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Doctoral Qualifying Exam

THERMAL MANAGEMENT SYSTEMS FOR AXIAL FLUX MOTORS: A REVIEW

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1. INTRODUCTION

Total global greenhouse gas emissions can be divided into five economic sectors [1]: energy generation, industry, buildings, transportation and agriculture. Transportation represents a significant category, responsible for 14.3% of total greenhouse gas emissions, with the most substantial portion coming from road transport, which contributes 10.7% to overall emissions [1].

From the figure 1.1. road transport is the second largest individual contributor to greenhouse gas emissions.

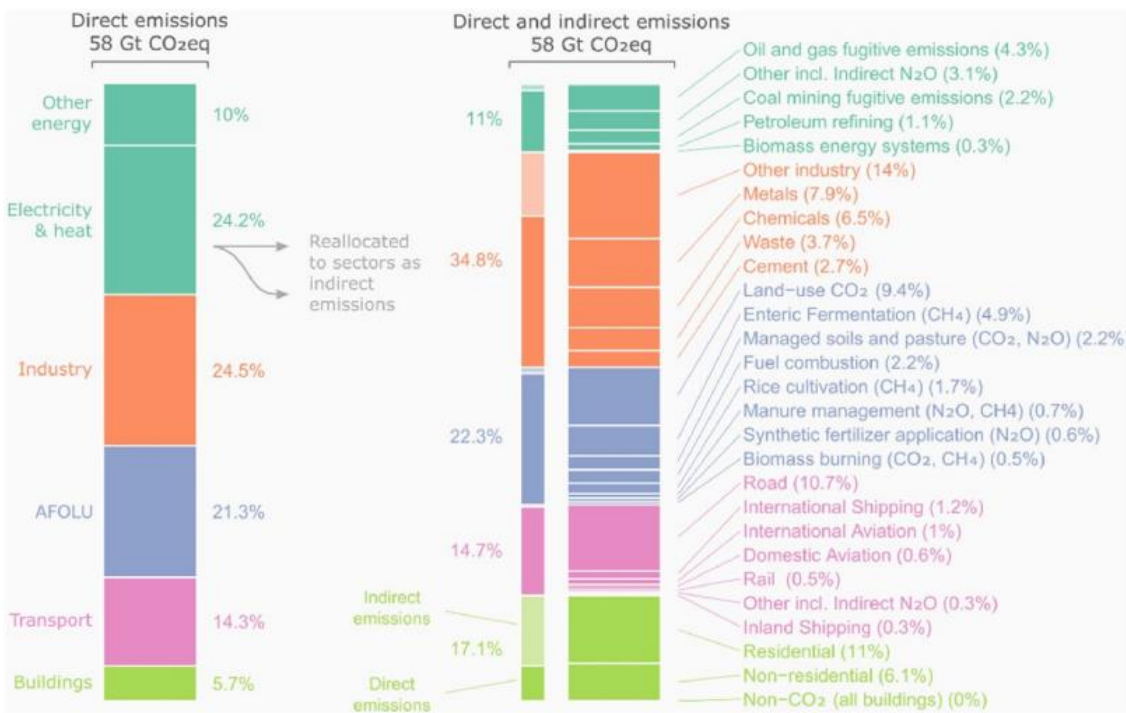

Figure 2. Direct versus indirect emissions. The stacked bar on the left indicates total global greenhouse gas emissions in 2018, split by sectors based on direct (scope 1) emissions accounting. The arrows shown next to the electricity and heat sector depict the reallocation of these emissions to final sectors as indirect (scope 2) emissions. This increases the contribution to global emissions from the industry and buildings sector (central stacked bar). The stacked bar on the far right indicates the shares of subsectors in global emissions when indirect emissions are included.

Figure 1.1. Contribution to greenhouse emissions by sector, [1]

Conventional vehicles that rely solely on an internal combustion engine consume fossil fuels and emit greenhouse gases (GHG) such as carbon oxides, nitrogen oxides and various hydrocarbons such as methane [2].

In densely populated areas, vehicle exhaust has become one of the main air pollutants. According to the China Vehicle Environmental Management Annual Report (CVEMAR) in 2018, exhaust gases contributed 52.1% of fine particulate matter (PM2.5) emissions in Shenzhen, China, and

45% in Beijing [3]. Due to the extremely negative impact on the environment and human health, the transportation sector is experiencing significant electrification efforts. Significant progress has been made in sales of electric passenger vehicles (figure 1.2.), which saw sales of 20,400 in 2010 and reached 13.8 million units in 2023 [4]. The global stock of electric passenger vehicles stood at 40 million in 2024 (figure 1.3.).

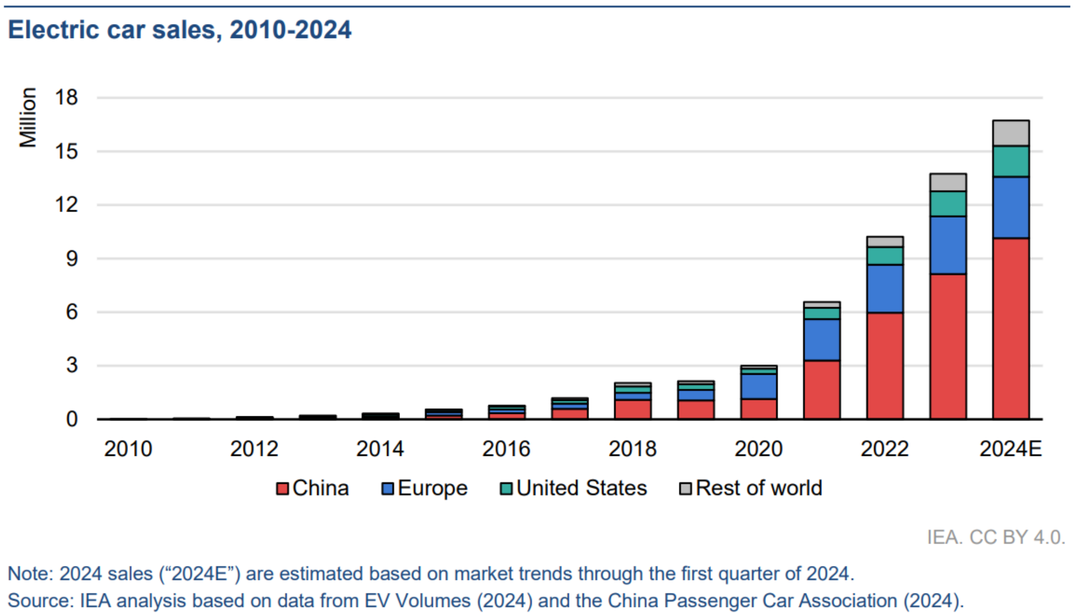

Figure 1.2. Sales of electric vehicles per year, [4]

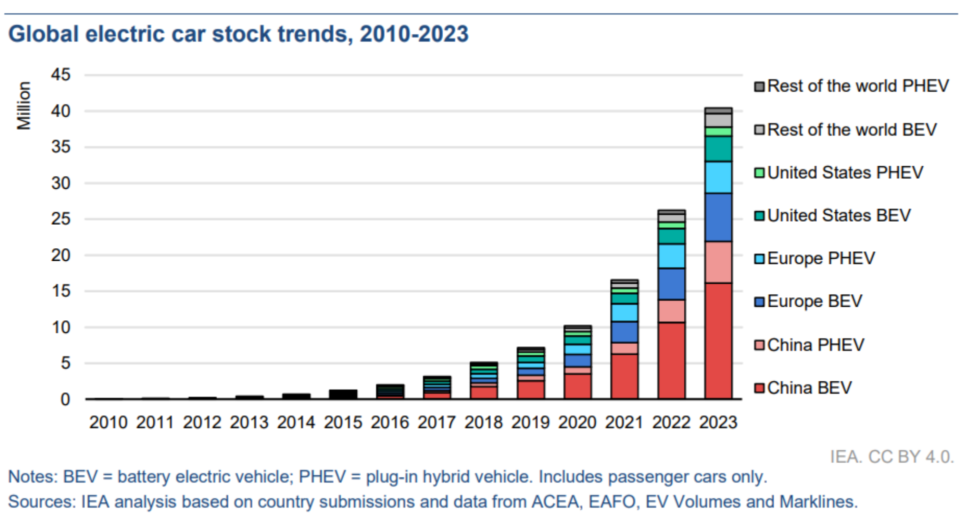

Figure 1.3. Global electric vehicle car stock trend, [4]

Electric vehicles use electric motors as their propulsion system, converting electrical energy stored in a battery into mechanical energy to drive the vehicle. The main requirements necessary for electric motors used in electric vehicles include high power density at low speeds, high efficiency across all operating range, overload capacity typically twice the rated motor torque for short durations, compact size, lightweight construction, shorter axial length and high reliability and durability [5], [6]. Electric motors can be categorized in several ways, and one fundamental division is between motors with radial magnetic flux and those with axial magnetic flux [7]. Currently, radial flux electric motors are predominantly used worldwide. Throughout the century of electromagnetic theory development from Maxwell to the present day, as well as the application of electromagnetism in electrical engineering from Tesla to the present day, radial flux electric motors have been studied and developed extensively. In contrast, axial flux motors have not been widely adopted due to several practical limitations, despite a clear theoretical advantage in certain aspects. In the last 20 years, advancements in technology and the development of new materials have led to a resurgence of interest and the beginning of using axial electric motors [8].

Axial electric motors differ from radial electric motors in that the magnetic flux is directed parallel to the axis or shaft of the motor, hence axially, whereas in radial electric motors, the magnetic flux is directed perpendicular or radially to the motor shaft [9]. Due to this change in topology, axial electric motors offer significant advantages but also come with certain drawbacks. As a result of the conceptual change in the geometry of the electric motor, the axial electric motor has a significantly shorter axial length, which is highly advantageous in applications such as electric vehicles [9]. Disc shaped rotor and stator structures as well as shorter axial length are advantageous if the motor is intended to be installed in the wheel of a vehicle [10]. Axial flux electric motors can be designed to achieve higher power to weight ratio, which results in reduced core material and increased efficiency. Another benefit is that they feature planar and adjustable air gaps, a characteristic not found in radial flux machines [9]. The ability to adjust the air gap enables mechanical field weakening, which is highly advantageous for applications in electric vehicles due to the potential to increase motor speed and expand the constant power range that the motor can deliver. In the case of the Yokeless and Segmented Armature (YASA) design, a simplified implementation of concentrated windings is possible, greatly reducing the length of the end windings and the amount of copper, which reduces the motor's weight and increases efficiency [11]. Given the high-power density enabled by the geometry of axial motors, a limiting factor for the design and implementation of the technology becomes the heat dissipation from the stator, where most of the losses are generated.

