipe and potting material hybrid thermal management [202] (a) heat pipe; (b) heat pipe and potting material

Regarding a higher level of thermal management integration, rotor cooling is 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 decreasing by 24.95%, 11.63%, 15.76% compared 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. 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. 13 (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. 13(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.

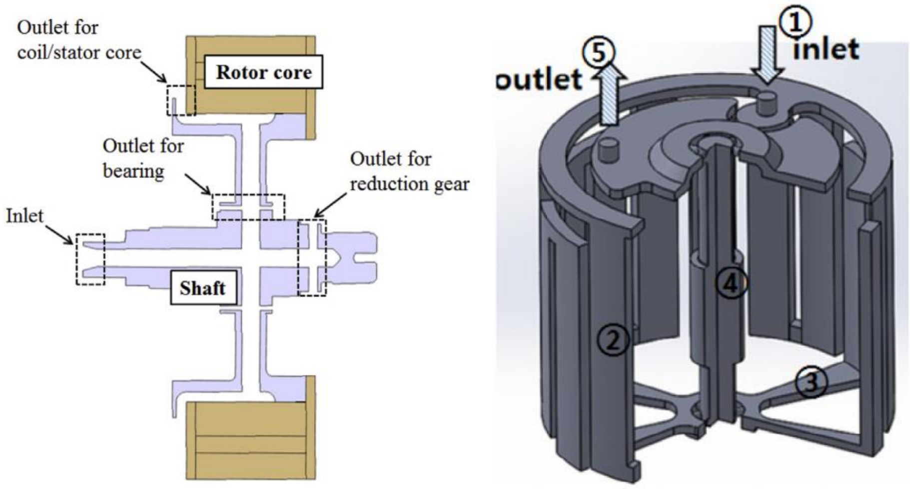


Fig. 13 hybrid cooling structures (a) [209] (b) [210]

The hybrid thermal management is expected to be more efficient than individual cooling methods. It can satisfactorily address the different cooling requirements of the winding, iron, and even the mechanical components of the motor simultanously. Nevertheless, the system will also be very intricate, and the flow path of the coolant is subject to elaborate designs. For cooling 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.

4.6 Future challenges on thermal management

Even with these outstanding thermal management technologies presented above, there are still some concerned 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.

5. Conclusions

In this paper, the latest thermal management technologies for electric motors are comprehensively reviewed and discussed. Generally, the theoretical models provide reliable and economical ways to analyze the temperature distribution of motors, while the experimental investigations validate many thermal management technologies and optimization strategies. 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 etc.) have been investigated and optimized to cool the motor with various temperature requirements, as shown in Fig. 14. 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 are used to predict the temperature distribution of the motors. Numerical models are generally able to provide accurate results and easily integrated with multi-physical simulations. The LPTN models deliver quick results and the accuracy is highly influenced by the modeling of the contact thermal resistance between solid interfaces, heat transfer correlations used for end space, and equivalent thermal properties evaluations (especially the thermal conductivity and thermal capacity) of winding. Furthermore, the determination of heat transfer area of end winding is 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 crucial, and indirect cooling and direct cooling methods are currently available. Basically, current thermal management technologies address well for the cooling of motors from low to high power density. For low power 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 power density (~12 A/mm^2), liquid cooling is more advisable to cool the

motor section. 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, thermal paste, PCM, and potting material can also be used to enhance the heat conduction among different components. For motors with even higher power density (> 15 A/mm^2), hybrid cooling technologies are recommended. For induction motors, the consideration of rotor cooling is strongly recommended.

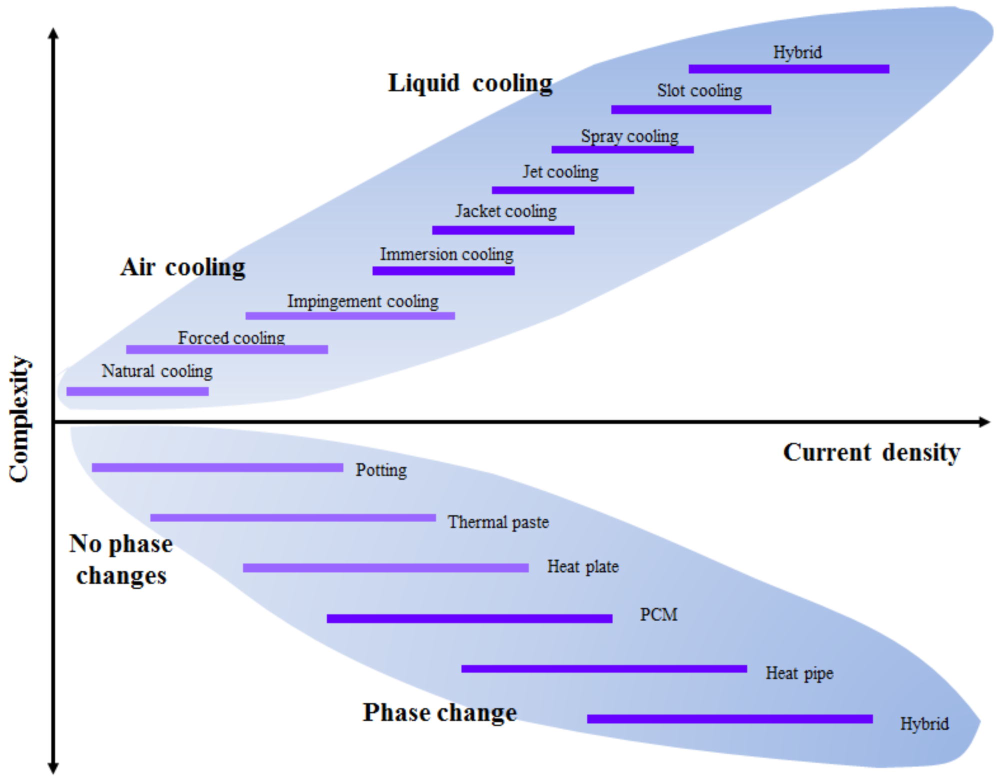


Fig. 14 Overall estimates on thermal management technologies for electric motors.

The paper is expected to provide valuable information and to inspire more remarkable innovative thermal management concepts for e-motors in the future.

