Deutscher Luft- und Raumfahrtkongress 2024
DocumentID: 630180

OVERVIEW AND WEIGHTED EVALUATION OF COOLING CONCEPTS FOR HIGH POWER ELECTRIC MACHINES IN ELECTRIFIED AIRCRAFT PROPULSION SYSTEMS

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Abstract

The electrification of commercial aircrafts is one key strategy to mitigate aviation-related emissions and hence climate change effects. This requires high power electric motors with low weight and volume for aircraft propulsion. The critical enablers of those MW-class high specific power electric machines are highly capable cooling systems, allowing to increase current densities and/or rotational speeds to obtain more power output, while maintaining geometrical extents and mass. Such cooling technology requires to be highly suitable for aviation purposes, leading to high demands on cooling effectiveness, energy efficiency, additional mass, safety and reliability as well as costs and durability. Consequently, the goal of this paper is to perform an assessment of such technologies based on aviation-adjusted weighted criteria.

As first step, an overview of electric motor cooling methods and relevant literature is established. To condense the obtained information, an ensuing classification and categorization according to different methodical approaches is performed. Subsequently, the selected assessment criteria are weighted through pairwise comparison, followed by the evaluation of each cooling concept based on the weighted criteria. Concept-specific evaluation parameters are obtained, enabling the comparison of technologies and the selection of preferred variants.

Promising options turn out to be the cooling by cooling channels, the hollow conductor cooling and the heat pipe cooling. Among these, the channel cooling stands out due to its decent overall criteria fulfillment. As different cooling approaches have different strengths and weaknesses, a combination of these variants seems expedient to realize a highly capable electric machine cooling system. After further investigation, such as refinement of the literature-based evaluation, analytical assessment, as well as numerical validation, informed design choices can be made.

This can potentially lead to an increase in electric motor power density, enabling electric aircraft propulsion and electrification of aviation. Thus, aviation-induced CO_2 emissions could be reduced and adverse impact on climate could be mitigated.

Keywords

Electrified Aviation; High Specific Power Electric Motors; High Power Density Electrical Machines; EM; HSP-EM; Thermal Management; Cooling Technology; Cooling Systems; Cooling Methods; Stator Cooling; Winding Cooling; Rotor Cooling; Jacket Cooling; Flooding Cooling; Duct Cooling; Channel Cooling; Heat Pipe Cooling; Direct Slot Cooling; DSC; Hollow Conductor Cooling; Spray Cooling; Jet Impingement Cooling; Filling; Potting; Heat Guide Insertion; Hollow Shaft Cooling.

1. INTRODUCTION

Due to the progress of climate change, the global reduction of greenhouse gas emissions continuously gains in importance. Among other sectors such as energy, industry and construction, the transportation sector is a substantial contributor to climate change. As part of the transportation sector, aviation leads to particularly high emissions and is also constantly growing in a globalizing world. Consequently, the reduction of aviation-related CO_2 emissions by 75 % until 2050 was proclaimed by European Commission's *Flightpath 2050* [1]. Electrification of commercial aviation with the long-term goal of CO_2 neutrality is hence becoming increasingly relevant and important for the industry.

One main assembly in an electrified aircraft is the drive train powering the propelling fan. This assembly's most important and critical component is a high power electric motor. Besides other challenges such as the gravimetric and volumetric energy density of the underlying energy carrier, progress in electric machine technology is a key enabler of electrified aircraft. Especially the machine's high power output up to MW-class [2] while maintaining low weight – resulting in high specific power and high power density, respectively – is crucial. Additionally, strict requirements regarding efficiency, durability and operational safety are imposed on applications in aviation propulsion systems. To comply with all of these demands, it is crucial to identify a cooling system with maximum effectiveness of heat discharge combined with low additional weight and high reliability. This potentially enables an increase of electric machine output power, while maintaining minimal geometrical dimensions and mass and being applicable for aviation operation.

Such cooling concepts have been investigated in literature: [3–10]. Technology overviews and literature-based evaluations as well as qualitative comparisons of different cooling methods were conducted. However, none of these authors included a systematic *weighted* evaluation of electric machine cooling methods. A precursory weighting of assessment criteria improves accuracy, significance and suitability with respect to the intended purpose of the evaluated systems. Additionally, a single numerical comparative parameter for each concept to enable an objective comparison and a precise selection of preferred options can be obtained. For these reasons, this paper aims for a weighted evaluation on the basis of criteria weighting by pairwise comparison [11], enabling the identification of the optimal electrical machine cooling methods for electrified aircraft propulsion. Following the introduction to this work in section 1, the methodology applied to meet the goals

doi: 10.25967/630180

of this paper is presented in section 2. Then, the current state concerning cooling technologies of high power electric machines is examined. An overview of cooling approaches, their working principles, related literature and established findings are provided in section 3. Subsequently, a classification summarizing, condensing and contextualizing the previously obtained information follows in section 4. Afterwards, in section 5, evaluation criteria are derived from the requirements and weighted according to the methodical approach of pairwise comparison [11]. The evaluation of cooling concepts by means of the weighted criteria is performed, obtaining characteristic assessment parameters for each technology. This enables their precise comparison leading to an identification of promising cooling approaches as preferred options. Finally, findings of this work are summarized and suggestions are derived in section 6.

2. METHODOLOGY

To meet the goal of this paper to perform a systematic weighted evaluation of electric machine cooling concepts identifying preferred variants, an overview of available and promising technologies has to be established first, see section 3. Initially, a description of the operating principle and an illustration is given for each cooling method. Then, relevant literature including authors who optimized, investigated, evaluated and/or compared respective technologies is presented, summarizing the authors' work and findings as well as identified influence factors and concept potentials. A first preliminary, literature-based evaluation of the respective approach follows.

Subsequently, the information gained from the overview is condensed by means of their classification in section 4. As there are two equally useful and expedient methodical approaches to categorize, both are united within the classification. On the one hand, the investigated technologies are grouped by their localization within the electrical machine and the heat source they are assigned to. On the other hand, they are categorized according to the technical properties and physical mechanisms they utilize.

After the previous steps, the key element of this work is addressed in section 5: an evaluation of cooling concepts with respect to weighted assessment criteria suitable for the requirements of aviation. An ensuing comparison based on the evaluation and the gained comparative parameters is performed, leading to an identification of promising technologies emerging as preferred options. These extracted variants can then be utilized to assemble a cooling system approach potentially increasing heat removal abilities and enabling a raise in specific power of electric motors for aircraft propulsion systems.

To perform the abovementioned weighted evaluation, initially, a selection of assessment criteria is necessary. The selected aviaton-related criteria then are weighted, as not all of them are equally important for their intended purpose. The criteria weighting is performed by pairwise comparison according to Pahl et al. [11] and Kazula [12]: a decision is made for each criterion i whether the criterion i itself is more important than the criterion j it is compared to, the criterion j is more important than the criterion i or both are equally important. Depending on this decision, the importance value $m_{i,j}$ is set to 2, 0 or 1, respectively. The absolute weight W_i of the criterion i can then be calculated according to (1).

$$W_i = \sum_j (m_{i,j}) \tag{1}$$

Its relative weight w_i corresponds to the ratio of the absolute weight and the sum of all criteria's weights $\sum_i W_i$, being 20 for the case of $i = 5$, see (2).

$$w_i = \frac{\sum_j (m_{i,j})}{\sum_i \sum_j (m_{i,j})} = \frac{W_i}{\sum_i W_i} \equiv \frac{W_i}{20} \tag{2}$$

Following this, the evaluation is conducted, assigning assessment values $v_{i,k}$ for each criterion i to each cooling concept k – the higher the value the better the criteria fulfillment of the concept. Based on all values of a technology, the absolute evaluation score R_k can be calculated by (3).

$$R_k = \sum_i (v_{i,k}) \tag{3}$$

Again, a relative parameter is more conclusive. Therefore the relative evaluation score r_k shown in (4) represents the cooling technology's achieved rating per maximum achievable rating $R_{k,max}$, being 20 in this case.

$$r_k = \frac{\sum_i (v_{i,k})}{\sum_i (v_{i,k,max})} = \frac{R_k}{R_{k,max}} \equiv \frac{R_k}{20} \tag{4}$$

As the criteria are of varying importance depending on the operational intention, the previously performed weighting of criteria is taken into account: the absolute weighted evaluation score $R_{k,weighted}$, see (5), provides a significance-related parameter applying the criteria's relative weights w_i.

$$R_{k,weighted} = \sum_i (w_i \cdot v_{i,k}) \tag{5}$$

As final assessment parameter describing the cooling concept's ability to comply with the requirements, the relative weighted evaluation score $r_{k,weighted}$ is obtained by (6) utilizing the maximum absolute weighted evaluation score $R_{k,weighted,max}$ being 4 in this case:

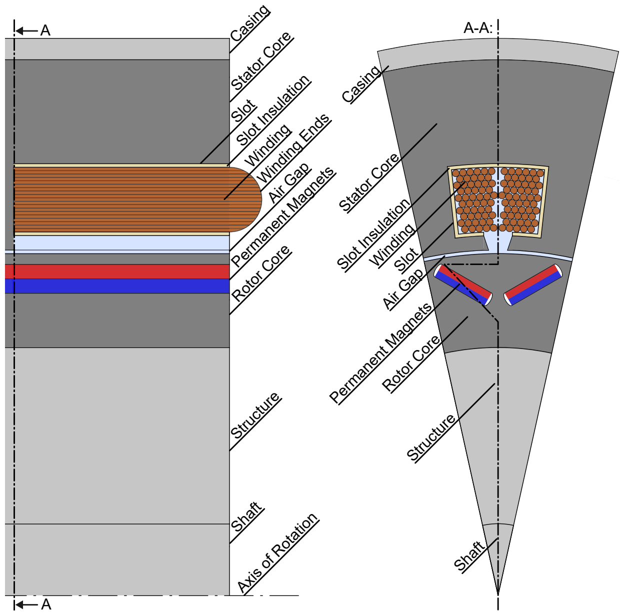
$$\begin{aligned} r_{k,weighted} &= \frac{\sum_i (w_i \cdot v_{i,k})}{\sum_i (w_i \cdot v_{i,k,max})} = \frac{R_{k,weighted}}{R_{k,weighted,max}} \\ &\equiv \frac{R_{k,weighted}}{4} \end{aligned} \tag{6}$$

3. OVERVIEW OF COOLING CONCEPTS

There are various cooling techniques for heat removal from the heat-generating components of an electric machine described in literature. This section intends to present the relevant ones, aiming to demonstrate their fundamental functionality, variations and applications. Furthermore, findings of authors exploring the corresponding subject as well as achieved improvements are summarized.