With the increasing prevalence of electric vehicles and the significant advantages of axial flux electric motor over radial electric motors, there is a pressing need to significantly enhance the cooling capability of axial electric motors. This enhancement is crucial for fully harnessing the technology's benefits, which is the primary goal of this research where different thermal management systems for axial flux motors have been reviewed.

1.1. Previous related review articles and necessity for review

This review work primarily focuses on thermal management systems for various topologies of axial electric motors and the thermal efficiency of these systems. Similar goals were pursued by the authors of reference [12]. However, the authors of this study focused on only three thermal management systems for one topology of axial electric motor. They covered stator cooling using a liquid jacket, forced cooling of the rotor by surrounding fluid, and rotor cooling through a hollow shaft. According to the LPTN model created, three distinct cooling topologies were examined. Furthermore, the thermal efficiency of combining shaft cooling with forced air cooling was investigated. These thermal management systems represent only a fraction of the potential systems used in the thermal management of axial flux motors. The review of thermal management systems from a mechanical perspective is provided in reference [13]. The paper places a strong emphasis on numerical techniques for heat transfer modelling in axial motors, with detailed descriptions of thermal management systems from a mechanical and physical implementation standpoint. Minimal attention is given to comparing the thermal efficiency of individual systems, expected temperatures in critical parts of the axial electric motor and thermal descriptions of the materials used. There are very few high-quality review papers that clearly compare the thermal efficiency of thermal management systems used in axial electric motors. One of the more specific recent papers was published in 2023 [14]. This paper provides detailed descriptions of various axial electric motor topologies, discusses the sources of losses and describes the thermal properties of the materials used as well as the thermal management systems employed. However, it lacks quantitative comparison of temperature rise in different thermal management systems, it's influence on performance of the machine as well as several examples of thermal management systems outlined in the patents. Compared to the review papers, this review covers a larger number of thermal management systems, including those described in patents. It quantitatively compares rotor and stator thermal management systems, describing temperatures within the system and the impact of each system on motor performance. Additionally, a greater number of management systems are covered, considering that some thermal management systems were omitted in previous review papers. The main novelty of the work is that it provides a clear description of the temperature rise in key motor components cooled by each cooling technique, as well as the impact of each cooling technique on parameters such as pressure drop and convective heat transfer.

1.2 Brief description of review methodology

Elsevier's Scopus database served as the primary source for reviewed articles, specifically existing research findings. The initial selection was based on the targeted keywords: Electric vehicle, axial flux motors, thermal management, thermal analysis. The subject area was limited to Energy, Energy engineering and power technology, Renewable energy sustainability and the environment and Automotive engineering. The articles written in English with the year of publication being between 2015 and 2024 were considered. After the primary selection, articles describing thermal management systems for axial electric motors and their impact on performance were chosen. The selection was made this way because many articles focused on methods of analysing heat transfer in axial motors without providing detailed descriptions of the thermal management systems themselves. Numerous innovative thermal management systems are described in patent applications. To obtain a comprehensive overview of cooling techniques, a patent search was conducted in the EPO patent office. The same key words, time frame and language were used. In this review paper, different methods of modelling heat transfer, such as Lumped Parameter Thermal Network (LPTN), Finite Element Analysis (FEA), and Computational Fluid Dynamics (CFD) modelling, were not taken into consideration. A review and summary of cooling fluids used in various cooling techniques were not conducted, nor was a theoretical description of heat transfer to various parts of the system.

2. TOPOLOGIES OF AXIAL FLUX ELECTRIC MOTORS

Axial flux electric motors can be produced in several configurations that differ based on the number of rotors and stators, as well as their geometric arrangement within the motor. There are four possible topologies [15]: single stator single rotor (SSSR), double stator single rotor (DSSR), single stator double rotor (SSDR) and multi stator multi rotor (MSMR) as shown in figure 2.1. [16].

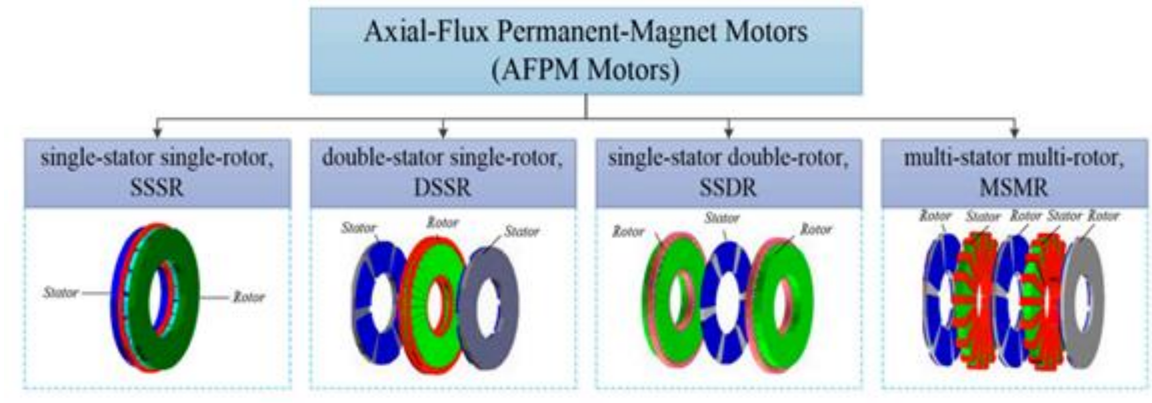

Figure 2.1. Topologies of axial flux electric motor, [16]

2.1. Single stator single rotor (SSSR)

This machine topology is conceptually straightforward and similar to traditional radial flux machines, necessitating a yoke in both the stator and rotor to complete the magnetic circuit [17]. The necessity of using a yoke in the stator complicates the use of Soft Magnetic Composites (SMC), which could otherwise simplify motor manufacturing. The resulting manufacturing difficulty is one of the major obstacles to the widespread adoption of axial electric motors of all topologies. The main disadvantage of SSSR axial flux motor is the imbalanced axials forces which stresses the bearings, shortens their lifespan, and increases friction loss [18]. The main advantage of the SSSR design is the ability to create an effective cooling system due to the large contact area on the back of the stator, which enables efficient heat transfer. However, due to the lower torque density and manufacturing difficulties, axial electric motors of this design are not available on the market.

2.2. Double stator single rotor (DSSR)

In this configuration, one rotor is situated between two stators, which are electrically separated [19]. The axial forces on the rotor are balanced. The DSSR topology generally requires fewer magnets compared to the SSDR design to achieve the same power. The reduced use of magnets positively impacts the cost of the motor, as magnetic material is the most expensive component. However, to compensate for the reduced use of magnetic material, more copper is needed, which negatively affects the motor's weight and efficiency. Additionally, the fact that the rotor is located between the stators complicates the cooling of the permanent magnets, which are at risk of permanent demagnetization with increasing temperature.

2.3. Single stator double rotor (SSDR)

This configuration is the most extensively researched as it allows for the use of minimal amounts of copper, reduces the axial length of the motor, increases power density and enhances motor efficiency. The three-dimensional nature of the magnetic flux permits a wide range of design variations, leading to a broad array of cooling techniques. One of the most popular designs is the YASA (Yokeless and segmented armature) configuration [11]. The main idea of this design is to eliminate the stator yoke, thereby reducing the weight, iron losses and axial length of the motor. The stator cores are segmented, which greatly simplifies manufacturing and allows for the use of SMC. These advantages are reflected in its dominant market presence and its distinction as the first successfully commercialized axial electric motor in the automotive industry. The most popular startup working on this design is YASA from Britain, which, in collaboration with Mercedes-Benz, plans to produce the first cars with axial electric motors in 2025. Due to the high torque density achievable with this configuration, optimal thermal management system becomes crucial. The motor's performance cannot be fully utilized unless the cooling system can manage the generated heat effectively.

2.4. Multi stator multi rotor (MSMR)

In applications where axial space is not restricted and a significantly higher torque is required, it is possible to use the Multi-Stator Multi-Rotor (MSMR) configuration of an axial electric motor [20]. This configuration is achieved by stacking an additional number of stators and rotors depending on the required power. This design is an extension of the Single stator dual rotor (SSDR) and Dual rotor single stator (DRSS) configurations and retains the characteristics of the design from which it originated.

3. THERMAL MANAGEMENT SYSTEMS FOR AXIAL FLUX ELECTRIC MOTORS

There are several ways to categorize cooling techniques, such as by the type of fluid used, the method of heat transfer employed, or the specific part of the motor being cooled [8]. In permanent magnet electric motors, special attention must be given to cooling the magnets and rotor, stator cores and windings.

3.1. Permanent magnet and rotor thermal management systems

Overheating of permanent magnets can lead to permanent demagnetization if the temperature rises above a certain threshold, which is defined by the type of magnet [21]. For neodymium magnets used in automotive electric motors, the temperature for permanent demagnetization is typically 150°C [22]. In addition to the risk of demagnetization, a negative effect of increasing the temperature of the magnets is the decline in their magnetic properties with rising temperature. For a neodymium magnet with an SH rating, where the demagnetization temperature is 150°C, the coefficient of remanence reduction is 0.105%/°C, and the coefficient of coercivity reduction is 0.55%/°C, the significantly higher rate of coercivity reduction poses a risk of demagnetization due to the negative d-axis current component when the motor operates in field weakening mode [23], [24]. Permanent magnets are secured to the rotor surface using high-strength adhesive. At high speeds, centrifugal forces on the thin adhesive layer can lead to adhesive separation, especially when the adhesive is heated to high temperatures where its properties significantly degrade [8]. For example, single-part heat-cured epoxy like Permabond ES550 loses 60% of its shear strength when heated from 20°C to 120°C [25]. The heat generated in the rotor is not particularly dangerous for the rotor itself, but because the magnets and adhesive are in direct contact with the rotor, the heat heats them up and exacerbates the rise in temperature. Given all off the above, it is essential to pay special attention to cooling the rotor and permanent magnets in an axial electric motor. This chapter will describe various attempts to improve heat dissipation from the rotor and permanent magnets.

3.1.1. Air cooling of permanent magnets and rotor

One of the advantages of air cooling for the rotor is the high relative rotor speed of an axial electric motor, due to the large diameter that is characteristic of this type of machine. Rasekh [26] investigated turbulent heat transfer in the air gap between the stator and rotor for the DRSS configuration. He examined flow characteristics and heat transfer for rotational Reynolds numbers ranging from 2.5×10^4 to 2.5×10^5 and for air gap-to-rotor diameter ratios of 0.00667, 0.01333, and 0.02667. The aim of the study was to improve heat transfer in the system to reduce the rotor temperature. To achieve this, it was proposed to add holes to the rotor which can be seen in figure 3.1.