Declare of Interest

None

Acknowledgement

This work was financially sponsored by the following research grants: H2020-MSCA-RISE - 778104 – ThermaSMART, Innovate UK (AceDrive No. 113167)

References

[1] Tran D, Vafaeipour M, El Baghdadi M, Barrero R, Van Mierlo J, Hegazy O. Thorough state-of-the-art analysis of electric and hybrid vehicle powertrains: Topologies and integrated energy management strategies. Renew Sust Energ Rev 2020; 119:109596.

[2] Cao WP, Mecrow BC, Atkinson GJ, Bennett JW. Overview of electric motor technologies used for more electric aircraft (MEA. IEEE T Ind Electron 2012; 59:3523-31.

[3] M. Sabri MF, Danapalasingam KA, Rahmat MF. A review on hybrid electric vehicles architecture and energy management strategies. Renew Sust Energ Rev 2016; 53:1433-42.

[4] Wang Q, Jiang B, Li B, Yan Y. A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles. Renew Sust Energ Rev 2016; 64:106-28.

[5] Du J, Ouyang M, Chen J. Prospects for chinese electric vehicle technologies in 2016 – 2020: ambition and rationality. ENERGY 2017; 120:584-96.

[6] Langbroek JHM, Franklin JP, Susilo YO. The effect of policy incentives on electric vehicle adoption. ENERG POLICY 2016; 94:94-103.

[7] IEA. IEA Technology collaboration programme on energy efficient end-user equipment (4E)., 2017. https://www.iea-4e.org/

[8] De Almeida A, Fong J, Brunner CU, Werle R, Van Werkhoven M. New technology trends and policy needs in energy efficient motor systems - A major opportunity for energy and carbon savings. Renew Sust Energ Rev 2019; 115:109384.

[9] Bilgin B, Emadi Ali. Electric motors in electrified transportation: a step toward achieving a sustainable and highly efficient transportation system. IEEE Power Electronics Mag 2014; 1:10-17.

[10] Arbab N, Wang W, Lin C, Hearron J, Fahimi B. Thermal modeling and analysis of a double-stator switched reluctance motor. IEEE T Energy Conver 2015; 30:1209-17.

[11] Kahourzade S, Mahmoudi A, Ping HW, Uddin MN. A comprehensive review of axial-flux permanent-magnet machines. Can J Elect Comput E 2014; 37:19-33.

[12] Shazly J, Wahsh S, Yassin A. Thermal modeling of an AFPMSM: A review. J Electr Sys and Informa Technol 2015; 2:18-26.

[13] Liao CM, Chen CL, Katcher T. Thermal management of ac induction motors using computational fluid dynamics modeling. IEEE International Electric Machines and Drives Conference. Seattle, USA, 1999.

[14] Du G, Xu W, Zhu J, Huang N. Power loss and thermal analysis for high-power high-speed permanent magnet machines. IEEE T Ind Electron 2020; 67:2722-33.

[15] Madonna V, Giangrande P, Lusuardi L, Cavallini A, Galea M. Impact of thermal overload on the insulation aging in short duty cycle motors for aerospace. IEEE, 2018. p.1-06.

[16] Salameh F, Picot A, Chabert M, Maussion P. Parametric and nonparametric models for lifespan modeling of insulation systems in electrical machines. IEEE T Ind Appl 2017; 53:3119-28.

[17] Zhang X, Yang Q, Ma M, Lin Z, Yang S. A switched reluctance motor torque ripple reduction strategy with deadbeat current control and active thermal management. IEEE T Veh Technol 2020; 69:317-27.

[18] Polikarpova M, Ponomarev P, Lindh P, Petrov I, Jara W, Naumanen V, Tapia JA, Pyrhonen J. Hybrid cooling method of axial-flux permanent-magnet machines for vehicle applications. IEEE T Ind Electron 2015; 62:7382-90.

[19] Staton DA, Popescu M, Hawkins D, Boglietti A. Influence of different end region cooling arrangements

on end-winding heat transfer coefficients in electrical machines. IEEE Energy Conversion Congress and Exposition. Atlanta, USA, 2010.

[20] Howey DA, Holmes AS, Pullen KR. Measurement and CFD prediction of heat transfer in air-cooled disc-type electrical machines. IEEE T Ind Appl 2011; 47:1716-23.

[21] SanAndres U, Almandoz G, Poza J, Ugalde G. Design of cooling systems using computational fluid dynamics and analytical thermal models. IEEE T Ind Electron 2014; 61:4383-91.

[22] Tuysuz A, Meyer F, Steichen M, Zwyssig C, Kolar JW. Advanced cooling methods for high-speed electrical machines. IEEE T Ind Appl 2017; 53:2077-87.

[23] Sciascera C, Giangrande P, Papini L, Gerada C, Galea M. Analytical thermal model for fast stator winding temperature prediction. IEEE T Ind Electron 2017; 64:6116-26.

[24] Gai Y, Kimiabeigi M, Chuan Chong Y, Widmer JD, Deng X, Popescu M, Goss J, Staton DA, Steven A. Cooling of automotive traction motors: schemes, examples, and computation methods. IEEE T Ind Electron 2019; 66:1681-92.

[25] Carriero A, Locatelli M, Ramakrishnan K, Mastinu G. A review of the state of the art of electric traction motors cooling techniques. SAE Technical Paper. https://doi.org/10.4271/2018-01-0057 2018.

[26] Li B, Huang K, Wang X, Chen Y, Wang Y, Gerada D, Worall S, Stone I, Yan Y. Thermal management of electrified propulsion system for low-carbon vehicles. Automotive Innovation 2020; 3:299-316.

[27] Ionel D, Popescu M, Cossar C, McGilp MI, Boglietti A, Cavagnino A. A general model of the laminated steel losses in electric motors with PWM voltage supply. IEEE, 2008. p.1-07.

[28] Yamazaki K, Fukushima N. Iron-loss modeling for rotating machines: comparison between bertotti's three-term expression and 3-d eddy-current analysis. IEEE T Magn 2010; 46:3121-24.

[29] Hong D, Woo B, Lee J, Koo D. Ultra high speed motor supported by air foil bearings for air blower

cooling fuel cells. IEEE T Magn 2012; 48:871-74.

[30] Wilson SD, Stewart P, Taylor BP. Methods of resistance estimation in permanent magnet synchronous motors for real-time thermal management. IEEE T Energy Conver 2010; 25:698-707.