To illustrate the various cooling concepts, a permanent magnet synchronous electrical machine (PMSM) is exemplarily used. FIG 1 presents such a machine in axial (1a) and radial section (1b).

In electric machines, different types of losses occur: electromagnetical losses in stator and rotor core, permanent magnets and slot windings as well as mechanical losses in bearings, sealings and within the fluid, e.g. air, situated in the rotor's cavity [10, 13]. Electromagnetical losses, such as copper losses – current-dependent Joule losses including frequency-dependent effects, i.e. skin effect and



(a) Axial section. **(b) Radial section.**

FIG 1. Illustration of a permanent magnet synchronous-type electric machine (PMSM) consisting of a stator assembly including casing, stator core and slot as well as a rotor assembly including rotor core, permanent magnets, potential rotor support structure and shaft.

proximity effect – in the winding conductors, iron losses – i.e. eddy current, hysteresis and excess losses – in stator and rotor core and magnet losses within the permanent magnets [14] are especially relevant for heat generation in the machine's components. Additionally, mechanical losses due to bearing and sealing friction and due to fluid friction caused by the rotor movement [14] occur.
Considering localizations and portions of the different loss types, stator core, stator windings and rotor core can be identified as main lossy components [4]. The permanent magnets, located within the rotor core, characterized by a comparably low loss portion and small size [15], can be assigned to the rotor core and its losses. In general, the more an electric machine of a certain power level is designed for high torque output, the more current-dependent copper losses occur within the stator windings. On the other hand, the more the machine is designed for high rotational speeds, the more prone it is to frequency-dependent iron losses in stator and rotor core [5, 6].
The generated heat within the lossy components requires to be dissipated by a cooling system, otherwise the continuous occurance of thermal power leads to an increase in temperature of the respective component. Even if the regarded component is not sensitive to temperature rise, heat flux is transferred to adjacent components following temperature differences. Especially the winding impregnation layers electrically insulating the conductors, and the permanent magnets generating and maintaining the machine's magnetic field are temperature-sensitive and prone to overheating. Therefore, they constitute the thermally limiting parts of the electric machine [6]. As these thermal restrictions are the dominating limitations for the machine's power output, power density, efficiency and durability, cooling technology is a key aspect that can potentially lead to a further exploration of electromagnetical potentials [5, 16]. A selection of such cooling techniques is presented below.

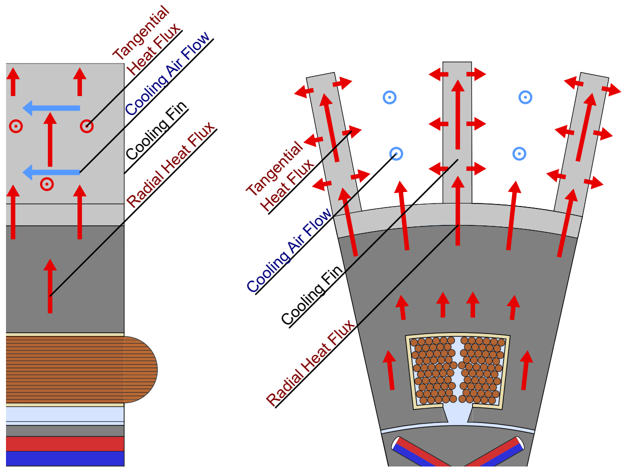


FIG 2. Axial and radial section of the Stator Surrounding Flow Cooling concept. Heat is dissipated trough heat fins attached to the outer casing.

3.1. Surrounding Flow Cooling (SFC)

One of the most straightforward ways to dissipate the produced heat of an electric machine is to cool it using the fluid surrounding the machine. The most common application of surrounding flow cooling is the heat removal by heat fins directly attached to the outer casing. Here, the heat produced within the machine's stator assembly heat sources, i.e. in the stator windings or in the stator core, is transferred conductively radially outwards through the stator core into the casing, where it is distributed along the height of the heat fins [5, 8]. On the casing and heat fin surfaces adjacent to the surrounding flow, convective heat transfer into the fluid occurs either by natural or forced convection, depending on the flow's relative velocity to the machine. This principle is illustrated in FIG 2. Many authors have described this cooling method in literature: [15, 18–24].
Another possibility of using the surrounding fluid as heat sink is leading the flow through a support structure consisting of a dense arrangement of heat fins, similar to a heat exchanger. In this case, the heat produced within the active assembly part is conducted radially into the heat exchanger-like structure. As its lamellas are perfused by the surrounding flow, the heat is again transferred into the fluid flow by convection. The setup is shown in FIG 3. This concept is introduced by Wrobel et al. in multiple publications [9, 17, 25] for the stator of an outrunner machine, where it additionally provides mechanical support for the stator. Also, concepts where air perfuses the machine without heat transfer improving structures are described [26].

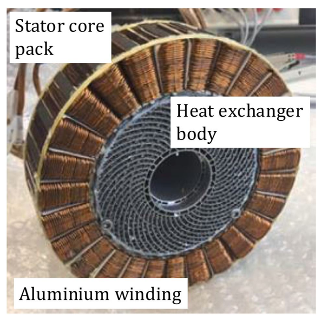


FIG 3. Stator cooling of an outrunner electric motor by surrounding air perfusing a lamella structure in axial direction [17].

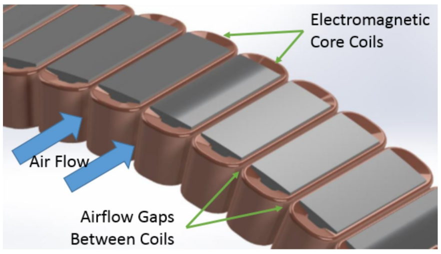


FIG 4. Direct cooling of stator winding packs by surrounding air perfusing slots in axial direction [15].

Cooling the windings by surrounding flow is described by Christie et al. [15], where the slots are perfused and the windings are directly cooled, as shown in FIG 4.

Regarding the rotor assembly and its heat sources, i.e. rotor core and permanent magnets, heat dissipation into the fluid situated in the rotor cavity takes places, as illustrated in FIG 5. This is advantageous as no additional cooling components and no internal coolant circuit are required for the rotor cooling. No additional fluid friction losses occur if the cavity is filled by air [5]. This very simple cooling concept is discussed by many authors [27–30]. As its effectiveness of heat removal is limited, Fawzal et al. [30] realized an improvement by attaching a centrifugal fan to the rotor, realizing an increase of torque of 20 % and an increase of continuous power of 43 %.

Christie et al. [15] generally state that the surrounding flow cooling shows high potentials by enlarging its convectively heat transferring surface area, high influence of heat conduction ability inside the machine and the properties of the heat fins, but exhibits no significant influence of propwash effects of operating propellers in close proximity. Dong et al. [8] referring to Ulbrich et al. [24] work out up to 20 % of difference in convective heat transfer ability depending on the number and dimensions of the heat fins. Nollau et al. [31] accomodate the heat transferring surface in the electromagnetical flux barriers of the machine. Miersch et al. [26] evaluate an increase of the string current of 40 %.

In general, this cooling concept is advantageous in terms of not influencing the electromagnetical behaviour of the electric machine, as it is applied outside of the active parts,

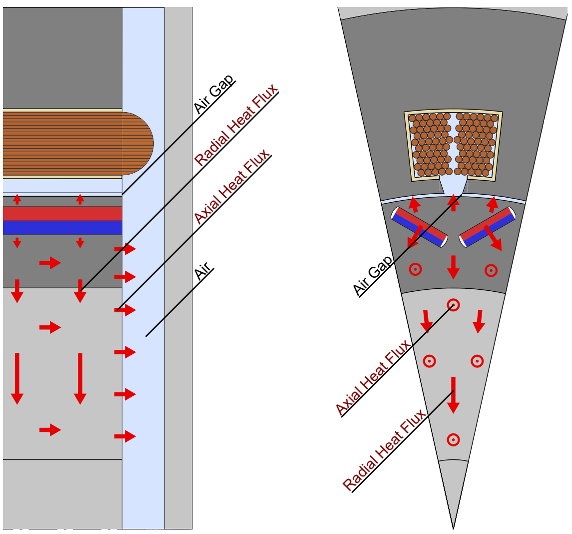


FIG 5. Axial and radial section of the Rotor Surrounding Flow Convective Cooling concept. Heat is dissipated by convection on the free surfaces of the rotor assembly such as rotor ends and outer circumference.

maintaining a sealed casing [5]. The cooling concept's manufacturing and maintenance costs are very low and the costs of cooling components are low, while the costs of electromagnetical materials are high due to thermal conductivity requirements [5]. On the other hand, operational faults can occur due to dust or particle accumulation on electrical components and abrasion of insulation layers caused by particles or vibrations [5] if the surrounding flow is in direct contact with electrical components. If the casing remains sealed, the method stands out due to its simplicity, operational safety and durability.