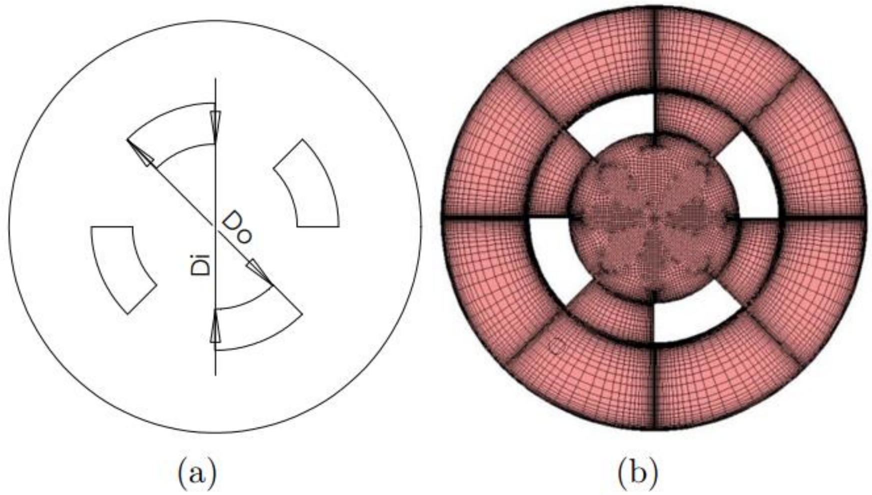

Figure 3.1. (a) Drawing of the rotor disk with the holes (D_i = 60 mm, D_o = 90 mm & D_{rotor} = 150 mm) (b) Surface mesh of the rotor disk with the holes, [26]

The study showed that the radial air velocity in the air gap increases from 1.9 m/s when there are no holes to 3.0 m/s when holes are incorporated. The result of the increased radial flow is a doubling of heat transfer from the rotor for a Reynolds number of 1.26×10^5 and an air gap-to-rotor diameter ratio of 0.0133. However, the study did not cover heat transfer in the laminar regime, and the maximum speed of 6300 RPM is insufficient considering that automotive axial electric motors can operate up to 10000 RPM. Additionally, the downside of adding holes is that they reduce the rotor's stiffness and cause greater rotor deflection due to attractive axial forces. Chong et al. [27] reached a similar conclusion. Adding holes increased the mass airflow in the air gap, but this study did not describe the extent to which heat transfer was improved. In previous studies, the rotor surface was smooth.

Rasekh et al. [28] investigated heat dissipation through channels formed between adjacent rotor magnets. The rotor disk with the magnets, then functions like a centrifugal fan, promoting efficient cooling of the air gap. The rotor also incorporates an annular opening. However, the effects of the radial spokes, connecting rotor parts, on the flow field were not considered. The study evaluated how factors such as the angle of the permanent magnets, the magnet thickness ratio, the air gap length, and the rotor speed affect heat transfer within the air gap. They demonstrated that adding an annular opening significantly improves heat dissipation from the rotor to the surrounding air.

Mohamed et al. [29] investigated the impact of holes in the rotor that are radially positioned beneath the channels formed between the magnets (figure 3.2.). The study considered the impact of the permanent magnet angle, the magnet thickness ratio, the air gap length, and the rotor speed on heat transfer in the air gap.

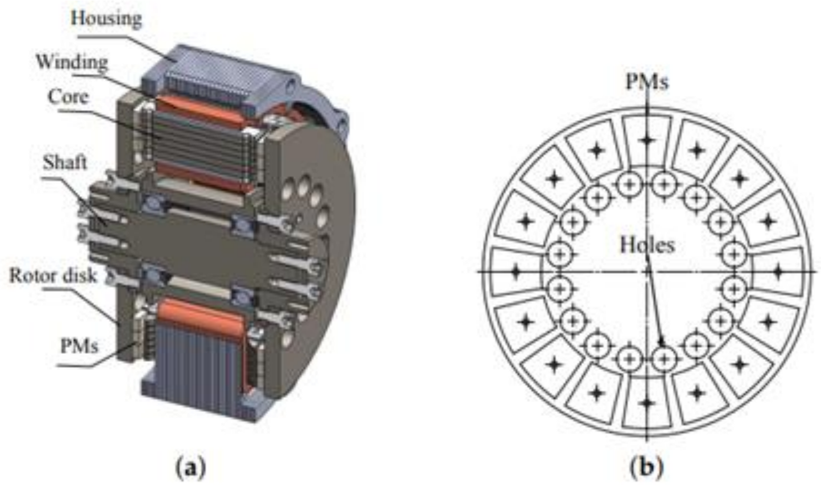

Figure 3.2. Prototype and rotor structure; a) Prototype cross section, b) Rotor geometry, [29]

In the study, only mechanical losses were considered as the source of heat in the magnets, so the resulting temperature is lower than expected. The results show that the magnet temperature increases with an increase in the magnet angle ratio due to reduced airflow through the channel between the magnets. For a magnet angle ratio of 0.7, the average temperature is 31.2°C, which rises to 42.2°C for a magnet angle ratio of 0.9. As the magnet thickness increases, the temperature decreases, but the effect is minimal. A significant impact is observed from the air gap ratio and the motor radius. For an air gap ratio of 0.00667, the average magnet temperature is 40°C, while for 0.0337 it is 32°C. The expected decrease in temperature with increasing speed due to improved heat dissipation was also confirmed. However, the study does not describe the geometry of the holes or their precise location. The influence of hole diameter on convective heat transfer has not been established.

Fawzal et al. [30], [31] transformed the rotor of an axial electric motor into a fan by adding blades of various shapes to the rear side. The shapes of the blades were adopted from various technical applications (figure 3.3.).

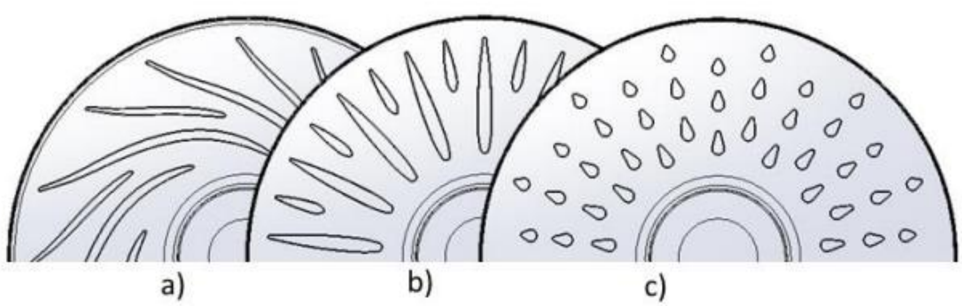

Figure 3.3. Types of blades used: a) backward-inclined aerofoil, b) radial aerofoil blade and c) tear drop pillar blade, [31]

The backward-inclined aerofoil blade was adopted from a force-draft blower [32], radial aerofoil blade from a typical fan engineering application [32] and tear drop pillar from an automotive disc brake [33]. For rotor cooling applications, the use of a backward-inclined aerofoil blade is restricted to unidirectional machines, while radial aerofoil blades and tear drop pillar blades can be employed in machines designed for bidirectional operation. The performance of each design was evaluated based on the average heat transfer coefficient, windage losses and mass flow rate. The research was performed using numerical simulations with a validated CFD model of the machine. The rotor wall temperature was set to 80°C in all three designs. It was shown that the radial blade design has the highest mass flow rate and the highest average heat transfer coefficient, which are 0.012 kg/s and 250 W/(m^2·K) at 3500 RPM, respectively. The pillar type has the highest windage losses, amounting to 50 W at 3500 RPM. Due to the rotor wall temperature being kept constant at 80°C, the thermal load was varied. Consequently, the study does not clarify how the different designs would perform under the same thermal load, that is, with the same amount of heat generation. Furthermore, adding an impeller to the rear side of the rotor increases the rotor's stiffness and reduces axial deflection. However, the downside is an increase in the axial length of the motor. Fawzal et al. [34], [35] also investigated different configurations of inlet and outlet openings for airflow. Three designs were proposed and tested [34]:

A) design 1 – inlet is introduced on the top and the outlet at the bottom of the cavity system
B) design 2 – both the inlet and the outlet are tangential to the cavity circular design
C) design 3 – inlet is at the centre and outlet is set tangential to the cavity circular design

The cooling performance of all the studied designs can be evaluated by examining their flow characteristics, windage losses, thermal properties and pressure drop. At 6000 RPM, design 1 has a pressure drop of 3720 Pa, which is 2.20 and 4.14 times greater than design 2 and design 3, respectively. At the same speed, design 1 has the highest windage losses, totalling 35 W, while design 2 has 30 W and design 3 has 26 W. At 4000 RPM, the losses in the magnets and rotor are at their maximum. The average magnet temperature is 89.6°C for design 1, 97.5°C for design 2, and the lowest at 85.0°C for design 3.

Zaher [36], [37] numerically tested different rotor design variations with the aim of determining the optimal configuration in terms of cooling performance. Based on previously proposed practical suggestions, Zaher defined six possible variations in rotor geometry and additions and conducted a comparative analysis of temperature rise for the same heat generation. This approach allows for a quantitative comparison of the proposed designs (figure 3.4.).