[31] Kral C, Haumer A, Lee SB. A practical thermal model for the estimation of permanent magnet and stator winding temperatures. IEEE T Power Electr 2014; 29:455-64.

[32] Luomi J, Zwyssig C, Looser A, Kolar JW. Efficiency optimization of a 100-w 500 000-r/min permanent-magnet machine including air-friction losses. IEEE T Ind Appl 2009; 45:1368-77.

[33] Huang Z, Fang J, Liu X, Han B. Loss calculation and thermal analysis of rotors supported by active magnetic bearings for high-speed permanent magnet electrical machines. IEEE T Ind Electron 2016:2027-35.

[34] Schwarz KK, Member MA. Survey of basic stray losses in squirrel-cage induction motors. Proceedings of the Institution of Electrical Engineers 1964; 111:1565-74.

[35] Pillay P, Al-Badri M, Angers P, Desai C. A new stray-load loss formula for small and medium-sized induction motors. IEEE T Energy Conver 2016; 31:1221-27.

[36] Boglietti A, Cavagnino A, Staton D, Shanel M, Mueller M, Mejuto C. Evolution and modern approaches for thermal analysis of electrical machines. IEEE T Ind Electron 2009; 56:871-82.

[37] Huang Z, Nategh S, Lassila V, Alakula M. Direct oil cooling of traction motors in hybrid drives. IEEE International Electric Vehicle Conference. Greenville, USA, 2012.

[38] Galloni E, Parisi P, Marignetti F, Volpe G. CFD analyses of a radial fan for electric motor cooling. Therm Sci Eng Prog 2018; 8:470-76.

[39] Nakahama T, Biswas D, Kawano K, Ishibashi F. Improved cooling performance of large motors using fans. IEEE T Energy Conver 2006; 21:324-31.

[40] Lundmark ST, Bergqvist A, Chakarova-Kaeck SD. Coupled 3-D thermal and electromagnetic modelling

of a liquid-cooled IPM traction motor. IEEE Vehicle Power and Propulsion Conference (VPPC). Belfort, France, 2017.

[41] Lee Y, Hahn S, Kauh S. Thermal analysis of induction motor with forced cooling channels. IEEE T Magn 2000; 36:1398-402.

[42] Baggu MM, Hess HL, Rink K. Thermal Modeling of "Direct Lamination Cooling (DLC)" induction motor for hybrid electric vehicle applications. IEEE Vehicle Power and Propulsion Conference. Chicago, USA, 2005.

[43] Kral C, Haumer A, Haigis M, Lang H, Kapeller H. comparison of a CFD analysis and a thermal equivalent circuit model of a TEFC induction machine with measurements. IEEE T Energy Conver 2009; 24:809-18.

[44] F A, E G, Kar NC. Transient thermal analysis of a copper rotor induction motor using a lumped parameter temperature network model. IEEE Transportation Electrification Conference and Expo (ITEC). Dearborn, USA, 2016.

[45] Boglietti A, Cavagnino A, Staton DA. TEFC induction motors thermal models- a parameter sensitivity analysis. IEEE Industry Applications Conference. Seattle, USA, 2004.

[46] Satrústegui M, Martinez-Iturralde M, Ramos JC, Gonzalez P, Astarbe G, Elosegui I. Design criteria for water cooled systems of induction machines. Appl Therm Eng 2017; 114:1018-28.

[47] Cavazzuti M, Gaspari G, Pasquale S, Stalio E. Thermal management of a formula e electric motor: analysis and optimization. Appl Therm Eng 2019; 157:113733.

[48] Mezani S, Takorabet N, Laporte B. A combined electromagnetic and thermal analysis of induction motors. IEEE T Magn 2005; 41:1572-75.

[49] Cai X, Cheng M, Zhu S, Zhang J. Thermal modeling of flux-switching permanent-magnet machines considering anisotropic conductivity and thermal contact resistance. IEEE T Ind Electron 2016; 63:3355-65.

[50] Nategh S, Zhang H, Wallmark O, Boglietti A, Nassen T, Bazant M. Transient thermal modeling and analysis of railway traction motors. IEEE T Ind Electron 2019; 66:79-89.

[51] Trigeol JF, Bertin Y, Lagonotte P. Thermal modeling of an induction machine through the association of two numerical approaches. IEEE T Energy Conver 2006; 21:314-23.

[52] Xiong YQ, Wang B, Chu CC, Gadh R. Electric vehicle driver clustering using statistical model and machine learning. IEEE Power & Energy Society General Meeting (PESGM). Portland, OR, USA, 2018.

[53] Wang X, Yan Y, Meng X, Chen G. A general method to predict the performance of closed pulsating heat pipe by artificial neural network. Appl Therm Eng 2019; 157:113761.

[54] Jiang WY, Jahns TM. Coupled electromagnetic/thermal machine design optimization based on finite element analysis with application of artificial neural network. IEEE Energy Conversion Congress and Exposition (ECCE). Pittsburgh, USA, 2014.

[55] Sim K, Lee Y, Jang S, Kim TH. Thermal analysis of high-speed permanent magnet motor with cooling flows supported on gas foil bearings: part I - coupled thermal and loss modeling. J Mech Sci Technol 2015; 29:5469-76.

[56] Camilleri R, McCulloch MD. A new flat winding construction for direct liquid cooled axial flux machine with segmented stators. XIII International Conference on Electrical Machines (ICEM). Alexandroupoli, Greece, 2018.

[57] Rehman Z, Seong K. Three-D numerical thermal analysis of electric motor with cooling jacket. ENERGIES 2018; 11:92.

[58] Yabiku R, Fialho R, Teran L, Ramos ME, Kawasaki N. Use of thermal network on determining the temperature distribution inside electric motors in steady-state and dynamic conditions. IEEE T Ind Appl 2010; 46:1787-95.

[59] Boglietti A, Cavagnino A, Parvis M, Vallan A. Evaluation of radiation thermal resistances in industrial motors. IEEE T Ind Appl 2006; 42:688-93.

[60] Camilleri R, Beard P, Howey DA, McCulloch MD. Prediction and measurement of the heat transfer coefficient in a direct oil-cooled electrical machine with segmented stator. IEEE T Ind Electron 2018; 65:94-102.