3.2. Jacket Cooling (JC)

A well-established cooling method is the jacket cooling [32]. In this concept, a cooling jacket containing ducts perfused by a coolant is applied to the outer casing radius. The jacket can either be a separate component mounted on the casing, or be integrated in the casing. Similar to the casing's surrounding flow cooling by heat fins, heat produced by the heat sources within the stator assembly is conducted radially through the stator core, penetrating the casing wall and finally being transferred by convection into the coolant perfusing the cooling ducts [5, 7, 8, 32, 33]. This cooling method can either be used to cool the stator core, the stator windings, or both. The respective setups are shown in FIG 6.

The cooling ducts implemented in the cooling jacket can be arranged in different configurations, as FIG 7 shows. They can either be oriented circularly, helically or meandering in tangential or axial direction [4, 8, 14, 34–37]. Also, different numbers of cooling channels have been investigated [38]. Liang et al. [39] found heat transfer coefficients to be higher by a factor of 1.6 when arranging the channels in axial direction compared to tangential direction. Zhang et al. [38] determined the highest heat transfers when arranging them in helical direction as a combination of tangential and axial direction, due to a larger heat transferring surface area and higher heat transfer coefficients.

One major issue of the jacket cooling method is the high overall thermal resistance between heat source and heat sink [32], especially if used for winding cooling, due to the very long heat paths [7, 33]. Main design parameters have been found to be heat transfer capacity through stator core and casing as well as the heat sink properties [5]. Therefore, optimizations have been conducted, e.g. concerning shapes and arrangements of the cooling ducts [40, 41].

The advantages of the jacket cooling are the simple setup and the coolant's high specific heat capacity when using water or similar fluids [3], as well as its large heat transferring surface area and the non-existent interaction with the active parts of the machine and therefore its electromagnetical behavior [5, 32]. Also, this technology has proven to be very robust but, simultaneously, to have only moderate heat removal potentials [4]. Its cooling effectiveness has been found to be higher than air cooling [14] and oil immersion cooling techniques' [4]. Also, its ease of implementation, volumetric power density, low noise emissions and sealed setup can be considered beneficial, while disadvantages are the higher costs compared to air cooling, the necessity of a coolant circuit, the risk of internal corrosion and leakage as well as the increased maintenance effort [14].

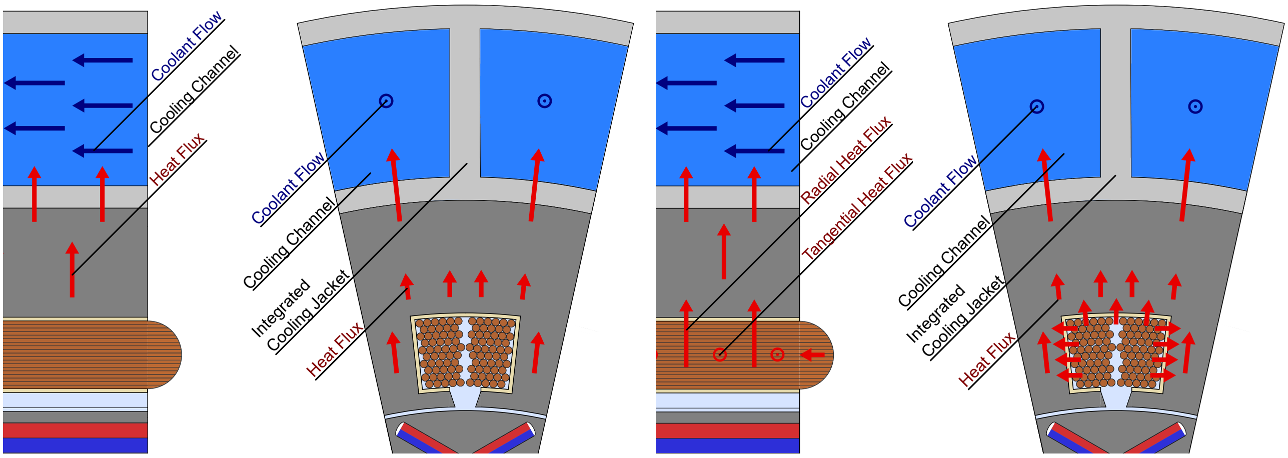


FIG 6. Axial and radial section of the Casing Jacket Cooling concept. Heat is conducted from the stator core (l.) and the winding pack (r.) to the cooling jacket and dissipated through convection inside the perfused cooling ducts.

3.3. Annular Gap Cooling (AGC)

One approach to cool the stator assembly more directly than the established casing cooling methods is the annular gap cooling. Here, the stator core does not adjoin the casing wall at its outer diameter, instead, an annular gap spreads out over the whole stator core's circumference. Therefore, the casing's conductive and contact thermal resistances are bypassed, as the core is in immediate contact with the coolant perfusing the annular gap in axial direction, see FIG 8. Another configuration is an annular gap situated at the inner diameter of the stator core [32].
Tuysuz et al. [32] mention benefits of the proximity of windings and heat sink as well as a potential positive thermal influence of the annular gap cooling on the rotor assembly if the gap is situated at the inner stator core diameter. Additionally, a lower thermal cycling leads to an increase in durability of the winding impregnation. However, design optimization efforts are advisable due to possible additional losses caused by competing geometrical extents between annular gap and winding. Tuysuz et al. [32] achieved a winding hot spot temperature reduction of 40 K compared to water jacket cooling and an increase of the electric machine's power density of 100 % compared to axial channel cooling.

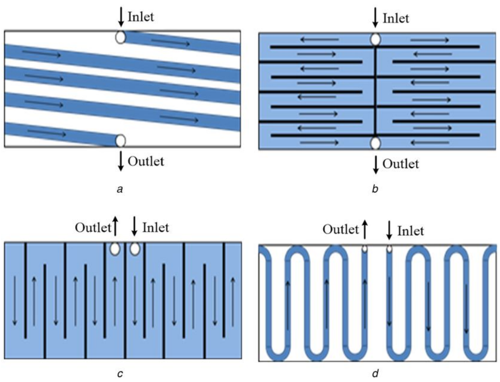


FIG 7. Selection of potential cooling duct configurations within a cooling jacket [14].

3.4. Flooding Cooling (FC)

Building upon the annular gap cooling, a further improvement is the cooling concept of flooding cooling. On the one hand, it contains the forementioned annular gap cooling. On the other hand, it extends its ability through additional heat removal from the stator ends as well as the machine's slots by convection, therefore further dissipating heat from the winding packs inside the slots and the winding ends. This is accomplished by connecting a coolant reservoir to both stator ends, feeding the annular gap and implemented cooling channels within the slot grooves with coolant and thereby maintaining an axial flow. The whole stator assembly is separated from the rotor assembly through a liner attached to the inner stator core radius. In summary, the flooding cooling isolates the stator core including windings from rotor and casing, as described by Dong et al. [5] and Wang et al. [8]. Multiple authors have examined the stator flooding cooling [42–46]. Its working prinicple is illustrated in FIG 9.
The potential of stator flooding cooling is investigated to be more effective than direct stator channel cooling regarding stator core heat removal and than oil spray winding end cooling regarding the winding end heat dissipation. It does, however, have disadvantagous influence on the magnetic flux in the airgap due to the liner [5]. Camilleri et al. [47] achieved a machine's hot spot temperature reduction of 13 K. Potential faults are identified to be structural failure, such as sleeve leakage, due to high coolant pressure or

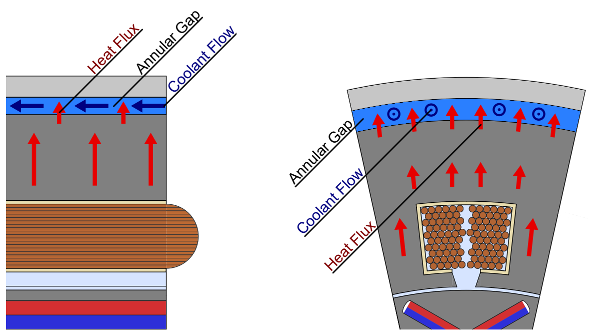


FIG 8. Axial and radial section of the Stator Annular Gap Cooling concept. Heat is conducted towards the annular gap enclosing the rotor core and dissipated through convection inside the gap.

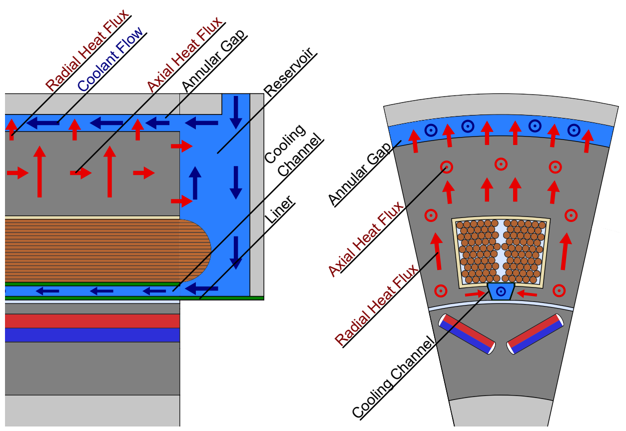


FIG 9. Axial and radial section of the Stator Flooding Cooling concept. Heat is dissipated through all free stator core, winding and winding end surfaces due to the coolant flooding the whole stator assembly.

cooling channel blockage. The costs of the method are estimated to be low regarding electromagnetic material but rather high regarding cooling components and manufacturing [5].