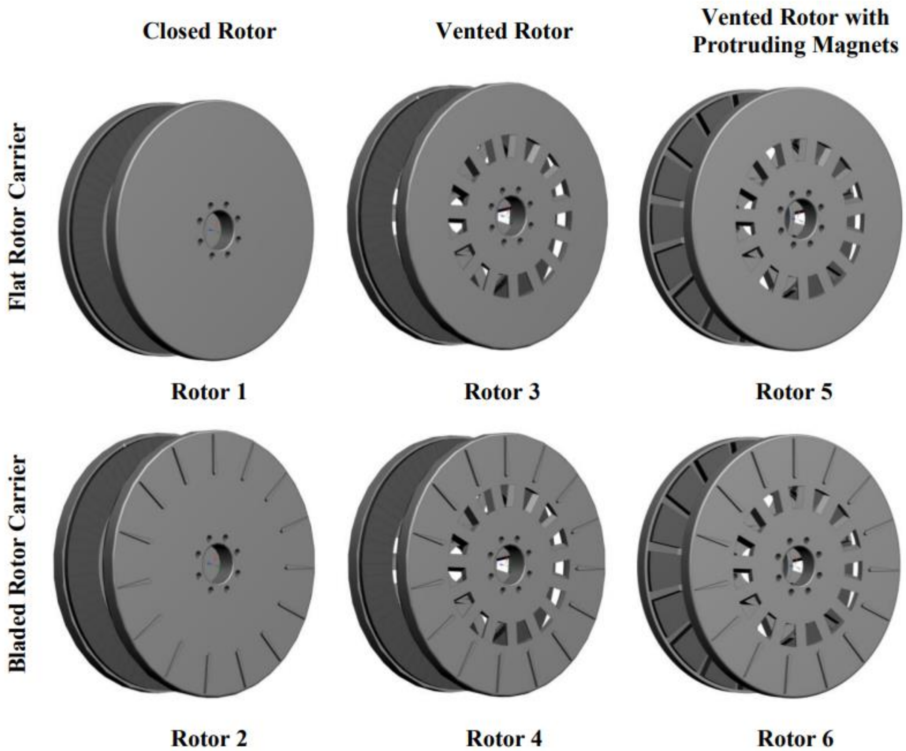

Figure 3.4. Different possible configurations, [14]

The improvement in rotor cooling is most effectively demonstrated by reducing the maximum temperature of the magnets under the same operating conditions. This temperature reduction is directly linked to an increase in either the mass flow rate, the rotor's average heat transfer coefficient, or both. The geometry of the rotor determines the amount of momentum transferred from the rotor to the air, which in turn defines the rotor's pumping power and, consequently, the mass flow rate. Flow turbulence, primarily influenced by the rotor's surface geometry, dictates the surface conductance and, therefore, the heat transfer coefficient. Additionally, there is a direct relationship between mass flow rate and windage losses, which represent the rotor's pumping power. This relationship was particularly evident in rotors with embedded fans or surface-mounted magnets, which create a centrifugal fan-like effect. For rotor 6, the maximum magnet temperature is 83.6°C, which is 73.2°C lower than in the worst-case scenario for rotor 1. On the other hand, for rotor 6, the windage losses are 263.5 W, which is 244.5 W higher than in rotor 1. Despite the improved heat dissipation in rotor 6, the significant increase in windage losses negatively impacts the efficiency of the axial electric motor, making it necessary to optimize the shape of the blades to reduce these losses.

Le et al. [38] proposed an enhanced rotor air-cooling method for axial flux machines with housing-cooling. To enhance the rotor's air-cooling performance, annular and rectangular fins have been placed on the inside of the housing, considering the fluid flow characteristics of axial flux motors within a cavity. The relationship between the thickness and width of the fins and cooling performance was investigated. It was concluded that for annular fins with a width of 4 mm and a thickness of 6 mm, the average magnet temperature is reduced from 121.2°C to 91.4°C, while for rectangular fins with a width of 48 mm and a thickness of 6 mm, the temperature is reduced from 121.2°C to 101.4°C. However, the study did not consider the impact of the fins on windage losses, or the pressure drop caused by rotor rotation.

In a similar design, Le et al. [39] proposed using tile-shaped fins for cooling the rotor of an axial flux electric machine. Proper positioning and sizing of the fins can significantly increase local airspeed and turbulence intensity, which can positively affect heat transfer. The impact of fin thickness and angle of spread was considered when defining the optimal design. For a fin thickness of 8 mm and a spread angle of 20 degrees, a temperature reduction of 17°C is achieved for the magnets. However, similar to previous studies, the impact of the fins on pressure drop and windage losses was not investigated.

3.1.2. Liquid cooling of permanent magnets and rotor

The advantage of liquid cooling is the enhanced thermal properties of liquids compared to air, however, the drawback is the increased windage losses and pressure drop within the system.

Jasper et al. [40] proposed an innovative direct cooling method for rotor magnets using oil from the stator. On the side covers of the stator, there is one or more openings on each side through which oil from the stator is sprayed under pressure. The openings are positioned at the bottom of the stator so that, due to centrifugal force, the oil spreads over the entire surface of the permanent magnets. The oil can be sprayed at a specific angle and flow rate, depending on the losses. Additionally, sufficient space must be left in the stator for the installation of nozzles, and between 10% and 30% of the circulating oil is used for cooling the magnets, depending on the losses. However, the temperature reduction achieved by this method has not been quantified.

Woolmer et al. [41] proposed cooling the magnets and rotor of an axial electric motor by creating a hermetically sealed enclosure around the rotor and filling its bottom with oil through which the rotor passes, dragging the oil along and thereby cooling the magnets. Various flow guides are placed inside the enclosure to better disperse the fluid across the rotor's surface and to induce turbulent flow, which enhances heat transfer. It has been proven that the rotor's temperature can be reduced from 100°C to 80°C under maximum motor load. However, the passage of the rapidly rotating rotor through the oil, which has a significantly higher viscosity than air, increases windage losses and introduces issues related to fluid leakage.

Chuan et al. [12] studied hybrid cooling of the stator and magnets in SSSR axial electric motor with axial shaft cooling and fan-assisted airflow. The study compared forced air cooling, water cooling through a hollow shaft, and combined cooling using both forced air and water through the shaft, evaluating their effects on magnet temperature for the same heat generation. Forced air cooling gave average magnet temperature of 102°C. Water cooled through the hollow shaft brought down the operating temperature of magnets to 70°C with combined cooling method giving the lowest temperature of 59.5°C. The study did not describe pressure drops or windage losses and did not consider the impact of water on magnet corrosion. Furthermore, under comparison of various designs, Lumped Parameter Thermal Network (LPTN) was used, therefore experimental verification is needed to validate these findings.

To improve the heat dissipation capabilities of the rotor components, Zhu et al. [42] proposed a self-circulating oil cooling system with a hermetic seal, in which the cooling liquid circulates through a hollow shaft. During operation, the oil flow, driven by the centrifugal blades, establishes a closed-loop oil circuit, creating an effective heat transfer path from the hot areas to the cooler regions. First, the structure of the motor and the temperature increase without cooling through the hollow shaft were described, focusing on the losses occurring at the point of maximum power generation. It was shown that the maximum temperature increase in the magnets is 129.5°C. It was demonstrated that by adding cooling through the hollow shaft, the magnet temperature was reduced by 12.8 °C. The main drawback of this cooling technique is the high cost and complexity of manufacturing a hermetically sealed hollow shaft and increase in weight of the rotating parts due to the oil filling the cavity. Table 3.1 provides a comparison of different thermal management systems for cooling the permanent magnets and rotors of axial flux motors.

Table 3.1. Comparison of different thermal management systems for permanent magnets of axial flux electric motor

Author	Cooling method	Setup	Coolant type	Windage losses (W)	Mass flow rate (kg/s)	Pressure drop (Pa)	Heat transfer rate (W/(m^2K))	Magnet temperature (°C)
Fawzal et al. [30]	Backward inclined aerofoil blade	SSDR	Air	20	0.009	25	249	80
Fawzal et al. [30]	Radial aerofoil blade	SSDR	Air	31	0.012	30	250	80
Fawzal et al. [30]	Tear drop pillar	SSDR	Air	50	0.01	39	198	80
Fawzal et al. [34]	Design 1	SSDR	Air	35	0.018	3720	110	89.6
Fawzal et al. [34]	Design 2	SSDR	Air	30	0.018	1690	76	97.5
Fawzal et al. [34]	Design 3	SSDR	Air	26	0.018	898	123	85
Zaher et al. [36]	Closed flat rotor carrier with gapless magnets	SSDR	Air	18.98	0.0112	-	48.2	156.8
Zaher et al. [36]	Straight aerofoil blades on the backside of the rotor carrier	SSDR	Air	161	0.0514	-	93	112.4
Zaher et al. [36]	Flat rotor carrier with holes	SSDR	Air	38.7	0.0263	-	117.9	95.7
Zaher et al. [36]	Straight aerofoil blades with ventilation holes	SSDR	Air	200	0.0677	-	161.5	82.6
Zaher et al. [36]	Flat rotor carrier with holes and protruding magnets	SSDR	Air	141.6	0.0427	-	168.7	88.2
Zaher et al. [36]	Straight aerofoil blades with ventilation holes and protruding magnets	SSDR	Air	263.5	0.074	-	206.6	83.6

3.2. Stator cores and windings thermal management systems

Stator overheating creates several downsides to the operation of electric motors. Above everything else, an elevated temperature leads to a copper winding's electrical resistance increase by 0.393%/°C increment in its temperature [43]. The rise in electrical resistance for a given rise in temperature further reduces efficiency and complicates cooling of the motor. Windings of electric motors are made of enamelled copper wires to avoid short circuits between windings of the same phase or windings of different phases. [44]. Depending on their temperature tolerance, enamel comes in various forms namely, grade H is typically used for motors in the automotive industry and operates at 180°C. It is common knowledge that enamel life span halves with every 10°C rise in operating temperature, thus, controlling this factor is crucial for avoiding short circuits [45]. When temperatures go up, they can also cause melting of SMC grain boundaries, which serves as an insulator between them. Additionally, thermal expansion of SMC is a problem due to reduction in air gap and possibility of impact between rotating rotor and stationary stator.

3.2.1 Indirect stator cooling

Indirect cooling involves air cooling over the external surface of the stator, as well as the use of channels through which coolant flows, supported by thermally conductive materials that transfer heat via conduction from the point of generation to the coolant.

3.2.1.1. Enhanced Air Cooling Using Conductive Elements

These cooling methods rely on heat dissipation through airflow across the stator's external surface, driven by the rotor's rotation or the surrounding air movement.

Vansompel et al. [46] proposed the addition of aluminium fins between the stator cores. With no cooling system on the outer surface of the stator, self-ventilation of the rotor disks achieved a heat dissipation rate of 40 W/(m²·K) at an external temperature of 25°C. Temperature sensors were installed at six locations in the stator, with the highest temperature for nominal losses being 83.2°C. The temperature difference between the windings and the outer stator surface was less than 10°C, which confirms the good contact between the copper and the fins. However, the proposed aluminium fins generate additional losses that reduce efficiency. While improved heat dissipation is beneficial despite the additional losses, it is possible to replace the aluminium fins with copper ones [47]. Given that copper has a significantly higher density than aluminium, it is not optimal to replace the entire stator lamination with copper. Instead, it is more effective to use copper only for the portion of the fins that extends between the stator cores and contacts the copper windings.

Vansompel et al. [48] proposed filling the space between aluminium fins with different kinds of epoxy resins. Adding epoxy resin to the gap ensures a reduction in thermal resistance between the copper windings and the fins. Additional benefits include vibration damping, increased rigidity of the stator, and prevention of contamination. Compared to [46], the maximum temperature was reduced to 75.4°C.