[61] Boglietti A, Cavagnino A, Staton D. Determination of critical parameters in electrical machine thermal models. IEEE T Ind Appl 2008; 44:1150-59.

[62] Kral C, Haumer A, Bauml T. Thermal model and behavior of a totally-enclosed-water-cooled squirrel-cage induction machine for traction applications. IEEE T Ind Electron 2008; 55:3555-65.

[63] Staton D, Boglietti A, Cavagnino A. Solving the more difficult aspects of electric motor thermal analysis. IEEE International Electric Machines and Drives Conference. Madison, USA, 2003.

[64] Nerg J, Rilla M, Pyrhonen J. Thermal analysis of radial-flux electrical machines with a high power density. IEEE T Ind Electron 2008; 55:3543-54.

[65] Wrobel R, Ayat S, Godbehere J. A Systematic Experimental approach in deriving stator-winding heat transfer. IEEE International Electric Machines and Drives Conference (IEMDC). Miami, FL, USA, 2017.

[66] Liang PX, Pei YL, Chai F, Cheng SK. Equivalent stator slot model of temperature field for high torque-density permanent magnet synchronous in-wheel motor. 17th International Conference on Electrical Machines and Systems (ICEMS). Hangzhou, China, 2014.

[67] Galea M, Gerada C, Raminosoa T, Wheeler P. A thermal improvement technique for the phase windings of electrical machines. IEEE T Ind Appl 2012; 48:79-87.

[68] Boglietti A, Carpaneto E, Cossale M, Vaschetto S, Popescu M, Staton DA. stator winding thermal conductivity evaluation: an industrial production assessment. IEEE T Ind Appl 2016; 52:3893-900.

[69] Boglietti A, Cavagnino A, Staton D. Determination of critical parameters in electrical machine thermal

models. IEEE T Ind Appl 2008; 44:1150-59.

[70] Tang Y, Chen L, Chai F, Chen T. Thermal Modeling and Analysis of Active and End Windings of Enclosed Permanent-Magnet Synchronous In-Wheel Motor Based on Multi-Block Method. IEEE T Energy Conver 2020; 35:85-94.

[71] Huang X, Tan Q, Li L, Li J, Qian Z. Winding temperature field model considering void ratio and temperature rise of a permanent-magnet synchronous motor with high current density. IEEE T Ind Electron 2017; 64:2168-77.

[72] Liu H, Ayat S, Wrobel R, Zhang C. Comparative study of thermal properties of electrical windings impregnated with alternative varnish materials. J Eng 2019; 2019:3736-41.

[73] Nategh S, Wallmark O, Leksell M, Zhao S. Thermal analysis of a pmasrm using partial fea and lumped parameter modeling. IEEE T Energy Conver 2012; 27:477-88.

[74] Liu X, Yu H, Shi Z, Huang L, Xia T, Guo R. Porous metal model for calculating slot thermal conductivity coefficient of electric machines. Appl Therm Eng 2017; 111:981-88.

[75] Kim C, Lee K. Numerical investigation of the air-gap flow heating phenomena in large-capacity induction motors. Int J Heat Mass Tran 2017; 110:746-52.

[76] Hosain ML, Bel Fdhila R, Rönnberg K. Taylor-Couette flow and transient heat transfer inside the annulus air-gap of rotating electrical machines. Appl Energ 2017; 207:624-33.

[77] Romanazzi P, Howey DA. Air-gap convection in a switched reluctance machine. Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER). Monte Carlo, Monaco, 2015.

[78] Becker KM, Kaye J. Measurements of diabatic flow in an annulus with an inner rotating cylinder. J Heat Trans 1962; 84:97-104.

[79] Staton DA, Cavagnino A. Convection heat transfer and flow calculations suitable for electric machines

thermal models. IEEE T Ind Electron 2008; 55:3509-16.

[80] Jakoby R, Kim S, Wittig S. Correlations of the convection heat transfer in annular channels with rotating inner cylinder. Journal of Engineering for Gas Turbines and Power 1999; 121:670-77.

[81] Kuzay TM, Scott CJ. Turbulent heat transfer studies in annulus with inner cylinder rotation. J Heat Trans 1977; 99:12-19.

[82] Howey DA, Childs PRN, Holmes AS. Air-gap convection in rotating electrical machines. IEEE T Ind Electron 2012; 59:1367-75.

[83] Fénot M, Bertin Y, Dorignac E, Lalizel G. A review of heat transfer between concentric rotating cylinders with or without axial flow. Int J Therm Sci 2011; 50:1138-55.

[84] Zhang B, Qu R, Wang J, Xu W, Fan X, Chen Y. Thermal model of totally enclosed water-cooled permanent-magnet synchronous machines for electric vehicle application. IEEE T ind appl 2015; 51:3020-29.

[85] Boglietti A, Cavagnino A, Staton DA. Impact of different end region cooling arrangements on endwinding heat transfer coefficients in electric motors. 35th Annual Conference of IEEE Industrial Electronics. Porto, Portugal, 2009.

[86] Boglietti A, Cavagnino A. Analysis of the endwinding cooling effects in tefc induction motors. IEEE T Ind Appl 2007; 43:1214-22.

[87] La Rocca S, Pickering SJ, Eastwick CN, Gerada C, Rönnberg K. Fluid flow and heat transfer analysis of TEFC machine end regions using more realistic end-winding geometry. J Eng 2019; 2019:3831-35.

[88] Micallef C, Pickering SJ, Simmons KA, Bradley KJ. Improved cooling in the end region of a strip-wound totally enclosed fan-cooled induction electric machine. IEEE T Ind Electron 2008; 55:3517-24.

[89] Hettegger M, Streibl B, Biro O, Neudorfer H. Measurements and simulations of the convective heat transfer coefficients on the end windings of an electrical machine. IEEE T Ind Electron 2012; 59:2299-308.

[90] Tovar-Barranco A, Lopez-de-Heredia A, Villar I, Briz F. Modeling of end-space convection heat-transfer for internal and external rotor pmsms with fractional-slot concentrated windings. Ieee T Ind Electron 2020:10-1109.

[91] Ahmed F, Roy P, Towhidi M, Feng G. CFD and LPTN hybrid technique to determine convection coefficient in end-winding of TEFC induction motor with copper rotor. 45th Annual Conference of the IEEE Industrial Electronics Society. Lisbon, Portugal, 2019.