Another approach to cool the winding ends of an electric machine is similar to the stator flooding cooling examined above, but only affects the winding ends. As Marcolini et al. [48] describe, the winding ends can be separated from the windings inside the machine's slots between the iron core teeth as well as from the stator ends by a sleeve or liner. With an outer wall, a flow chamber can be created and perfused by a coolant, like oil. Through maximization of the heat transferring area, Marcolini et al. were able to minimize the overall thermal resistance between heat source and heat sink, increasing the cooling effectiveness by a factor of 2.87 and the electric machine's power density by a factor of 2.

3.5. Channel Cooling (CC)

An equally flexible and potentially effective approach is the electric machine cooling by cooling channels or ducts. The channels can be inserted flexibly into any component to be cooled and in any direction, such as axial or radial [5, 8, 50, 51]. A sophisticated way is to position them in the machine's magnetic flux barriers, if existing [31].

In case of a direct stator channel cooling, cooling channels are inserted into the active electromagnetical part of the stator, the stator core [51]. Those channels can, exemplarily, be orientated axially within the stator core. Heat, primarily from the stator core and indirectly from the winding packs within the slots, is led radially towards the cooling channel, driven by a certain temperature difference between heat source and heat sink. At the inner duct wall, the heat is absorbed by the coolant perfusing the channels and carried away in flow direction. It seems advisable to position the channels in the outer area of the core to mitigate the interdependencies with the magnetic flux inside the part [8, 50]. This is presented in FIG 10.

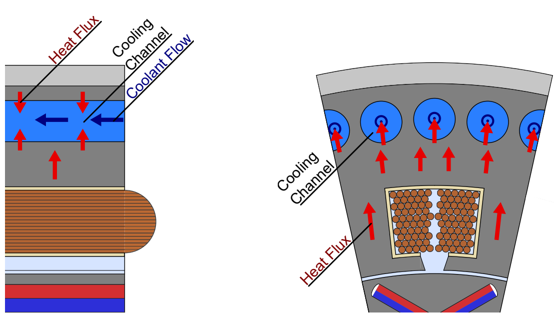


FIG 10. Axial and radial section of the Stator Axial Channel Cooling concept. Heat is directly dissipated within the stator core through cooling channels.

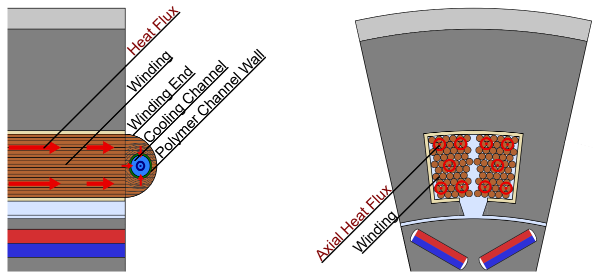


FIG 11. Axial and radial section of the Winding End Channel Cooling concept. Heat is axially conducted inside the winding pack towards the stator end and conductively dissipated by a cooling channel implemented in circumferential direction in the winding ends.

Furthermore, winding ends of electric machines can be cooled by channels, as Madonna et al. [49] show. In this concept, a pipe is inserted in tangential, circumferential direction into the winding ends, splitting them in a two parts. The pipe can either include a regular cooling channel or a heat pipe transporting the absorbed heat towards a heat sink. FIG 11 and FIG 12 illustrate such an implementation of a cooling channel in the winding ends.

To cool the stator winding packs situated inside the slots, winding channel cooling is an adequate option. In many publications, this concept is known as *Direct Slot Cooling* (*DSC*) and realized in various configurations. In this work, the winding cooling channel by axial channels is examined, either within the slot center separating the neighboring windings, or separating both neighboring windings in upper and lower parts, see FIG 13, or alternatively replacing the slot wedge in the slot groove, the passage between slot and air gap, see FIG 14 [4, 52–61]. The winding cooling channels operate analogous to other channel cooling concepts: heat of the adjacent heat source, the winding conductors, is conducted radially and/or tangentially through the winding pack towards the coolant-perfused cooling channel. There, it crosses the cooling channel wall, e.g. made of thermally conductive polymer. On the inner cooling channel wall, convective heat transfer occurs carrying away the heat in

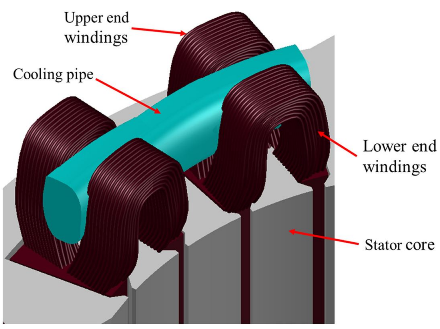


FIG 12. Cooling of the winding ends by an inserted circumferential pipe containing either a cooling channel or a heat pipe, splitting the winding ends in upper and lower part [49].

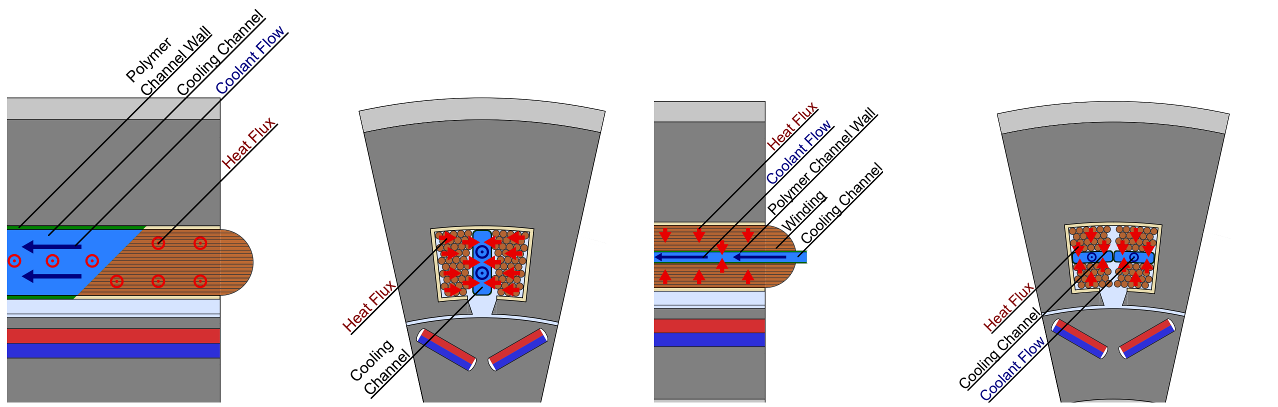


FIG 13. Axial and radial section of the Winding Axial Channel Cooling concept. Heat is dissipated by slot-implemented axial ducts in e.g. radial (l.) or tangential (r.) orientation.

flow direction. As the geometrical extents of the winding pack and the cooling channels are likely to be in competition, optimizations have to be performed during the design process to achieve ideal trade-offs.
The presented concept of winding channel cooling can be optimized, e.g. by replacing the ordinary cooling channels by additively manufactured micro-feature cooling channels [56]. This is presented in FIG 15, referring to Schiefer et al. [57] and Acquaviva et al. [62].
Finally, cooling of the rotor assembly is also realizable through channels. Coolant-perfused cooling ducts can be inserted in any configuration and orientation into the rotor core, where heat losses of the rotor core itself as well as the permanent magnets occur. Exemplarily, two configurations are presented: the rotor cooling by axial cooling channels and by radial cooling channels, see FIG 16. Similar to the stator channel cooling, the ducts influence the electromagnetical behavior of the machine, as they are placed within the active rotor part. Therefore, holistic cooling system design with regard to the electromagnetical domain should be performed.

General and specific suggestions concerning channel cooling are made by various authors: if applied in close proximity to a heat source, the overall thermal resistance between heat source and heat sink can be mitigated significantly. However, as cooling channels within active parts of the machine inevitably cause a competition between the geometrical extents of the cooling system and the active part, optimizations are required for ideal cooling design, find Tuysuz et al. [32]. Wang [64] suggests the implementation of pressure reservoirs at the beginning and end of the cooling ducts and the precise setting of flow resistances within the channels for a proper flow distribution. Huang et al. [50] identified cooling effectiveness of direct stator core cooling by cooling channels to be higher than of water jacket cooling. Compared to other cooling methods, it leads to lower temperatures within the core assuming equal pressure losses from the coolant flow. For stator cooling, Lu et al. [51] achieved a significant increase in electromagnetic force by a factor of 2.86 and, simultaneously, a positive influence on the rotor leading to a temperature reduction within the permanent magnets. The direct stator and rotor core channel cooling are especially applicable to maintain moderate temperature gradients between inner and outer core radius and in machines with high iron loss portions, such as high speed and high frequency machines [8, 51]. According to Gieras [65], direct winding cooling provides the highest effectiveness regarding heat removal from the winding pack. Liu et al. [7, 33] state that direct winding cooling by cooling channels can decrease conductor temperatures leading to lower ohmic losses and efficiency increase. Sixel et al. [53, 66, 67] insert additively manufactured T-shaped cooling channels made of polymer and ceramics, respectively, into slots and achieve 44 % temperature reduction within the winding and up to 30 A/mm^2 of current density. Canders et al. [3] emphasize the high potential of direct slot cooling, but point out high fluid pressure losses in a potential serial arrangement of cooling channels. Especially compared to indirect

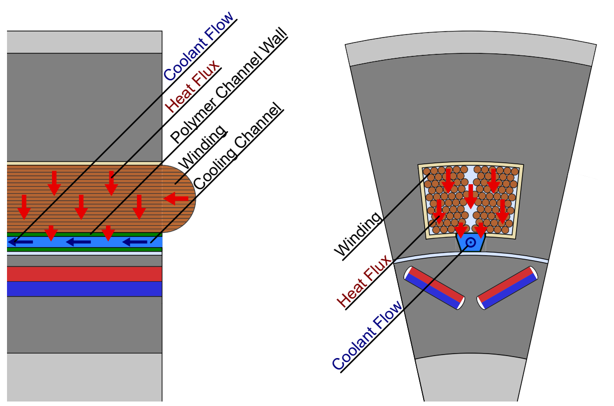


FIG 14. Axial and radial section of the Winding Groove Channel Cooling concept. Heat is dissipated by slot-implemented axial ducts in the slot groove, analogous to a slot wedge.