A new cooling arrangement that has been proposed by Winterborne et al. [49] contains heat spreading materials on individual armature segments to improve heat dissipation. The method of approach involves putting aluminium heat transfer fins on each tooth of the stator located between the coil and tooth. These fins extend to the outer aluminium casing where they are bolted with a joining area of large surface which is attached with a thermal compound for optimal thermal contact. The fin design and their connection with coil serve as trade-off between good thermal conductivity along the heat path and sufficiently low impedance resistance. Eddy currents due to the magnetic field generated by coils can be problematic. Consequently, fins are slotted in line with heat flow, thereby shortening paths for eddy currents while minimizing disruptions to intended course of heat transfer. Estimated losses were computed considering 5 A/mm² current density resulting in maximum temperature being 157.8°C at the stator core. Losses had been linearly increased in finned model until reaching this maximum temperature. When current density rose up to 6.9 A/mm², temperature remained at the same level thus indicating a 39.7% rise in current density. The increased radial length due to fins enlarges the motor's diameter, and these fins generate losses that reduce the motor's efficiency.

Zhang et al. [50] proposed a combined cooling method using heat pipes and forced air circulation around the perimeter of the stator. Since the heat transfer path in a single stator double rotor AFPM machine is limited, the heat pipes offer additional heat dissipation routes for the windings and stator. The heat pipes occupy space that could otherwise be used for copper windings, and due to magnetic leakage, some losses will occur in them. Therefore, the shape and position of the heat pipes were optimized to define the optimal balance between heat dissipation and the generation of additional losses in the system. Fins were added to the outer surface of the stator to increase the surface area for heat dissipation. Optimal performance is achieved when the heat pipe is positioned at the centre of the slot, with dimensions of 18 mm in length, 5 mm in width, and 102.5 mm in height. At an airflow velocity of 5 m/s, the maximum temperature in the windings is 146.31°C. However, the additional losses in the heat pipes, the reduced space for windings, and the high cost are negative aspects of this cooling method.

A new area of development for high-efficiency axial electric motors involves axial motors with two rotors and a single stator, where the stator is designed with copper windings embedded in a Printed Circuit Board (PCB). In these motors, there are no iron losses, and losses in the rotor and magnets are negligible. Practically all losses occur in the copper, due to eddy currents generated by the rotation of the magnets and the flow of current. Bauer et al. [51] proposed an enhanced cooling strategy for the multilayer PCB motor windings. The use of thermal vias for parallel multilayer PCB winding systems was proposed in combination with a heat sink. The main reason for adding thermal vias is the poor thermal conductivity of the FR4 material used in PCB fabrication. When designing PCB motor windings, trace width must be kept small to minimize parasitic eddy current effects, and through-hole vias are employed along the winding tracks to optimize vertical thermal flow. To determine the difference in temperature rise, a direct current of up to 25 A is injected into both winding systems—one with thermal vias and one without—and the steady-state surface temperatures are measured. The maximum temperature in the case without thermal vias is 63°C, whereas with thermal vias it is 51°C, representing a reduction of 12°C.

3.2.1.2. Outside diameter water jacket cooling

In this cooling method, cooling tubes are placed on the outer diameter of the motor stator to reduce the thermal resistance between the point of loss generation and the cooling fluid. Water is the most commonly used fluid, and the channels are typically made of copper due to its high thermal conductivity.

In their study, Chuan et al. [12] used stator indirect liquid cooling by a water jacket having only one coolant path. They examined a single stator, single rotor axial flux permanent magnet motor of 1.5 kW power rating at 4500 RPM. At the nominal power, the efficiency of the motor was observed to be 89.9%, leading to losses of 176.6 W which were distributed as follows; stator generated 148 W while rotor generated a mere 28.6 W. The research aimed at comparing three ways of cooling and how it influenced on winding temperature; forced air cooling, stator water jacket cooling and liquid cooling through hollow shaft respectively. Water jacket cooling resulted in constant average winding temperature at 98°C, whereas forced air-cooling maintained it at 140°C and cooling through the hollow shaft kept it at 150°C. Stator water jackets are effective in keeping the temperature of windings down, but their greatest limitation is that they do not cool magnets effectively whose temperatures become limiting factor. Moreover, they neither stated what pressure drop nor identified maximum temperature for the stator core which are important parameters with significant impact on performance of such cooling systems.

Veg et al. [52] examined two cooling possibilities for axial electric motors: one is the cooling through a channel on the outer periphery of the stator as in SSDR design, while the other is cooling integrated in rear of the stator such as designs SSSR and DSSR. The researchers compared these cooling methods using similar motor performance parameters, and it turned out to be that maximum temperature with respect to first type of cooling was 136.1°C whereas for second type this value accounted for 102.2°C. Furthermore, better temperature uniformity was achieved by means of liquid contacting entire heat generating surface which characterize second method of cooling. However, the second method of cooling increases the axial length of the motor significantly and adds to the overall weight of the system.

For in-wheel automotive applications, Chang et al. [53] put forward a new cooling system for an axial electric motor. Before being improved, the cooling system consisted of a water channel on the surface of the casing. The new concept of this cooling system is based on two main improvements. First, windings are placed near the aluminium fins that are located inside water-cooled housing. Second, U-shaped water-cooling pipes are integrated into those fins to enhance heat dissipation. This method notably decreases the thermal resistance between the heat source and the coolant resulting in reduced temperature rise. After these improvements were made, maximum winding temperature was reduced from 187.6°C to 100.9°C. During optimization of the system layout, number of pipes was optimized to decrease pressure drop within it. Following this optimization, there was a drop in pressure from 213.2 kPa to 117.9 kPa. The motor's power density is adversely affected by locating the fins in between the windings and stator core. The efficiency of the motor reduces due to losses caused by generating eddy currents inside aluminium fins.

Improved temperature distribution of the stator could be achieved through a new stator cooling structure that combined heat pipes and a housing water-cooling method, as proposed by Le et al. [54]. Heat pipe system, characterized by small size, light weight and high efficiency of passive phase change cooling has gained popularity as an alternative for thermal management of electric motors. Heat pipes are placed between the stator cores and have a rectangular cross-section to provide a larger surface area for heat transfer. The gap between them is filled with resin to improve structural strength while minimizing heat resistance. Three types of jackets are used on the outer diameter of the stator. In these three cases, water entering the reservoir has a temperature 25°C and mass flow rate remains constant at 0.2 kg/s. It is important to note that parallel channel yields the lowest pressure drop (306 Pa) which means it consumes less energy compared to other options. On the contrary, axial channels exhibit a higher pressure drop (9902 Pa) than spiral channels (6857

Pa). The average winding temperature reduces to 70.1°C upon plugging in heat pipes into it. However, the study does not specify the extent of this temperature reduction compared to the situation without heat pipes.

Damme et al. [55] compared the electromagnetic and thermal performance of an axial flux motor using anodised aluminium foil and enamelled copper wire as stator winding materials. Foil windings limit electromagnetic design flexibility and pose additional manufacturing challenges, such as requiring open slots or removable teeth for (semi-)closed slots. In an axial flux permanent magnet synchronous machine, coils can be wound before being assembled into a single stator, which addresses these issues and enables innovative, highly automated manufacturing methods. A significant advantage of anodised aluminium foils is their higher thermal conductivity compared to enamelled copper wires, which can significantly enhance heat transfer. Two cooling cases were studied on the outer perimeter of the stator: forced air cooling and indirect liquid cooling. For air cooling, the maximum temperature with aluminium foil is 31°C lower than with enamelled copper, while for liquid cooling, the temperature is 68°C lower. Therefore, it is possible to achieve a higher torque density by using anodised aluminium foil. However, due to the lower electrical conductivity of aluminium, losses are higher compared to copper wire.

3.2.1.3. End cover water cooling

In end cover water cooling, the cooling fluid encounters the rear side of the axial motor's stator. Due to the large contact area, it is possible to achieve better temperature uniformity across the stator.

Four types of cooling structures were compared by Liu et al. [56] which are a channel with spoilers, a helical structure, a tandem structure and Z-shaped structure. The inlet and outlet diameters of all four types of channels are the same. For selecting an appropriate cooling structure, it simplified the motor by ignoring the effect of rotor. The complex stator structure was assumed as a homogenous heater whose thermal conductivity is constant, and energy yielded per unit volume by equivalent stator was maintained uniform. Thus, this method ensured that comparisons between different cooling methods were made under identical conditions. It should be noted that maximum temperature increases of 90.76°C occurred in spoiler channel, while minimum rise of 81.28°C was observed in case of the tandem channel. Among them, Z-shaped channel had greatest pressure drop of 7087 Pa while spoiler channel experienced minimum pressure drops of 376.2 Pa. However, machine loss as well as distribution of these losses is unknown such that there can be no certainty as to where temperatures encountered at any operational point are compared from.

Chai et al. [57], [58] suggested using a central cavity in the end of the windings equipped with the potting material to improve the heat transfer in end windings. The effect of thermal conductivity of potting materials upon cooling effectiveness was also investigated. It was found that adding epoxy resin around end winding reduced the heat resistance between them and an end shield. This results in a temperature reduction of 8.3°C after 300 seconds of overload. Elevating epoxy's thermal conductivity from 0.8 W/(m·K) to 1.4 W/(m·K), will reduce the maximum temperature for about 9.8°C.

In a report by Polikarpova et al. [59], [60] a novel hybrid cooling system was proposed. The hybrid cooling system includes the copper bars embedded in stator teeth, water channels inside the frame, and end windings encapsulated within a potting material. In combination with three copper pipes and potting material, the maximum temperature reduces from 139°C to 118°C as compared to initial case of only using liquid. However, addition of copper tubes into the stator cores causes an increased loss at the stator cores due to reduction in area for magnetic flux passage. This leads to higher magnetic field density causing more losses.

The cooling strategy proposed by Odvarka et al. [61] included the use of an aluminium water jacket inserted between two laminated stator cores. The jacket is circular in shape and has a small diameter hole at its centre through which the coolant passes. This duct contains a width gradient across it, due to the presence of grooves. As a result, these grooves promote turbulence in the flow of coolants thus increasing heat transfer. Temperature and heat transfer analysis was carried out using CFD simulations. They compared temperature rise in windings with respect to volumetric flow rate of coolant. The winding temperature went up by 53°C for a flow rate of 5 L/min in this case. However, adding an aluminium void to stator increases air gap length effectively, hence requiring larger magnets. Additionally, eddy currents generated in the aluminium will reduce the motor's efficiency.

3.2.1.4. Internal cooling channels

To further reduce the thermal resistance between the heat generation points and the cooling fluid, cooling tubes can be positioned between individual windings in the stator of an axial motor. Although this approach may lead to losses due to the varying magnetic field in the active part of the stator, the rate of heat dissipation can be significantly improved.