[92] Basso GL, Goss J, Chong YC, Staton D. Improved thermal model for predicting end-windings heat transfer.: IEEE, 2017. p.4650-57.

[93] Li CP, Pei YL, Ni RG, Cheng SK. Analysis of 3d static temperature field of water cooling induction motor in mini electric vehicle. International Conference on electrical machines and systems. Beijing, China, 2011.

[94] Rocca SL, Pickering SJ, Eastwick CN, Gerada C. Numerical study on the impact of end windings porosity on the fluid flow and heat transfer in a Totally Enclosed Fan-Cooled electrical machine. IEEE International Electric Machines & Drives Conference (IEMDC). San Diego, USA, 2019.

[95] La Rocca S, Pickering SJ, Eastwick CN, Gerada C, Rönnberg K. Fluid flow and heat transfer analysis of TEFC machine end regions using more realistic end-winding geometry. J Eng 2019; 2019:3831-35.

[96] Hettegger M, Streibl B, Bíró O, Neudorfer H. Identifying the heat transfer coefficients on the end-windings of an electrical machine by measurements and simulations.: IEEE, 2010. p.1-05.

[97] Vansompel H, Yarantseva A, Sergeant P, Crevecoeur G. An inverse thermal modeling approach for thermal parameter and loss identification in an axial flux permanent magnet machine. IEEE T Ind Electron 2019; 66:1727-35.

[98] Boglietti A, Cossale M, Popescu M, Staton DA. Electrical machines thermal model: advanced calibration techniques. IEEE T Ind Appl 2019; 55:2620-28.

[99] Karnavas YL, Chasiotis ID, Peponakis EL. Cooling system design and thermal analysis of an electric

vehicl's in-wheel PMSM. XXII International Conference on Electrical Machines (ICEM). Lausanne, Switzerland, 2016.

[100] Anderson KR, Lin J, McNamara C, Magri V. CFD study of forced air cooling and windage losses in a high speed electric motor. J Electronics Cooling and Therm Contr 2015; 05:27-44.

[101] Montonen J, Nerg J, Polikarpova M, Pyrhonen J. Integration principles and thermal analysis of an oil-cooled and -lubricated permanent magnet motor planetary gearbox drive system. IEEE Access 2019; 7:69108-18.

[102] Jiang TT, Liu GH, Zhou HW. Simplified thermal modeling of fault-tolerant permanent-magnet motor by using lumped parameter network. IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific). Beijing, China, 2014.

[103] Li H, Shen Y. Thermal analysis of the permanent-magnet spherical motor. IEEE T Energy Conver 2015; 30:991-98.

[104] Acquaviva A, Wallmark O, Grunditz EA, Lundmark ST, Thiringer T. Computationally efficient modeling of electrical machines with cooling jacket. IEEE T Transp Electr 2019; 5:618-29.

[105] Li J, Lu Y, Cho Y, Qu R. Design, analysis, and prototyping of a water-cooled axial-flux permanent-magnet machine for large-power direct-driven applications. IEEE T Ind Appl 2019; 55:3555-65.

[106] Nategh S, Krings A, Wallmark O, Leksell M. Evaluation of impregnation materials for thermal management of liquid-cooled electric machines. IEEE T Ind Electron 2014; 61:5956-65.

[107] Wrobel R, Hussein A. A feasibility study of additively manufactured heat guides for enhanced heat transfer in electrical machines. IEEE T Ind Appl 2020; 56:205-15.

[108] Boglietti A, Cavagnino A, Lazzari M, Pastorelli A. A simplified thermal model for variable speed self cooled industrial induction motor. IEEE Industry Applications Conference. Pittsburgh, USA, 2002.

[109] Xyptras J, Hatziathanassiou V. Thermal analysis of an electrical machine taking into account the iron

losses and the deep-bar effect. IEEE T Energy Conver 1999; 14:996-1003.

[110] Aglen O, Andersson A. Thermal analysis of a high-speed generator., vol. 1: IEEE, 2003. p.547-54.

[111] Polikarpova M, Lindh PM, Tapia JA, Pyrhonen JJ. Application of potting material for a 100 kw radial flux pmsm. international conference on electrical machines (icem). Berlin, Germany, 2014.

[112] Zhang F, Gerada D, Xu Z, Zhang X, Tighe C, Zhang H, Gerada C. Back-iron extension thermal benefits for electrical machines with concentrated windings. IEEE T Ind Electron 2020; 67:1728-38.

[113] Li J, Lu Y, Cho Y, Qu R. Design an analysis of a water-cooled axial flux permanent-magnet machine for large power direct-driven applications. IEEE, 2018. p.118-24.

[114] Grabowski M, Urbaniec K, Wernik J, Wołosz KJ. Numerical simulation and experimental verification of heat transfer from a finned housing of an electric motor. Energ Convers Manage 2016; 125:91-96.

[115] Ulbrich S, Kopte J, Proske J. Cooling fin optimization on a TEFC electrical machine housing using a 2-d conjugate heat transfer model. IEEE T Ind Electron 2018; 65:1711-18.

[116] Kimotho JK, Hwang P. Thermal management of electric vehicle bldc motor. 16th Asia Pacific Automotive Engineering Conference. India, 2011.

[117] Kuria J, Hwang P. Optimizing heat sink geometry for electric vehicle bldc motor using CFD. Sustainable Research and Innovation Proceeding, 2011.

[118] Chen YC, Chen CL, Dong QM, Stephenson RW. Thermal management for motor. 8th intersociety conference on thermal and thermomechanical phenomena in electronic systems. San Diego, USA, 2002.

[119] Peng H, Lai F. Investigation of parameters affecting heat transfer and fluid flow of a tefc electric motor by using taguchi method. IOP Conference Series: Materials Science and Engineering 2019; 491:12021.

[120] Kim SC, Kim W, Kim MS. Cooling performance of 25kW in-wheel motor for electric vehicles. INT J AUTO TECH-KOR 2013; 14:559-67.

[121] Xu Z, Timimy A, Degano M, Giangrande P. Thermal management of a permanent magnet motor for an directly coupled pump. XXII International Conference on Electrical Machines (ICEM). Lausanne, Switzerland, 2016.