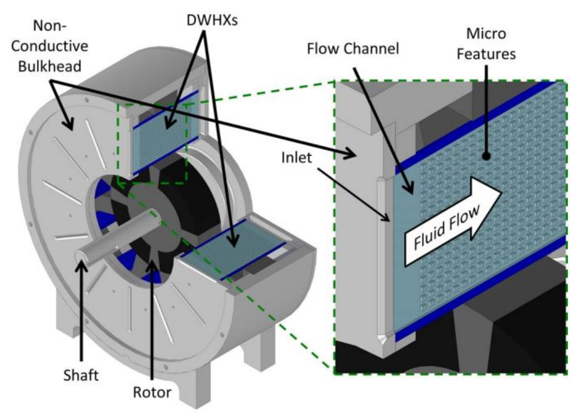


FIG 15. Winding cooling through additively manufactured micro-feature cooling channels inserted in winding slots [56].

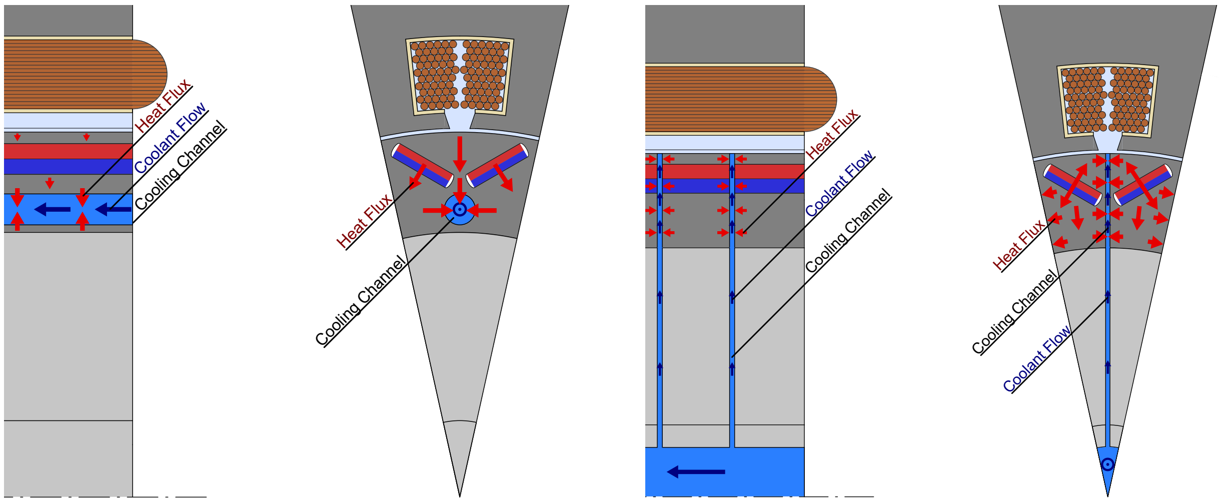


FIG 16. Axial and radial section of the Rotor Channel Cooling concept. Heat is directly dissipated within the rotor core through cooling channels in axial (l.) or radial (r.) direction.

cooling like water jacket cooling, direct winding cooling potentials are high [4, 52, 53, 56]. Yang et al. [14] evaluate high heat transfer abilities at low pressure losses using micro-feature heat exchangers, like Semidey et al. [56]. Madonna et al. [49] determine a temperature reduction of 20 % and therefore moderate potentials of the winding end channel cooling concept. Dong et al. [5] generally describe moderate to high potentials for channel cooling, leading to an increase in absorbed heat by the coolant indicated by a temperature increase by a factor of 1.5 to 3. Furthermore, the cooling method exhibits only small additional losses. The costs of this cooling method regarding cooling components as well as manufacturing are estimated by Dong et al. [5] to be high. Structural requirements are evaluated to be high mechanical strength of cooling channel walls due to potential high fluid pressure. Potential failures are identified to be deformation and leakage when operating under high pressures and temperatures.

3.6. Heat Pipe Cooling (HPC)

Heat pipes are tube-shaped, closed and sealed systems, able to effectively transport heat from a machine region in close proximity to a heat source which is difficult to cool, to another region, where heat dissipation is simply possible. Within the heat pipe, a refrigerant, mostly water, evaporates in the hot region, flows in gaseous state to the cold region and condensates there. In ordinary heat pipes, the condensed fluid in liquid state is transported back to the heat source by a wick, utilizing capillary forces. In pulsating heat pipes, the transport back to the heat source is carried out by the mechanism of expansion and contraction of the gaseous coolant phase. The described thermodynamical processes lead to highly effective passive heat transfer from the hot side to the cold side of the heat pipe, making use of the refrigerant's phase change enthalpy without requiring additional power input [4, 8, 63, 72–76]. An exemplary setup of an electric machine with heat pipe-cooled slots, dissipating the transported heat outside the machine, is presented by Zhang et al. [63], see FIG 17. Wu et al. [68] implemented heat pipes directly in additively manufactured hollow conductor windings, as shown in FIG 18.

Zhang et al. [63] utilized U-shaped heat pipes for the above-mentioned slot cooling, maintaining a winding temperature of 100 $°C$ with a current density of 12.5 A/mm^2. Madonna et al. [49] integrate annular heat pipes in split winding ends and refer to a temperature reduction of 25 %. Charoensawan et al. [72] and Adera et al. [73] invoke a higher heat dissipation by 2-phase, such as heat pipes, than by 1-phase

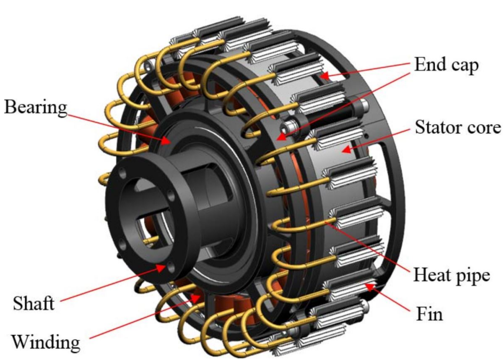


FIG 17. Cooling of windings by heat extraction through U-shaped heat pipes and heat dissipation outside the electric machine [63].

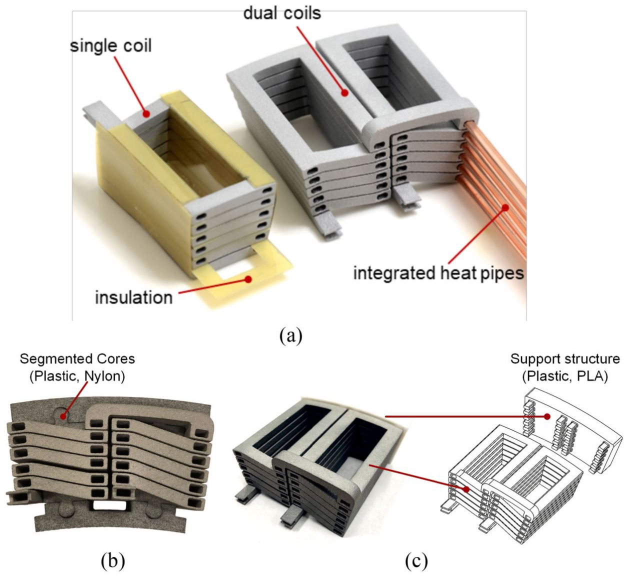


FIG 18. Direct conductor cooling by heat pipes implemented in additively manufactured hollow conductor windings extracting heat from the conductors [68].

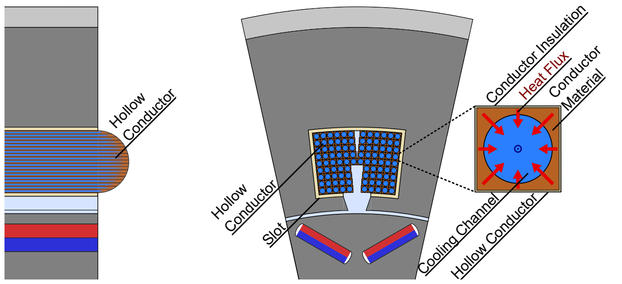


FIG 19. Axial and radial section of the Winding Hollow Conductor Cooling concept. Heat is dissipated directly from the conductor material by a coolant perfusing channel inside each conductor.

cooling systems. Tuysuz et al. [32] judge the heat removal of heat pipes to be very effective but point out a competition of geometrical extents between heat pipe and winding conductor cross-section. Fang et al. [74], Ponnappan et al. [75], Li et al. [76] and Zhang et al. [63] estimate the potentials of heat pipes for heat removal to be high, referring to excellent conductive heat transfer along the heat pipe due to an extremely low overall thermal resistance and consider heat pipes especially suitable when adjacent components of heat sources are not supposed to be thermally loaded. Dong et al. [5] identified challenging material requirements for heat pipes, such as a high mechanical strength due to high vapor pressures inside the heat pipes when applying high temperatures. Consequently, potential failure mechanisms are identified to be vapor pressure-caused deformation and leakage. Additionally, costs for manufacturing and for the cooling components themselves are assessed to be medium and high, respectively.