Jones-Jackson et al. [62] analysed three cooling designs that were integrated into the stator potting and established the difference in efficiency for each design. While considering a variety of parameters related to design, they attempted to determine how the maximum temperature of winding and pressure drop changed. Three potential designs have been investigated: full inter-winding, horseshoe winding and central winding. The first design involves using pipes along the outer and inner diameters and between adjacent windings. The second design is like the first but omits the pipes in the inner diameter section. The last design uses a cavity for fluid flow between adjacent windings. The pressure drop, heat transfer coefficient, and thermal resistance were calculated for the three cases. The highest-pressure drop was observed for the horseshoe design, measuring 6933 Pa, while the lowest was for the central winding design, at 4758 Pa. However, there is a lack of quantitative comparison of the maximum temperature.

Li et al. [63] have explored a new cooling pipe structure for the segmented core of a large axial flux permanent magnet generator. The stator tooth base contains a copper cooling pipe that has two parallel channels. The prevailing factor is the short distance between the water-cooling pipe and the windings, which leads to minimum thermal resistance between the heating source and cooling system. This enables quick transfer of heat produced by copper and iron losses to water under consideration. With an inner diameter of 14 mm, 1 mm thickness, and a water flow rate of 1.5 m/s, the copper pipe had an average heat transfer coefficient calculated both analytically and numerically using computational fluid dynamics of 8039.7 $W/(m^2{\cdot}K)$. At rated power, a maximum temperature of 90°C is found at end winding on this generator's cooling pipes. However, pressure drop study was not carried out; nevertheless, large cross-sectional area in the tube with low flow velocity indicates that there should not be significant issue about it.

Le et al. [64] compared three types of water channel structures positioned in the stator of SSDR motors. The SSDR implementation with YASA configuration was investigated in this study. In the first design, water travels in a zigzag pattern between 12 stator cores in a single direction. In the second design, water also flows in the same direction, but the water pipes are arranged so that when the first pipe covers the upper side of the core, the second pipe covers the lower side. In the third design, the water flows as in the second design, but the inlet and outlet are positioned 180° apart. All three designs have the same inlet conditions: fluid velocity of 1 m/s and inlet temperature of 25°C. The second design recorded the minimum temperature whereas the lowest pressure drop occurred in the third design. This study did not consider any loss generation within copper tubes that were used for cooling. Besides, no attention was paid to reducing space available for copper and stator cores, as well as its impact on power density in this paper.

Lai et al. [65] proposed an innovative cooling for DSSR. The proposed cooling system includes water-cooled frames, cooling rings, and potting material inside the frame. The system uses a water jacket and potting to manage heat. The epoxy helps to mitigate overheating of the end windings by providing a thermal path that directs heat towards the frame. An innovative feature of this system is the cooling ring, which is integrated into the aluminium frame. These rings tightly surround the stator, significantly increasing the cooling area of the yoke. The temperature rise in the windings was compared across three types of models. Model 1 employs traditional potting without thermal grease or a cooling ring. Model 2 uses an improved potting version with a cooling ring. Model 3 features a potting version with both a cooling ring and thermal grease. The winding temperature was 132°C for the first model, 125°C for the second model, and 113°C for the third model (Table 2).

Mueller et al [66] investigated an air-cored axial flux generator. The stator does not have iron which is why conventional designs are not efficient in providing conductive heat transfer for the windings. Three cooling approaches to the windings were considered: natural air cooling, direct liquid cooling, and application of heat pipes. For heat pipe cooling, three thermocouples were placed within the stator and analysis was done for different sizes and shapes of heat pipes. The least temperature was achieved using a bent top part of a heat pipe which 15°C less compared to no use of any heat pipe. Table 3.2. provides a comparison of different thermal management systems for indirect cooling of stator windings and cores.

Table 3.2. Comparison of different thermal management systems for stator windings and cores

Autor	Cooling method	Setup	Coolant type	Inlet coolant temperature (°C)	Nominal power (kW)	Losses (kW)	Stator losses (kW)	Max. temperature (°C)	Pressure drop (Pa)	Flow rate (L/min)
Chuan et al. [12]	OD water jacket	SSSR	Water	50	1.5	0.1766	0.148	98	-	5
Veg and Laksar [52]	OD water jacket	SSDR	Water	90	25	1.67	1.27	136.1	-	20
Veg and Laksar [52]	End cover water jacket	DSSR	Water	90	25	1.67	1.27	102.2	-	20
Chang et al. [53]	U shape water cooling pipes	SSDR	WEG	60	65	5.6	4.2	100.9	117900	8
Le et al. [54]	OD spiral channel/heat pipes	SSDR	Water	25	60	2839	1633	-	6857	12
Le et al. [54]	OD axial channel/heat pipes	SSDR	Water	25	60	2839	1633	-	9902	12
Le et al. [54]	OD parallel channel /heat pipes	SSDR	Water	25	60	2839	1633	-	306	12
Liu et al. [56]	Channel with spoilers/end cover	DSSR	Water	20	50	-	-	90.7	376.2	8
Liu et al. [56]	Helical channel/end cover	DSSR	Water	20	50	-	-	82.89	1794	8
Liu et al. [56]	Tandem channel/end cover	DSSR	Water	20	50	-	-	81.28	2813	8
Liu et al. [56]	Z-shaped channel/end cover	DSSR	Water	20	50	-	-	82.31	7087	8
Chai et al. [57]	End winding potting/end cover	DSSR	Water	25	33	6266.5	6266.5	131.7	-	10.7
Polikarpova et al. [59]	Hybrid cooling system	DSSR	Water	17	100	4900	2055	118	-	6.2
Jones-jackson et al. [62]	Full inter winding in resin	SSDR	WEG	82	-	-	4422	-	4941	11
Jones-jackson et al. [62]	Horshehoe winding in resin	SSDR	WEG	82	-	-	4422	-	6933	11
Jones-jackson et al. [62]	Central winding in resin	SSDR	WEG	82	-	-	4422	-	4758	11
Li et al. [63]	Cooling pipes	DSSR	Voda	30	130	8.44	7.41	89	-	13.86
Le et al. [64]	Water channels 1	SSDR	Voda	25	60	2770	1564	68.6	28618	10
Le et al. [64]	Water channels 2	SSDR	Voda	25	60	2770	1564	66.2	28568	10
Le et al. [64]	Water channels 2	SSDR	Voda	25	60	2770	1564	66.3	25070	10
Lai et al [65]	Cooling ring	DSSR	Voda	60	63	3030	2485	113	-	-

3.2.2. Immersion cooling

The stator is directly cooled by immersing its cores and windings in a hermetic container. In these enclosed stator housings, some liquid usually oil or a specific coolant circulates so that it removes heat from the stator cores and windings. A key characteristic of this system is improved heat dissipation, which allows for greater energy efficiency and longevity of the motor.

Camilieri et al. [67] advanced a design where the stator is enclosed in a glass fiber casing to enable injection of coolant directly into the stator and thus contact with windings. They made each piece for the YASA machine's stator pole using concentrated winding which is built from square cross-section wire. Usually, epoxy is injected into these windings to fill up any air gaps. Flow stoppers are used to prevent the coolant from bypassing around the periphery so that it effectively divides the machine into four similar sections as shown in below (figure 3.5.). Accordingly, this design provides liquid flow distribution in the stator comparable with parallel flow liquid cooled heat sinks.

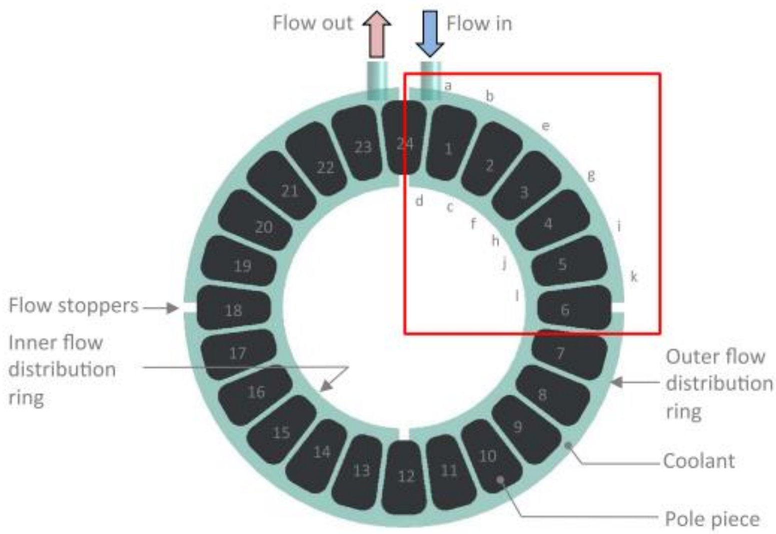

Figure 3.5. Immersion cooling, [67]

The absence of a physical back plate in the stator results in relatively low thermal mass for individual pole pieces, making them very sensitive to the liquid flow distribution within the stator. For an inlet fluid temperature of 80°C and a flow rate of 6 litres/minute, average first core temperature near inlet is equal to 171.3°C, while hottest core temperature was as high as 197.2°C. As compared to cooling without flow stoppers, this reduces hot spot temperature by about 13°C. Consequently, there will be an approximate seven percent increase in current density possible through one new design for a stator with roughly same external dimensions but higher power rating than its predecessor. However, the increase in pressure drop due to the use of baffles was not investigated.

Camilieri et al. [68] proposed improving the current density by developing a new construction for concentrated windings in which a heat sink is integrated into the coil. This design allows for more effective cooling of the inner winding layers by reducing thermal resistance. In addition to evaluating the effectiveness of the heat sink, the optimal placement of the heat sink was investigated. Various thicknesses of copper heat sinks were considered. While very thin sheets limited the heat transfer capacity, thicker sheets proved to be quite brittle when processed. A compromise was reached with a copper heat sink thickness of 0.1 mm. Copper enamelled wire AWG 14 and the synthetic dielectric fluid Opticool were used. For the original design without the heat sink, the heat load in the coils and the iron was increased proportionally until the hotspot temperature of the AWG 14 square magnetic wire, which has an insulation rating of 250°C according to IEC60085, was reached. The new construction was found to reduce the maximum temperature by 87°C and due to the heat sink design, the hotspot temperature was at the iron. However, adding a copper heat sink between the windings will lead to loss generation due to eddy currents in the copper, which, in turn, will reduce the motor's efficiency. Additionally, the high electrical conductivity of copper poses a risk of short circuits between the windings if the enamel insulation is damaged.