[122] Kim C, Lee K. Thermal nexus model for the thermal characteristic analysis of an open-type air-cooled induction motor. Appl Therm Eng 2017; 112:1108-16.

[123] Roffi M, Ferreira F, Almeida A. Comparison of different cooling fan designs for electric motors. IEEE International Electric Machines and Drives Conference (IEMDC). Miami, USA, 2017.

[124] Gilson GM, Pickering SJ, Hann DB, Gerada C. Piezoelectric fan cooling: a novel high reliability electric machine thermal management solution. IEEE T Ind Electron 2013; 60:4841-51.

[125] Chen YC, Chen CL, Dong QM. CFD modeling for motor fan system. IEEE International Electric Machines and Drives Conference. Madison, USA, 2003.

[126] Kim C, Lee K, Yook S. Effect of air-gap fans on cooling of windings in a large-capacity, high-speed induction motor. Appl Therm Eng 2016; 100:658-67.

[127] Fawzal AS, Cirstea RM, Gyftakis KN, Woolmer TJ, Dickison M, Blundell M. Fan performance analysis for rotor cooling of axial flux permanent magnet machines. IEEE T Ind Appl 2017; 53:3295-304.

[128] Fawzal AS, Cirstea RM, Gyftakis KN, Woolmer TJ. The fan design impact on the rotor cooling of axial flux permanent magnet machines. XXII International Conference on Electrical Machines (ICEM). Lausanne, Switzerland, 2016.

[129] Chang C, Kuo Y, Wang J, Chen S. Air cooling for a large-scale motor. Appl Therm Eng 2010; 30:1360-68.

[130] Wen J, Zheng J. Numerical analysis of the external wind path for medium-size high-voltage asynchronous motors. Appl Therm Eng 2015; 90:869-78.

[131] Kim M, Lee K, Um S. Numerical investigation and optimization of the thermal performance of a brushless DC motor. Int J Heat Mass Tran 2009; 52:1589-99.

[132] Moon SH, Yun JH, Kim WG, Kim JP. Thermal-flow analysis and cooling performance enhancement of a totally enclosed fan-cooled motor. International Conference on Electrical Machines and Systems (ICEMS). Busan, South Korea, 2013.

[133] Nakahama T, Suzuki K, Hashidume S, Ishibashi F, Hirata M. Cooling airflow in unidirectional ventilated open-type motor for electric vehicles. IEEE T Energy Conver 2006; 21:645-51.

[134] Li H. Cooling of a permanent magnet electric motor with a centrifugal impeller. Int J Heat Mass Tran 2010; 53:797-810.

[135] Sun X, Cheng M. Thermal analysis and cooling system design of dual mechanical port machine for wind power application. IEEE T Ind Electron 2013; 60:1724-33.

[136] Asef P, Perpina RB, Barzegaran MR. An innovative natural air-cooling system technique for temperature-rise suppression on the permanent magnet synchronous machines. Electr Pow Syst Res 2018; 154:174-81.

[137] Fawzal AS, Cirstea RM, Woolmer TJ, Dickison M, Blundell M, Gyftakis KN. Air inlet/outlet arrangement for rotor cooling application of axial flux PM machines. Appl Therm Eng 2018; 130:1520-29.

[138] Xu Z, Tighe C, Galea M, Hamiti T, Gerada C, Pickering SJ. Thermal design of a permanent magnetic motor for direct drive wheel actuator.: IEEE, 2014. p.2186-92.

[139] Song L, Li Z, Gao J, Zeng Q. 3D thermal analysis of water cooling induction motor used for HEV. International Conference on Electrical Machines and Systems. Wuhan, China, 2008.

[140] Fasquelle A, Laloy D. Water cold plates cooling in a permanent magnet synchronous motor. IEEE T Ind Appl 2017; 53:4406-13.

[141] Li J, Lu Y, Cho Y, Qu R. Design, analysis, and prototyping of a water-cooled axial-flux permanent-

magnet machine for large-power direct-driven applications. IEEE T Ind Appl 2019; 55:3555-65.

[142] Pechanek R, Bouzek L. Analyzing of two types water cooling electric motors using computational fluid dynamics. 15th International Power Electronics and Motion Control Conference (EPE/PEMC). Novi Sad, Serbia, 2012.

[143] EL-Refaie AM, Alexander JP, Galioto S, Reddy PB, Huh K, de Bock P, Shen X. Advanced high-power-density interior permanent magnet motor for traction applications. IEEE T Ind Appl 2014; 50:3235-48.

[144] Wu P, Hsieh M, Cai WL, Liu J, Huang Y, Caceres JF, Chang SW. Heat transfer and thermal management of interior permanent magnet synchronous electric motor. Inventions 2019; 4:69.

[145] Li CP, Guan ZW, Li JH, Zhao B, Ding XC. Optimal design of cooling system for water cooling motor used for mini electric vehicle. 20th International Conference on Electrical Machines and Systems (ICEMS). Sydney, Australia, 2017.

[146] Bennion K, Cousineau J. Sensitivity analysis of traction drive motor cooling. IEEE Transportation Electrification Conference and Expo (ITEC). Dearborn, USA, 2012.

[147] Nategh S, Huang Z, Krings A, Wallmark O, Leksell M. Thermal modeling of directly cooled electric machines using lumped parameter and limited CFD analysis. IEEE T Energy Conver 2013; 28:979-90.

[148] Deriszadeh A, de Monte F, Villani M, Di Leonardo L. hydrothermal performance of ethylene glycol and water mixture in a spiral channel for electric motor cooling. EPE Association, 2019. p.1-10.

[149] Yang C, Wang H, Niu X, Zhang J, Yan Y. Design and analysis of cycling oil cooling in driving motors for electric vehicle application. IEEE, 2016. p.1-06.

[150] Michal S, Radek V, Petr N. The unusual water cooling applied on small asynchronous motor. Eng Mech 2011; 18:143-53.

[151] Moghaddam GK, Gould RD, Bhattacharys S. Thermomagnetic liquid cooling: a novel variable speed

motor drives thermal management solution. IEEE International Electric Machines & Drives Conference (IEMDC). Coeur, USA, 2015.

[152] Montonen J, Nerg J, Polikarpova M, Pyrhonen J. Integration principles and thermal analysis of an oil-cooled and -lubricated permanent magnet motor planetary gearbox drive system. IEEE Access 2019; 7:69108-18.