3.7. Hollow Conductor Cooling (HCC)

As the influence of thermal resistances increases with the length of the heat path between heat source and heat sink in an electrical machine, cooling methods with heat sinks in close proximity to the heat sources and to temperature-sensitive locations are expedient [77]. Direct conductor cooling is, accordingly, an advisable approach already being practiced in high power generators of $\geq$ 200 MW using gaseous hydrogen or deionized liquid water [4]. A further development of direct conductor cooling is the hollow conductor cooling: here, the copper or aluminium conductors are hollow and pipe-shaped, as illustrated in FIG 19. They are traversed by current and simultaneously

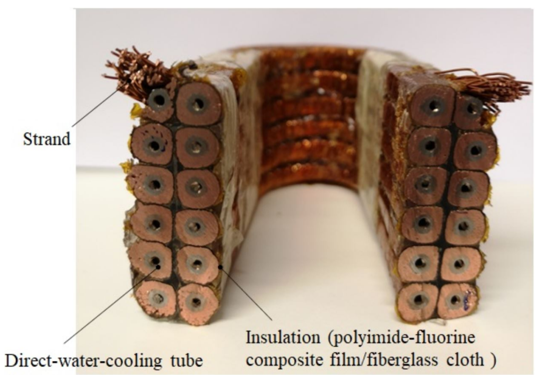


FIG 20. Conductor cooling through coolant-perfused steel pipes wrapped in loss-minimizing Litz wire conductors [69].

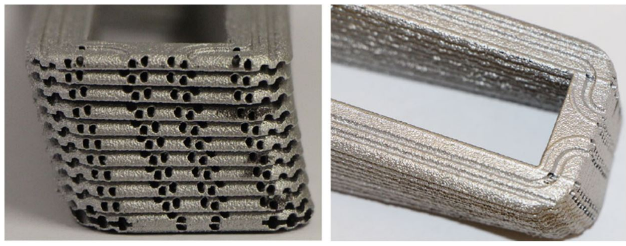


FIG 21. Additively manufactured aluminium windings with implemented cooling channels [70].

perfused by coolant during operation, leading to a dissipation of heat losses and maintaining reasonable conductor temperatures [69, 70, 78–84].

Wrobel, Lindh, Petrov, Di et al. [69, 79, 81–83] implemented a stainless steel cooling channel wrapped with loss, minimizing Litz wire conductors using deionized water as perfusing coolant, see FIG 20. They achieve continuous current densities of 18 A/mm^2, increased by a factor of 3.5. Haller et al. [84] even estimate higher potentials of up to 50 A/mm^2. Wohlers et al. [70] even exceed this estimation, reaching 100 A/mm^2 with additively manufactured aluminium windings with integrated cooling ducts, as illustrated in FIG 21.

Furthermore, Ayat et al. [71, 85] investigated hollow conductors filled with phase change material, achieving temporary temperature decreasing effects of 8 % and a winding mass reduction of 18 %. For this approach, paraffin was filled into differently shaped inner profiles of hollow conductors as phase change material, enabling a buffering of temperature peaks. This is presented in FIG 22.

In general, Canders et al. [3] point out that very high pressure drops of more than 6 bar are likely to occur in hollow conductors. The pressure losses can be optimized by parallel arrangement of hollow conductors, requiring a separate inlet and outlet for each tube [70, 81]. However, manufacturing difficulties, pressure supply and poor slot fill factor remain as problems, according to Ayat et al. [85] and Lindh et al. [80, 81]. Similarly to channel cooling, Dong et al. [5] identify challenging requirements regarding mechanical strength under high temperatures and high pressures of the conductor material. Potential failures are estimated to be deformation and leakage. In addition, manufacturing and cooling component costs are estimated to be high, while electromagnetic material costs are considered low.

FIG 22. Hollow conductors with various inner profile shapes serve as cavities for phase change materials buffering temperature peaks by absorbing thermal power [71].

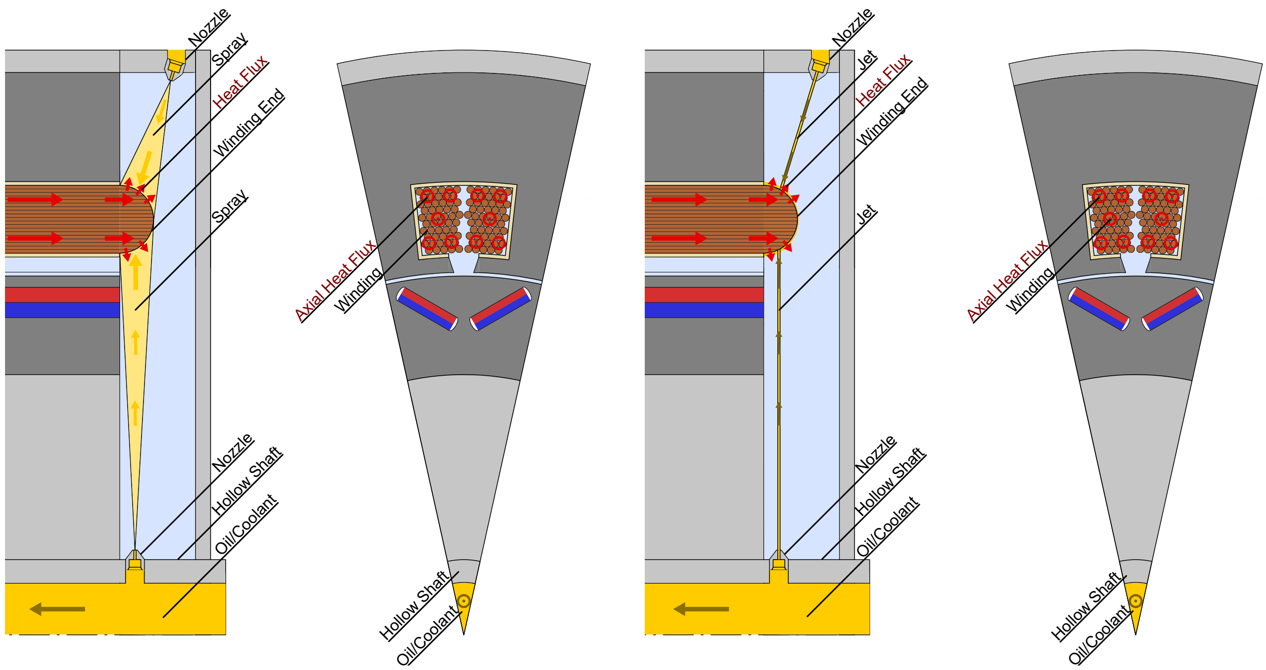


FIG 23. Axial and radial section of the Winding End Cooling concept. Heat is axially conducted inside the winding packs and dissipated over the exposed winding end surface area through an impinging coolant spray (l.) or coolant jet (r.).

3.8. Spray & Impingement Cooling (SIC)

An approach to cool the windings and, indirectly, the stator core, of an electric machine is to remove heat from the winding ends. In this case, heat from inside the stator assembly is axially conducted through the winding pack towards the winding ends, where it is dissipated over the surface of the external winding ends. Two different winding end cooling concepts are presented in this context: spray cooling and jet impingement cooling [86, 87], see FIG 23. To provide a convective flow, circumferencially arranged nozzles supplied with coolant, mostly oil, are placed in the casing and hollow shaft walls, ejecting coolant from the outer and inner side, respectively, onto the winding ends. Regarding the spray cooling, the coolant is atomized within the nozzle, forming a spray. Concerning jet impingement cooling, the nozzle accelerates the coolant, creating a high velocity jet [10, 88–92]. Both cooling methods exhibit advantageous heat transfer properties to dissipate heat from the outer winding end surface. The heat transfer of spray cooling can be further increased using the coolant's phase change enthalpy by the coolant being evaporated when impinging onto the hot winding end surface [4, 93, 94].
Zhang et al. [95] provide an approach for modeling spray cooling. Liu et al. [89, 96] estimate and predict heat transfer coefficients. Davin et al. [88] investigate different types of sprays and jets, optimizing the configurations and identifying the main influence factor of the cooling effectiveness to be the coolant flow rate.
According to Liu et al. [7, 33], disadvantages of both cooling methods are the sole heat removal from the salient, exposed winding regions and the long conductive heat path from the axial center of the slot to the winding ends, leading to a hot spot in the axial center of the machine. Very high heat dissipation effectiveness even for small coolant flow rates is stated by Wrobel et al. [10]. Guechi et al. [94] also figure very high cooling effectiveness and reliability but contrarily refer to the necessity of high volume flows for the use of phase change. According to Canders et al. [3], high flow rates are significantly increasing viscous fluid friction losses within the casing, though. For enabled phase change, Agostini et al. [93] identify better heat removal per input power and significantly higher heat transfer coefficients compared to non-phase change cooling. Davin et al. [88], Liu et al. [89], Ponomarev et al. [90], Lim et al. [91] and Ye et al. [92] estimate the general heat removal potentials to be high, referring to reductions of temperature raise of 40 % to 50 % and doubled current densities compared to indirect water cooling techniques. However, they also note worse overall potentials than stator and winding flooding cooling concepts and name non-uniform heat removal as a disadvantage. Dong et al. [5] identify potential failure mechanisms in nozzle blockage and non-uniform temperature distributions due to uneven heat transfer.

3.9. Filling & Potting Cooling (FPC)

The cooling by filling or potting can be seen as thermal enhancements rather than cooling techniques, as no heat dissipation into a heat sink occurs. In fact, the method facilitates the heat transfer from a region of the electric machine which is difficult to cool to another more easily coolable region. The functional principle is to simplify heat conduction in locations where no full surface contact between components persists and conductive heat transfer therefore is impeded [8, 16] by filling or potting a thermally conductive material into the cavities between components [52, 97, 98]. Consequentially, thermal resistances between components can be overcome. The winding conductors, only interfacing each other through line-shaped contacts and therefore exhibiting poor thermal conductivity in orthogonal direction, are the common application field. FIG 24 illustrates the method's setup for the use case of winding slot filling and winding end potting.
Experiments concerning casting of winding ends in thermally conductive and castable polymer material lead to improvements of heat transport into adjacent parts, influencing the rotor assembly positively [49, 99].