Traditional concentrated windings exhibit several thermal resistances across their interwinding layers. As a result, a hot spot temperature is generated at the winding with the longest thermal path. To eliminate this problem, Camilieri et al. [69] proposed using flat windings. To address the issue of radial thermal resistances from multiple winding layers, the new flat windings design replaces these layers with a single current-carrying conductor that is directly exposed to the coolant. This approach involves stacking multiple thinner flat windings along the axis to achieve effective thermal management. Similar to the study in [120], the heat load in the coils and the iron of the original multi-layer winding was increased proportionally until a temperature of 250°C at the inner layer was reached. Under the same operating conditions, the maximum temperature, which is now between the SMC and the winding, was reduced by 97°C. The new construction was found to enhance the steady-state current density of the coil by 130%–150% before reaching the same hotspot temperature as the conventional design. However, the increased cross-sectional area of the copper wire significantly raises the AC losses in the windings, which negatively impacts the machine's efficiency. Furthermore, although the thermal resistance between the stator core and the circulating fluid has been reduced by using flat copper wire, further reduction is necessary, as a significant portion of losses is generated in the stator core.

To address the issue of temperature non-uniformity in stator cores [67], Wanjiku et al. [70] investigated the impact of positioning the inlet and outlet on the maximum temperature and temperature distribution in immersion-cooled stators. Three designs were used in this investigation. They include single-channel series cooling, single-channel parallel cooling and dual-channel series cooling. Here the highest hotspot temperature for the single-channel parallel cooling design was 205°C while that of single-channel series cooling design was 175°C. For double channel series cooling design, the maximum reached 175°C with significantly reduced hot spot non-uniformity. However, the chemical incompatibility between copper insulation and water was not considered in the study making this proposed solution of no practical use to real applications. Moreover, it used only numerical methods for its research methodology and thus experimental analysis is needed to validate these findings.

Liu et al. [71] proposed cooling for the stator of an axial flux motor without stator cores for energy storage applications. They proposed a high-strength oil-immersed cooling stator with non-overlapping concentrated windings. Since stator cores are not used, it is necessary to devise a method for securing the windings in place. A high-strength, nonconductive, and nonmagnetic supporter is crucial to protect the stator winding and avoid additional losses in the ironless stator design. At 9,000 RPM and 53.7 kW power, the maximum temperature is 100°C.

Tan et al. [72] presented a novel additive manufactured windings that integrated heat sinks to enhance the thermal performance of an oil-cooled axial flux motor. The heat sinks are designed with pin-fin structures and can be found on both sides and top of the windings in order to increase the convective heat transfer coefficient and improve the heat transfer surface area. The present work examines how pin spacing downstream, tilt angle, flow rate and resistances affect pressure drops and thermal performances of proposed winding. Rated at 120 kW under 3000 RPM nominal speed, this motor has 20 poles and 24 slots. In contrast to other forms of immersion cooling suggested by other authors, this investigation proposes a system where there are twelve inlets and outlets alternatively arranged between windings. This reduces pressure losses as well as increases temperature uniformity in those regions accordingly. For these specially designed windings, maximum temperature was compared with that for standard rectangular windings using numerical method and experimental data. The newly designed windings attain a maximum temperature of 78.6°C which is lower than that of regular rectangular shapes by 33.2°C. The pressure drop for the new windings is 26.0 kPa, which is 22% higher than that of the standard windings. On decreasing spacing between pins the rise in temperature went down while the pressure drop reduced. However, fabrication of new winding resulted in an increased electrical resistance detracting from an overall reduction in power loss due to heat conduction losses.

Leijnen [73] proposed the installation of guiding walls between adjacent stator cores to better direct the fluid between the outer and inner channels. The guiding walls are specifically designed to align with the fluid dynamics of the cooling fluid, the flow rate generated by the external pump, and the dimensions of the cooling channels. The guiding walls direct the cooling fluid to flow in a controlled manner between the inner and outer channels, ensuring a predetermined path and speed at specific locations within the stator. This controlled flow optimizes the cooling medium's path and speed, maximizing heat extraction from the stator.

To further reduce the thermal resistance between the stator core and the circulating fluid, Leijnen [73] proposed the design of spaced windings, where adjacent turns of a coil are not in contact but instead create a channel for fluid flow. This approach allows the cooling fluid to come into direct contact with the stator core while simultaneously increasing the contact area between the cooling fluid and the copper windings. By adjusting the spacing of the windings, it is possible to influence the fluid's volumetric flow rate and the rate of heat dissipation. Additionally, it is known that due to the proximity effect, not all turns of coil experience equal losses; those closest to the edges of the stator incur higher losses due to magnetic flux leakage. By designing windings with variable spacing, a greater volume of fluid can be directed toward the windings that experience more heat. However, constructing windings in this manner reduces the copper fill factor and negatively impacts power density. To leverage the advantages of this cooling concept while maintaining power density, Leijnen [73] proposed a modification to the previous method. In this design, the turns have a tapered cross-section with one end larger than the other. The larger end faces the ferromagnetic core when wound, resulting in radial channels with a V-shaped cross-section. However, the manufacturing and winding of tapered windings is significantly more complex. However, since these cooling techniques are described in patents, their impact on temperature reduction and pressure drop is not specified.

Marcolini et al. [74] proposed an innovative direct oil cooling system designed for Torus-type axial-flux permanent-magnet machines. They proposed direct oil cooling for the end windings, which reduces the thermal resistance between the copper and the cooling fluid. The end windings at the outer radius serve as fins, with forced oil flowing axially over them. This configuration maximizes the heat exchange surface and ensures that all the flat ribbon conductors are in direct contact with the oil. In other words, the end windings function as a heat exchanger between the stator and the oil. When the losses in the winding and core are 1000 W, with an inlet oil temperature of 20°C, the maximum temperature of the winding at the inner radius of the coil reaches 181°C. A key limitation of direct end winding oil cooling is the potential for oil to leak into the airgap, which inevitably leads to increased windage losses.

Lindh et al. [75] studied the feasibility of direct liquid cooling for thermal management in a low-power, low-voltage permanent-magnet machine. Initially, a tooth-coil axial-flux permanent-magnet double-stator-single-rotor test machine was equipped with indirect liquid cooling via water jackets, followed by direct winding cooling. The winding material is a hybrid conductor, which includes a stainless-steel coolant conduit wrapped tightly with stranded Litz wire. The coolants tested with the same stator were polyalphaolefin oil and distilled water. Distilled water is required because impurities and ions can easily form in the direct cooling system. Consequently, it may be necessary to monitor the electrical conductivity of the fluid during operation to prevent short circuits in the system. The original copper windings of the two-stator-one-rotor axial-flux permanent-magnet machine were replaced with a new directly liquid-cooled winding made of Litz wires. The winding consists of 188 strands with a diameter of 0.5 mm, achieving an effective copper space factor of about 61%. The stainless-steel water tubes have inner and outer diameters of 3 mm and 4 mm, respectively. The net slot copper space factor under the slot key is 37%, which could have been improved with better selection of Litz conductor dimensions. The data at 380 Nm and 1500 rpm were chosen for comparison. For indirect cooling of the stator, the maximum temperature in the end windings was 110°C. With direct cooling using PAO oil, the maximum temperature was 86°C, while direct cooling with deionized water further reduced the maximum temperature of the end windings to 57°C.

Shent et al. [76] studied the direct oil cooling of the stator in an SSDR axial electric motor. Unlike other methods where stator cores are immersed in transformer oil, this design employs oil spraying from inlet channels, which then flows through the passages between adjacent windings. The oil groove is equipped with spray holes that force the liquid coolant through tiny openings, converting it into small droplets that are sprayed onto the surface of the upper half of the windings, thus providing direct cooling. Due to gravity, the cooling oil then flows down through the winding pitch and exits through the outlet. The study examined the effects of varying the number of inlet channels, the diameter of the inlet channels, and the distance between adjacent coils. The highest temperature achieved in the stator windings due to operational losses is 121°C. However, the study was conducted numerically, and to confirm the results, it is essential to perform an experimental analysis of temperature rise.

Wang et al. [77] proposed the use of a new cooling method with multi cooling channels for an axial motor with distributed windings. They compared the temperature rise in the windings for the proposed cooling system with the temperature rise using standard cooling methods, such as forced air flow and water cooling in an external jacket. The proposed oil cooling system, with an oil flow rate of 10 L/min, maintained the maximum winding temperature at 78°C, while water cooling kept the temperature at 138°C, and forced air cooling at 10 m/s maintained the temperature at 180°C.

The temperature comparison between direct oil cooling and indirect water cooling was conducted for the same volumetric flow rates; however, the pressure drop was not compared, which is necessary for a complete evaluation of the efficiency of the two cooling methods. Table 3.3. provides a comparison of different thermal management systems for direct cooling of stator windings and cores.

Table 3.3. Comparison of different thermal management systems for stator windings and cores with direct liquid cooling

Autor	Cooling method	Setup	Coolant type	Inlet coolant temperature (°C)	Nominal power (kW)	Losses (kW)	Stator losses (kW)	Max. temperature (°C)	Pressure drop (Pa)	Flow rate (L/min
Camilieri et al. [67]	Immersion cooling with baffles	SSDR	Opticool oil	80	100	6.7	3.6	197.2	-	6
Camilieri et al. [68]	Immersion cooling with integrated heat sink	SSDR	Opticool oil	80	100	6.7	3.6	163	-	6
Camilieri et al. [69]	Immersion cooling with flat wire	SSDR	Opticool oil	80	100	6.7	36	153	-	6
Wanjiku et al. [70]	Single channel series	SSDR	WEG	105	30	-	-	178	21000	10
Wanjiku et al. [70]	Single channel parallel	SSDR	WEG	105	30	-	-	205	5000	10
Wanjiku et al. [70]	Double channel series	SSDR	WEG	105	30	-	-	175	22000	10
Liu et al. [71]	Immersion cooling	SSDR	oil	-	53.7	-	-	100	-	-
Tan et al. [72]	Additively manufactured windings	SSDR	oil	20	120	7.5	5600	78.6	26000	-
Marcolini et al. [74]	Immersion cooling of end winding	SSDR	oil	20	25	2.8	2240	181	-	-
Lindh et al. [75]	Direct cooling through tube	DSSR	Distilled water	20	100	7.6	4395	57	-	-
Shent et al. [76]	Oil spraying	SSDR	Oil	65	62	2.448	2253	121	-	10
Wang et al [77]	Multi cooling channels	SSDR	Oil	20	70	4.15	4.0	78	-	10

4. CONCLUSION AND FUTURE DIRECTIONS IN FIELD

This work focuses on the thermal management systems of axial electric motors, a critical aspect of motor design. Enhancing this area is essential for the continued advancement and broader implementation of axial electric motors across numerous applications. The primary focus was on describing cooling techniques, categorizing them based on the motor components they cool, and comparing motor configurations, rated power, losses, and temperature rise in key areas. Based on the analysed existing research findings, several general conclusions can be drawn, along with valuable directions and recommendations for the field. Overheating of permanent magnets can lead to permanent demagnetization if temperatures exceed certain thresholds, which vary by magnet type. Elevated temperatures not only risk demagnetization but also degrade magnetic properties which is why multiple studies investigated cooling of permanent magnets. Thermal management systems were divided based on type of fluid used. Air cooling techniques for magnets rely on heat transfer due to the high rotational speed of the rotor. The impact of magnet thickness, the number and placement of holes in the rotor, and rotational speed on heat transfer and magnet temperature have been investigated. It has been found that the best cooling of magnets is achieved using air when holes are placed under the magnets in the rotor, as this significantly improves heat dissipation. Liquid based cooling approaches have outrun others in the enhancement of thermal management systems for the magnets. Although water has the best thermal properties, it cannot be used due to its corrosive effects on permanent magnets. That is why many kinds of oil is used instead. Furthermore, high temperatures in stator components negatively impact several parameters. Primarily, the electrical resistance of the windings increases significantly with higher temperatures, which reduces motor efficiency. Increased temperatures also raise the risk of short circuits and can damage the SMC material, leading to potential operational issues. Depending on the type of heat sink, provision of cooling fluid to the stator cores and windings is done through direct and indirect means. For indirect cooling methods, heat must travel a certain distance to reach the cooling fluid, which is why these techniques are generally used for lower-power motors. To enhance heat dissipation in indirect cooling methods, materials with high thermal conductivity are often used to fill the gap between the cooling fluid and the heat source. On the other hand, in direct cooling methods, the cooling fluid is in direct contact with the heat source, which significantly enhances heat transfer. However, it is essential to use a fluid with high electrical resistance in direct cooling methods to prevent the risk of short circuits.