[153] Jungreuthmayer C, Bauml T, Winter O, Ganchev M, Kapeller H, Haumer A, Kral C. A detailed heat and fluid flow analysis of an internal permanent magnet synchronous machine by means of computational fluid dynamics. IEEE T Ind Electron 2012; 59:4568-78.

[154] Alexandrova Y, Semken RS, Pyrhönen J. Permanent magnet synchronous generator design solution for large direct-drive wind turbines: Thermal behavior of the LC DD-PMSG. Appl Therm Eng 2014; 65:554-63.

[155] Acquaviva A, Skoog S, Thiringer T. Design and verification of in-slot oil-cooled tooth coil winding pm machine for traction application. IEEE T Ind Electron 2020:1.

[156] Semidey SA, Mayor JR. Experimentation of an electric machine technology demonstrator incorporating direct winding heat exchangers. IEEE T Ind Electron 2014; 61:5771-78.

[157] Rhebergen C, Bilgin B, Emadi A, Rowan E. Enhancement of electric motor thermal management through axial cooling methods: a materials approach. IEEE Energy Conversion Congress and Exposition (ECCE). Montreal, Canada, 2015.

[158] Lindh P, Petrov I, Pyrhonen J, Scherman E, Niemela M, Immonen P. Direct liquid cooling method verified with a permanent-magnet traction motor in a bus. IEEE T Ind Appl 2019; 55:4183-91.

[159] Lindh PM, Petrov I, Semken RS, Niemela M, Pyrhonen JJ, Aarniovuori L, Vaimann T, Kallaste A. Direct liquid cooling in low-power electrical machines: proof-of-concept. IEEE T Energy Conver 2016; 31:1257-66.

[160] Reinap A, Marquez-Fernandez FJ, Alakula M, Deodhar R. Direct conductor cooling in concentrated windings. XIII International Conference on Electrical Machines (ICEM). Alexandroupoli, Greece, 2018.

[161] Schiefer M, Doppellbauer M. Indirect slot cooling for high-power-density machines with concentrated winding. IEEE International Electric Machines & Drives Conference (IEMDC). Coeur, USA, 2015.

[162] Liu Z, Winter T, Schier M. Comparison of thermal performance between direct coil cooling and water jacket cooling for electric traction motor based on lumped parameter thermal network and experimentation. EVS28 International Electric Vehicle Symposium and Exhibition. Kintex Korea, 2015.

[163] Sixel W, Liu M, Nellis G, Sarlioglu B. Cooling of windings in electric machines via 3d printed heat exchanger. IEEE, 2018. p.229-35.

[164] Chen X, Wang J, Griffo A, Spagnolo A. Thermal modeling of hollow conductors for direct cooling of electrical machines. IEEE T Ind Electron 2020; 67:895-905.

[165] Wohlers C, Juris P, Kabelac S, Ponick B. Design and direct liquid cooling of tooth-coil windings. Electr Eng 2018; 100:2299-308.

[166] Reinap A, Andersson M, Marquez-Fernandez FJ, Abrahamsson P, Alakula M. Performance estimation of a traction machine with direct cooled hairpin winding. IEEE, 2019. p.1-06.

[167] Chen JX, Ruan L. The stator bar' s transient temperature characteristic of evaporative cooling generator-motor. 17th International Conference on Electrical Machines and Systems (ICEMS). Hangzhou, China, 2014.

[168] Li ZG, Ruan L. Optimization design of the spray evaporative-cooling large electrical machine. 19th International Conference on Electrical Machines and Systems (ICEMS). Chiba, Japan, 2016.

[169] Rahman NA, Bostanci E, Fahimi B. Thermal analysis of switched reluctance motor with direct in-winding cooling system. IEEE Conference on Electromagnetic Field Computation (CEFC). Miami, FL, USA, 2016.

[170] Madonna V, Walker A, Giangrande P, Serra G, Gerada C, Galea M. Improved thermal management and analysis for stator end-windings of electrical machines. IEEE T Ind Electron 2019; 66:5057-69.

[171] Madonna V, Giangrande P, Walker A, Galea M. On the effects of advanced end-winding cooling on the

design and performance of electrical machines. XIII International Conference on Electrical Machines (ICEM). Alexandroupoli, Greece, 2018.

[172] Marcolini F, Donato GD, Caricchi F. Direct oil cooling of end-windings in torus-type axial-flux permanent-magnet machines. IEEE, 2019. p.5645-51.

[173] Li Y, Fan T, Sun W, Li Q. Experimental research on the oil cooling of the end winding of the motor. IEEE Energy Conversion Congress and Exposition (ECCE). Milwaukee, USA, 2016.

[174] Kevin Bennion. Electric motor thermal management research annual progress report. NREL, 2017.

[175] Liang G, Mudawar I. Review of spray cooling – Part 1: Single-phase and nucleate boiling regimes, and critical heat flux. Int J Heat Mass Tran 2017; 115:1174-205.

[176] Li Y, Fan T, Li Q, Wen XH. Experimental investigation on heat transfer of directly-oil-cooled permanent magnet motor. 19th International Conference on Electrical Machines and Systems (ICEMS). Chiba, Japan, 2016.

[177] Davin T, Pellé J, Harmand S, Yu R. Experimental study of oil cooling systems for electric motors. Appl Therm Eng 2015; 75:1-13.

[178] Liu C, Zhang H, Xu Z, Gerada D, Li J, Gerada C, Chong YC, Popescu M, Goss J, Staton D. Experimental investigation on oil spray cooling with hairpin windings. IEEE T Ind Electron 2019:1.

[179] Guechi MR, Desevaux P, Baucour P, Espanet C, Brunel R, Poirot M. Spray cooling of electric motor coil windings. J Comput Multiphas Flow 2016; 8:95-100.

[180] Rouws R, Jaarsveldt HV. Impact of thermoelectric cooling modules on the efficiency of a single-phase asynchronous machine. J Energy South Afr 2014; 25:13-18.

[181] Rocca SL, Rocca AL, Walker A, Vakil G. Numerical study of the impact of different cooling arrangements on a high length-diameter ratio motor for electric commerical vehicle. International Conference on Electrotechnical Complexes and Systems (ICOECS). Ufa, Russia, 2019.