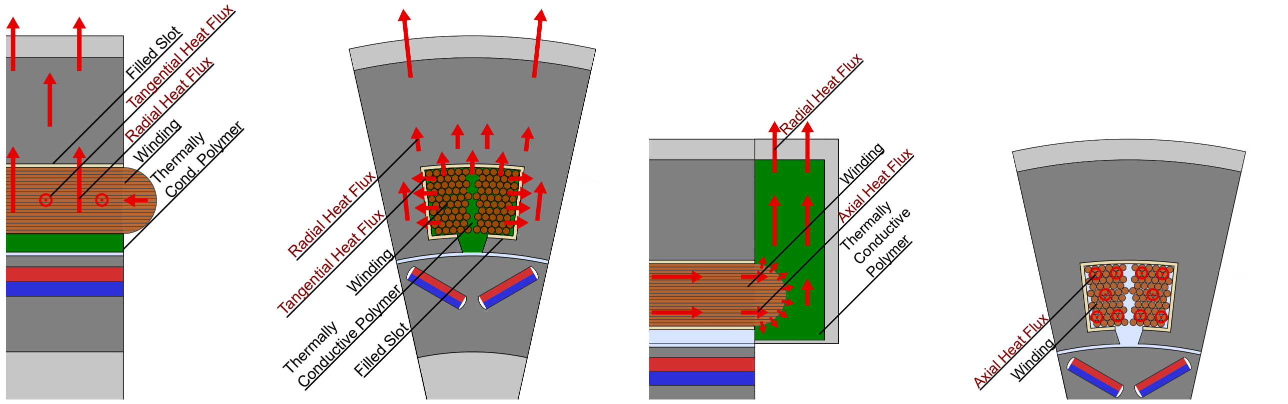


FIG 24. Axial and radial section of the Winding Cooling concept. Thermal enhancement by increasing the low radial/tangential thermal conductivity of the winding pack through in-slot filling (l.) or winding end potting (r.) with thermally conductive casting material.

Madonna et al. [49] achieved an increase in the machine's current density from 19 A/mm^2 to 26.5 A/mm^2 and Vansompel et al. [99] were able to decrease winding end and permanent magnet temperatures by 6 K to 7 K. Due to undesired electrical conductivity of the polymer material, eddy current losses, risk of short circuits and safety concerns resulted as well. Schuffenhauer et al. [16], on the other hand, combine the winding end potting cooling with the application of phase change material. In this case, the potting material enclosed by a reservoir melts when heat is conducted into the material and absorbs heat until it is completely liquefied, temporarily maintaining its temperature. Polikarpova et al. [100, 101] and Sun et al. [102] figure the heat removal potential to be rather low and refer to mass increase and challenging material requirements such as dielectricity and thermomechanical strength. Dong et al. [5] argue similarly, referring to high material requirements and potential short circuit failures, material rupture or deformation and dripping off when the melting point is exceeded. Additionally, costs for electromagnetic material and manufacturing are estimated to be high and medium, respectively.

3.10. Insertion Cooling (ISC)

The insertion cooling method works through the insertion and embedding of a thermally highly conductive solid heat guide, such as a copper plate or bar, connecting a machine region in close proximity to a heat source and a region with decent heat transferring ability [55, 103–106]. As this concept does not include a heat sink and does not transport heat out of the machine, it rather constitutes a thermal enhancement technique, similar to the potting and filling cooling methods. However, it can be expedient when encountering geometrical constraints not permitting the implementation of e.g. a cooling channel [32]. The working principle of the insertion cooling is shown in FIG 25.

Pyrhonen et al. [103] implemented an insertion cooling embedding thermally conductive plates and bars in the stator core sheet metal in direction of the highest thermal resistance. They notice minor to moderate effects on heat removal and a slight increase in stator core iron losses, while increasing simultaneously the machine's power output. Xu et al. [104] and Galea et al. [55, 107] inserted T-shaped copper plates into the winding interstice inside the slot to establish a direct heat path into the stator core, achieving a high heat removal potential with a temperature reduction up to 70 K [5] and 44 % hot spot temperature reduction, respectively, and an improvement of 55 % to 85 % in heat transfer into the stator core [8]. Wrobel et al. [106] used additively manufactured heat guides, improving heat removal by 20 % to 40 %. Regarding reliability and failure tolerance, Dong et al. [5] see moderate manufacturing costs and potential fault potentials through partial discharge and short circuit.

3.11. Immersion Cooling (IMC)

A simple way to improve the heat dissipation from both, stator and rotor, is the immersion cooling presented in FIG 26. Here, the casing containing stator and rotor is partially or completely filled by a non-electrically conductive but magnetically permeable coolant, such as transmission oil [4, 14, 90, 108]. Due to the coolant's physical properties and, if the casing is only partially filled, the multiple phase fluid flow, heat transfer from stator and rotor into the coolant is increased.

Deisenroth et al. [4] mention that there are an additional cooling effect and lower fluid friction loss due to spray and spatter formation when the casing is only partially filled. The cooling potential of the immersion cooling with oil as coolant is evaluated to be more effective than air cooling but worse than water jacket cooling. The advantages of a simple and universal cooling of all relevant heat sources are opposed by many disadvantages, such as a high amount of losses due to viscous fluid friction, especially at high rotational speeds, and disturbance of the magnetic flux in the machine's air gap.

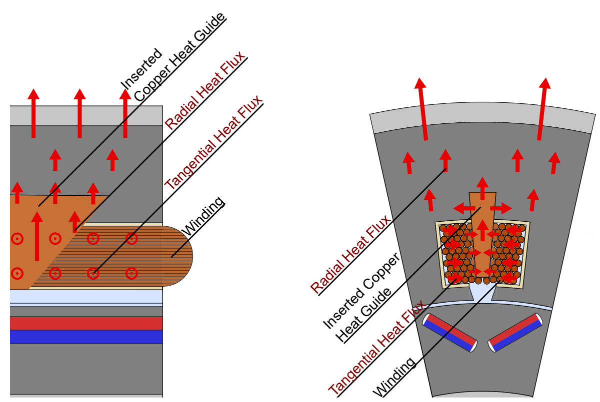


FIG 25. Axial and radial section of the Winding Insertion Cooling concept. Thermal enhancement by bypassing the winding pack's low radial/tangential thermal conductivity through the insertion of a heat guide.

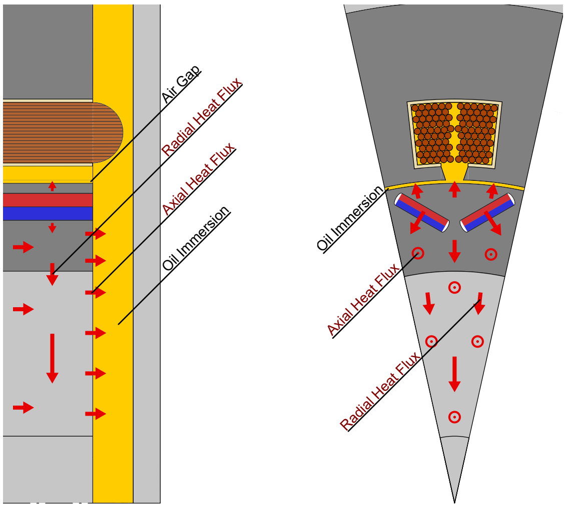


FIG 26. Axial and radial section of the Rotor Immersion Cooling concept. Thermal enhancement by partially or completely filling the machine casing with coolant, improving heat dissipation convection on the free surfaces of the stator and rotor assemblies.

3.12. Hollow Shaft Cooling (HSC)

Another approach to rotor assembly cooling is the hollow shaft cooling. Here, the machine's shaft connecting the rotor assembly with e.g. an aircraft propeller is designed with an internal channel perfused by coolant. Heat generated by the rotor assembly's heat sources, i.e. rotor core and permanent magnets, is conducted radially towards the shaft, penetrating its wall. There, it is dissipated by the coolant flow and transported away [109, 110]. The principle is illustrated in FIG 27.

Lee et al. [110] achieve temperature reductions in the windings by 50 % and 38 % and in the stator by 42 % and 10 % compared to air cooling and jacket cooling, respectively. Gerstler et al. [109] and Lee et al. [110] attribute high potentials of heat removal to the hollow shaft cooling technique, but also see high complexity and manufacturing costs as leakage has to be prevented and mechanical strength has to be assured. The high heat dissipation ability of the cooling method results from a positive influence of the shaft rotation on the heat transfer coefficients at the inner shaft surface, as Gai et al. [111] point out, determining an increase by a factor of 4 at high speed operation with 30 $krpm$. The technique's weaknesses [109, 110] are confirmed by Dong et al. [5], who see potential failures in leakage and fracture due to vibration, bending and torsion as well as high manufacturing costs.

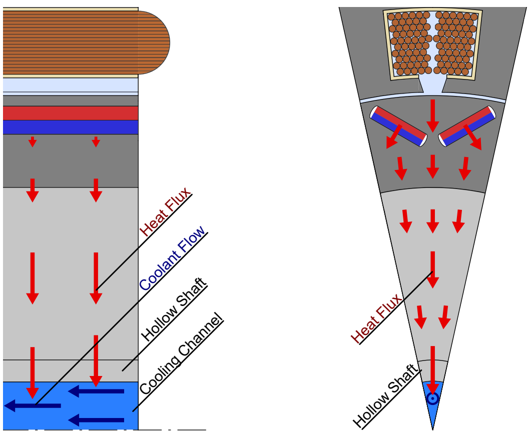


FIG 27. Axial and radial section of the Rotor Hollow Shaft Cooling concept. Heat is conducted radially through the rotor assembly towards the hollow shaft and perfused in the shaft's implemented, coolant-perfused cooling channel.