In future studies of axial electric motor cooling methods special attention should be paid to definition of pressure drop and the internal heat transfer achieved with convection. This will allow comparing the effectiveness and efficiency with which different cooling techniques operate upon completion. Furthermore, regarding rotor cooling, the cooling system can be improved by using an air blower, which allows for regulation of airflow and enhances heat transfer at lower rotor speeds. Regarding the stator, combined cooling through a hollow tube and direct cooling is a promising technique that could further increase the motor's power density.

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SYMBOLS AND ABBREVATIONS

AFPM	Axial Flux Permanent Magnet
CFD	Computational Fluid Dynamics
CVEMAR	China Vehicle Environmental Management Annual Report
DSSR	Double Stator Single Rotor
FEM	Finite Element Analysis
LPTN	Lumped Parameter Thermal Analysis
MSMS	Multi Stator Multi Rotor
PCB	Printed Circuit Board
SSDR	Single Stator Double Rotor
SSSR	Single Stator Single Rotor
YASA	Yokeless and Segmented Armature

ABSTRACT

THERMAL MANAGEMENT SYSTEMS FOR AXIAL FLUX MOTORS: A REVIEW

Axial flux motors are becoming increasingly popular across multiple applications because of their compact design, high power density, short axial length and high efficiency. The particularly interesting application area for axial flux motors is in electric vehicles, where axial length, the potential for mechanical field weakening, high efficiency and power density across the entire operating range are of great importance. The inherent high-power density of axial flux motors requires an effective thermal management system to ensure reliable operation of the motor. This review work describes and analyses various thermal management systems implemented in axial flux motors, analysing their advantages and disadvantages. Thermal management systems are divided depending on which part of the motor is cooled, distinguishing between systems designed to cool the permanent magnets and rotors, and those that cool stator cores and windings. For different cooling techniques, the temperature rise in critical components, pressure drop in the pump system and convective heat transfer were compared, followed by an assessment of the thermal efficiency of each cooling system.

Keywords:

Electric vehicle, Axial flux motors, Thermal management, Thermal analysis.

SAŽETAK

SUSTAVI TOPLINSKOG UPRAVLJANJA ZA AKSIJALNE ELEKTRIČNE MOTORE: PREGLEDNI RAD

Sektor transporta predstavlja značajan udio u generiranju stakleničkih plinova koji imaju negativan utjecaj na okoliš i zdravlje ljudi, zbog čega je u tijeku proces elektrifikacije svih oblika transporta s najvećim naglaskom na cestovni transport. Električna vozila koriste elektromotore za pretvorbu skladištene električne energije u bateriji u mehaničku energiju za pokretanje vozila. Glavni zahtjevi za elektromotore korištene u električnim vozilima uključuju visoku gustoću snage, visoku učinkovitost u cijelom rasponu rada, kompaktne dimenzije, kratku aksijalnu duljinu te visoku razinu pouzdanosti i trajnosti. Elektromotori se mogu grupirati na više načina, a jedna od temeljnih podjela je na elektromotore s radijalnim magnetskim tokom i na elektromotore s aksijalnim magnetskim tokom. Elektromotori aksijalnog magnetskog toka postaju sve popularniji u različitim primjenama zbog kompaktnog dizajna, visoke gustoće snage, kratke aksijalne duljine i visoke učinkovitosti, a mogu se izraditi u nekoliko različitih konfiguracija ovisno o broju i rasporedu statora i rotora u motoru. Postoje četiri moguće konfiguracije: jedan stator jedan rotor (SSSR), jedan rotor dva statora (DSSR), jedan stator dva rotora (SSDR) te više statora i više rotora (MSMR). Konfiguracija s dva rotora i jednim statorom najistraživanija je konfiguracija zbog visoke gustoće snage koju postiže. Posebno zanimljivo područje primjene motora aksijalnog magnetskog toka je u električnim vozilima, gdje su aksijalna duljina, potencijal za mehaničko slabljenje magnetskog polja, visoka učinkovitost i gustoća snage u cijelom radnom rasponu od velike važnosti. Visoka gustoća snage kod motora s aksijalnim magnetskim tokom zahtijeva učinkovit sustav toplinskog upravljanja kako bi se osigurale pouzdane radne performanse motora. Ovaj pregledni rad opisuje i analizira različite sustave toplinskog upravljanja korištene u elektromotorima aksijalnog magnetskog toka, analizirajući njihove prednosti i nedostatke. Sustavi toplinskog upravljanja podijeljeni su ovisno o dijelu motora koji se hladi, razlikujući sustave dizajnirane za hlađenje permanentnih magneta i rotora te one koji hlade statorske jezgre i namotaje. Magnetska svojstva permanentnih magneta smanjuju se s rastom temperature magneta uz mogućnost trajne demagnetizacije u slučaju rasta temperature iznad granične vrijednosti koja ovisi o tipu magneta. Značajno smanjenje koercitivnosti predstavlja rizik od demagnetizacije zbog negativne komponente struje u d-osi motora. Povišena temperatura negativno utječe na strukturna svojstva ljepila koje se koristi za pričvršćivanje magneta na rotor, zbog čega je moguće odvajanje magneta od površine rotora uslijed djelovanja centrifugalne sile na magnete. Uslijed visoke brzine vrtnje rotora aksijalnog elektromotora, značajan dio gubitaka magneta može se odvesti korištenjem ukruta sa stražnje strane rotora čije postavljanje uzrokuje poboljšano odvođenje topline. Izrada rotora s rupama radijalno ispod magneta često se koristi s ciljem poticanja strujanja zraka u prostoru između statora i rotora, a mnogi sustavi hlađenja oslanjaju se na optimiziranje geometrije kanala koji nastaje između dva susjedna magneta postavljena na površinu rotora. S ciljem daljnjeg unaprjeđenja hlađenja magneta i rotora razvijeni su sustavi hlađenja tekućinom. Hlađenje vodom

nije moguće zbog visoke korozivnosti magneta u vodi, zbog čega je hlađenje uljem najčešće korištena metoda. Povišena temperatura statora ima negativan utjecaj na performanse elektromotora. Električna otpornost bakra značajno raste s rastom temperature zbog čega se smanjuje efikasnost elektromotora i značajno otežava hlađenje. Životni vijek električne izolacije bakrenih namotaja značajno se smanjuje pri radu na povišenim temperaturama što negativno utječe na pouzdanost elektromotora i povećava mogućnost kratkog spoja u sustavu. Volumensko širenje statorskih jezgri uslijed porasta temperature može uzrokovati dodir između rotora i statora prilikom rada motora, a električna izolacija zrna praha SMC-a može se otopiti pri povišenim temperaturama što negativno utječe na gubitke vrtložnih struja u jezgrama. Hlađenje statorskih jezgri i namotaja može se vršiti neizravnim ili izravnim putem. Kod neizravnog hlađenja, toplina mora prijeći određenu udaljenost između mjesta gdje nastaje do rashladnog fluida, zbog čega se u međuprostoru koriste materijali s visokom toplinskom vodljivošću. Često se koriste epoksi smole s visokom toplinskom vodljivošću zbog toga što imaju malu gustoću, povoljna elektromagnetska svojstva te nisku viskoznost što sprječava nastanke džepova zraka. U novije vrijeme sve češće se koriste toplinske cijevi koje mogu značajno poboljšati prijenos topline, ali nedostatak im je visoka cijena i dodatni gubitci koji nastaju zbog električne vodljivosti materijala ovojnice cijevi. Cijevi za hlađenje postavljaju se u vanjski prsten statora kod izvedbe s jednim statorom i dva rotora, dok se kod izvedbe s jednim rotorom i dva statora postavljaju sa stražnje strane statora. Kod poboljšanih sustava hlađenja, rashladne cijevi postavljaju se u prostoru između zavojnica što dodatno smanjuje toplinski otpor i poboljšava odvođenje topline. Kod neizravnog hlađenja, najčešće se koristi voda kao rashladno sredstvo što je povoljno za odvođenje topline. Izravno hlađenje podrazumijeva dodir između dijelova motora u kojima nastaje toplina i rashladnog fluida što smanjuje toplinski otpor i poboljšava prijenos topline. Zavojnice i statorske jezgre postavljaju se u hermetički zatvoren statorski sustav kroz koji struji rashladni fluid. Kod izravnog hlađenja nužno je korištenje fluida s visokom dielektričnom čvrstoćom i električnom otpornošću zbog mogućnosti nastanka kratkog spoja u sustavu. Najčešće se koriste transformatorska i sintetička ulja koja imaju značajno lošija toplinska svojstva u odnosu na vodu. Kod hlađenja izravnim putem, značajan problem predstavlja povećana mogućnost curenja fluida. Posebna kategorija hlađenja izravnim putem je integriranje čelične cijevi kroz koju protječe rashladni fluid u statorske namotaje. Bakreni namotaji namotavaju se oko čelične cijevi čime se značajno smanjuje toplinski otpor i povećava prijenos topline. Za različite sustave hlađenja uspoređeni su porast temperature u kritičnim komponentama, pad tlaka u sustavu i konvektivni prijenos topline, nakon čega je provedena procjena toplinske učinkovitosti svakog sustava hlađenja.

Ključne riječi:

Električna vozila, Motori aksijalnog toka, Toplinsko upravljanje, Toplinska analiza.