[182] Fawzal AS, Cirstea RM, Gyftakis KN, Woolmer TJ, Dickison M, Blundell M. Fan Performance analysis for rotor cooling of axial flux permanent magnet machines. IEEE T Ind Appl 2017; 53:3295-304.

[183] Chuan H, Burke R, Wu Z. A comparative study on different cooling topologies for axial flux permanent magnet machine. IEEE Vehicle Power and Propulsion Conference (VPPC). Hanoi, Vietnam, 2019.

[184] Gai Y, Kimiabeigi M, Widmer JD, Chong YC, Goss J, SanAndres U, Staton DA. Shaft cooling and the influence on the electromagnetic performance of traction motors. IEEE, 2017. p.1-06.

[185] Jaeger M, Ruf A, Hameyer K, Tongeln TG. Thermal analysis of an electrical traction motor with an air cooled rotor. IEEE, 2018. p.467-70.

[186] Ponomarev P, Polikarpova M, Pyrhonen J. Thermal modeling of directly-oil-cooled permanent magnet synchronous machine. XXth International Conference on Electrical Machines. Marseille, France, 2012.

[187] Sun Y, Zhang S, Yuan W, Tang Y, Li J, Tang K. Applicability study of the potting material based thermal management strategy for permanent magnet synchronous motors. Appl Therm Eng 2019; 149:1370-78.

[188] Yao Y, Gu L, Fan T, Sun W, Luo J. Evaluation of heat transfer characteristic of aluminum nitride (aln) potting compound for the end windings of permanent magnet synchronous machines. International Conference on Electrical and Control Engineering. Yichang, China, 2011.

[189] Polikarpova M, Lindh P, Gerada C, Rilla M, Naumanen V, Pyrhönen J. Thermal effects of stator potting in an axial-flux permanent magnet synchronous generator. Appl Therm Eng 2015; 75:421-29.

[190] Kulan MC, Baker NJ. A thermal equivalent circuit to quantify the effect of thermal paste on heat flow through a pm machine. IEEE International Electric Machines and Drives Conference (IEMDC). Miami,USA, 2017.

[191] Kulan MC, Baker NJ. Development of a thermal equivalent circuit to quantify the effect of thermal paste on heat flow through a permanent magnet alternator. IEEE T Ind Appl 2019; 55:1261-71.

[192] Xu Z, Galea M, Tighe C, Hamiti T, Gerada C, Pickering SJ. Mechanical and thermal management design

of a motor for an aircraft wheel actuator.: IEEE, 2014. p.3268-73.

[193] Wang J, Li Y, Wang S, Zhang H, Ning X, Guo W. Experimental investigation of the thermal control effects of phase change material based packaging strategy for on-board permanent magnet synchronous motors. Energ Convers Manage 2016; 123:232-42.

[194] Wang SN, Li YZ, Liu Y, Zhou H, Li YH. Temperature control of permanent-magnet synchronous motor using phase change material. IEEE International Conference on Advanced Intelligent Mechatronics (AIM). Busan, South Korea, 2015.

[195] Wang S, Li Y, Li Y, Wang J, Xiao X, Guo W. Transient cooling effect analyses for a permanent-magnet synchronous motor with phase-change-material packaging. Appl Therm Eng 2016; 109:251-60.

[196] Bellettre J, Sartre V, Biais F, Lallemand A. Transient state study of electric motor heating and phase change solid-liquid cooling. Appl Therm Eng 1997; 17:17-31.

[197] Ayat S, Serghine C, Klonowski T, Yon S, Mutabazi A. The use of phase change material for the cooling of electric machine windings formed with hollow conductors. IEEE International Electric Machines & Drives Conference (IEMDC). San Diego, USA, 2019.

[198] Groll M, Krahling H, Munzel WD. Heat pipes for cooling of an electric motor. J Energy 1978; 2:363-67.

[199] Fang G, Yuan W, Yan Z, Sun Y, Tang Y. Thermal management integrated with three-dimensional heat pipes for air-cooled permanent magnet synchronous motor. Appl Therm Eng 2019; 152:594-604.

[200] Nandy Putra, Bambang Ariantara. Electric motor thermal management system using L-shaped flat heat pipes. Appl Therm Eng 2017; 126:1156-63.

[201] Aprianingsih N, Winarta A, Ariantara B, Putra N. Thermal performance of pulsating heat pipe on electric motor as cooling application. E3S Web of Conferences 2018; 67:3035.

[202] Sun Y, Zhang S, Chen G, Tang Y. Experimental and numerical investigation on a novel heat pipe based

cooling strategy for permanent magnet synchronous motors. Appl Therm Eng 2020; 170:114970.

[203] Huang J, Shoai Naini S, Miller R, Rizzo D, Sebeck K, Shurin S, Wagner J. A hybrid electric vehicle motor cooling system—design, model, and control. IEEE T Veh Technol 2019; 68:4467-78.

[204] Polikarpova M, Ponomarev P, Lindh P, Petrov I, Jara W, Naumanen V, Tapia JA, Pyrhonen J. Hybrid cooling method of axial-flux permanent-magnet machines for vehicle applications. IEEE T Ind Electron 2015; 62:7382-90.

[205] Pyrhönen J, Lindh P, Polikarpova M, Kurvinen E, Naumanen V. Heat-transfer improvements in an axial-flux permanent-magnet synchronous machine. Appl Therm Eng 2015; 76:245-51.

[206] Assaad B, Mikati K, Tran TV, Negre E. Experimental study of oil cooled induction motor for hybrid and electric vehicles. XIII International Conference on Electrical Machines (ICEM). Alexandroupoli, Greece, 2018.

[207] Lim D, Lee M, Lee H, Kim S. Performance evaluation of an in-wheel motor cooling system in an electric vehicle/hybrid electric vehicle. Energies 2014; 7:961-71.

[208] Park MH, Kim SC. Thermal characteristics and effects of oil spray cooling on in-wheel motors in electric vehicles. Appl Therm Eng 2019; 152:582-93.

[209] Lim DH, Kim SC. Thermal performance of oil spray cooling system for in-wheel motor in electric vehicles. Appl Therm Eng 2014; 63:577-87.

[210] Lee K, Cha H, Kim Y. Development of an interior permanent magnet motor through rotor cooling for electric vehicles. Appl Therm Eng 2016; 95:348-56.