4. CLASSIFICATION OF COOLING CONCEPTS

The selection of cooling concepts presented in the previous section (3) has no certain structure arranging and grouping the concepts. For example, hollow shaft cooling can be employed in the rotor assembly to cool the rotor core and permanent magnets. It applies the physical mechanisms of conduction and convection to dissipate sensitive heat, being driven by a certain input power. Contrarily, for example the heat pipe cooling uses a fluid's phase change enthalpy and therefore latent heat to remove heat loss from a region, mostly the stator winding pack, without requiring any additional energy.

To condense the provided overview of possible cooling solutions, a classification is made and the various concepts are categorized following different methodologies: in the pertinent literature, cooling methods are often classified by their location of operation or by their assigned heat source to dissipate heat from. This can be the assembly – stator or rotor – or the heat-generating component, such as the stator windings or the rotor core, or the actually cooled part, such as housing or shaft. As different types of electric machines can have different lossy components, the heat sources are dependent on the machine type. Another approach to categorize electric machine cooling concepts is the classification through their properties. This can be the use of additional energy, i.e. power consumption, or the proximity to the heat source they are assigned to, for example if the heat sink/coolant is directly adjacent to the heat source or if the source's heat loss has to be conducted through other components first before being dissipated indirectly. More considerations are the applied physical mechanisms – type of extracted heat, e.g. temperature-coherent sensitive heat or phase change enthalpy-coherent latent heat – or the physical mechanism of heat transfer, such as conductive transport through solid materials, convective transport by absorption and carriage in fluids, or radiative transport by electromagnetic waves. Both approaches of categorization are united by a systematic classification, presented in FIG 28.

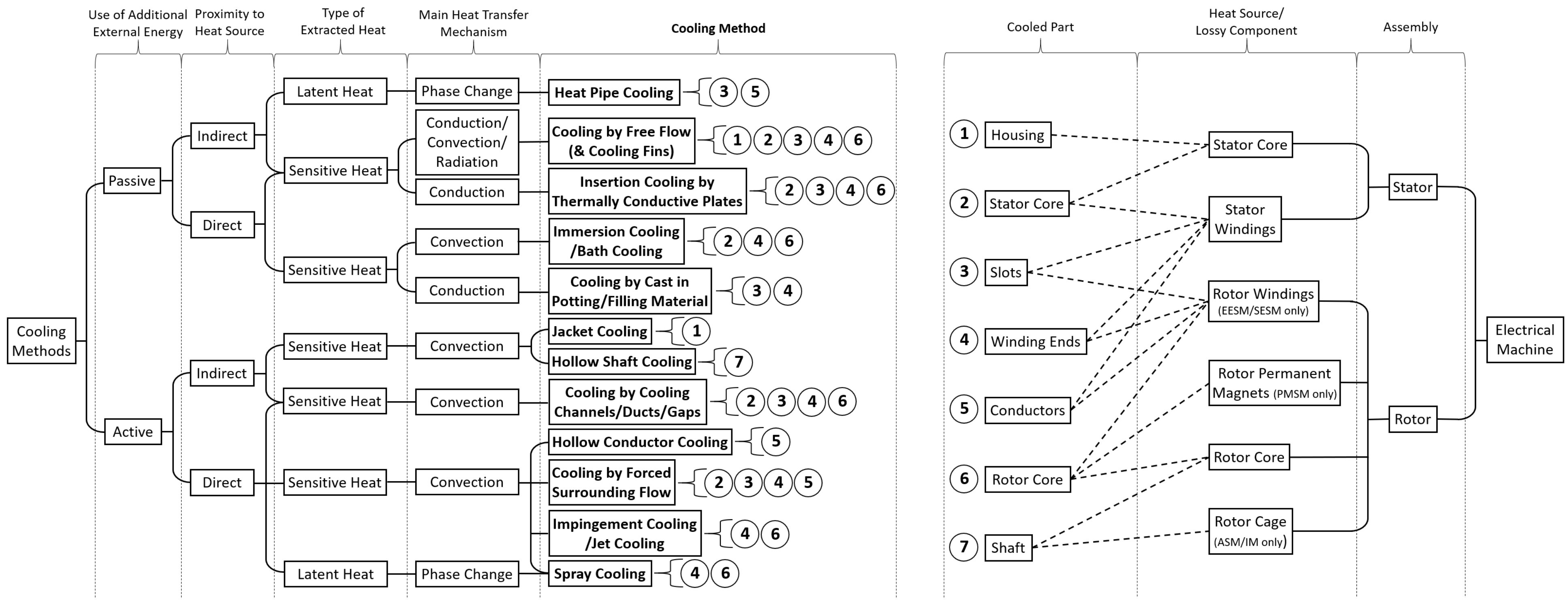


FIG 28. Overview and classification of cooling concepts for electric machines. Categorization by technical properties and physical mechanisms (l.) or concept localization and assigned heat source being cooled. Cooled parts: housing (1), stator core (2), slots (3), winding ends (4), conductors (5), rotor core (6) and shaft (7).

5. WEIGHTED EVALUATION OF COOLING CONCEPTS

To identify optimal cooling technologies, a choice of preferred options of cooling concepts to enable the design of a whole cooling system needs to be made. For a well-founded selection, an evaluation suitable for aviation requirements is necessary. For this purpose, Kazula et al. [11, 12] provide a methodology of weighted evaluation by pairwise comparison in combination with a weighted point rating.

In this methodical approach, the initial step is the criteria selection and weighting by pairwise comparison: first, a selection of relevant evaluation criteria is made. Then, each criterion is compared to every other criterion, deciding if either the one or the other is more important for the technology to be evaluated regarding its specific objectives. In the case of this work, five relevant criteria for the cooling of electric machines for aircraft propulsion purposes were elaborated – Cooling Effectivity (CE) describing the ability of heat dissipation, Energy Efficiency (EE) characterizing the energy consumption per heat removal, Additional Mass (AM) representing the weight added by cooling components and auxiliary systems, Safety & Reliability (SR) constituting the operational safety and fault tolerance as well as Cost & Durability (CD) characterizing the system-correlated economic effort and lifespan. For the comparison and weighting of these criteria, a survey in tabular form was created, as presented in TAB 1. The criteria comparison is performed by evaluating if the row criterion is more, equal or less important than the column criterion in the respective tabular cell. Depending on this decision, a value assignment of 2, 1 or 0 points, respectively, is conducted. This comparison is repeated for every table row. Subsequentially, the values of each row are summed up according to (1) to obtain the absolute weight of the respective row criterion. The relative weight is obtained through dividing the absolute weight by the sum of all absolute weights, indicated by (2).

Afterwards, the evaluation of cooling concepts is conducted. To this end, a value for each criterion and each concept has to be assigned, depending on how well the cooling concept fulfills the criterion. The values assigned to the criteria fulfillment levels are presented in TAB 2. The allocation of criteria fulfillment levels to the concepts is listed in TAB 3. To substantiate the criteria fulfillment assignments, TAB 4, attached in the appendix section of this work, provides detailed information regarding the choice of the respective criteria fulfillment level. The criteria fulfillment of each tabular cell can now be replaced by its numerical value according to TAB 2. The values of each row, being the evaluation for a certain cooling concept, are summed up to obtain its absolute evaluation score, as shown by (3). A more intuitive rating is the relative evaluation score, where the absolute score is related to the maximum achievable score, dividing the absolute score through the highest possible score of the row, see (4). As the forementioned scores do not yet take into account the relevance and significance of each criterion for the objective of cooling high power electric machines for aviation propulsion systems and therefore have limited informative value and significance, a score weighting is performed. For this purpose, each criterion rating is multiplied with its respective relative weight before being summed up to the absolute weighted evaluation score, see (5). Again, the absolute score is converted to the relative weighted evaluation score constituting the evaluation's main result, according to (6). This score provides each cooling concept's final evaluation rating, enabling comparison of the various cooling methods through a numerical parameter as an objective performance indicator.

For enhanced clarity, the results of the evaluation of cooling concepts are illustrated as follows: the final evaluation result, represented by the relative weighted evaluation score of each concept, is presented in FIG 29. Hereby, comparison of the evaluated technologies is enabled. FIG 30 in the appendix provides each cooling concept's criteria fulfillment ratings, taking into account the weight of the criterion illustrated by its bar width.

TAB 2. Assignment of symbols and assessment values to criteria fulfillment levels.

Criteria Fulfillment	Symbol	Value $v_{i,k}$ $[-]$
Very Good	$++$	4
Good	$+$	3
Moderate	$\pm$	2
Bad	$-$	1
Very Bad	$--$	0

TAB 1. Weighting of criteria through pairwise comparison. Assignment of importance value depending on criteria importance: row criterion is more important than column criterion (2), row and column criteria are equally important (1) or column criterion is more important than row criterion (0).

			Criterion j					Weighting	
			Cooling Effectivity	Energy Efficiency	Additional Mass	Safety & Reliability	Cost & Durability	Absolute Weight	**Relative Weight**
			CE	EE	AM	SR	CD	W_i $[-]$	$\boldsymbol{w_i}$ $[-]$
Criterion i	Cooling Effectivity	**CE**	–	2	2	2	2	8	**0.4**
	Energy Efficiency	**EE**	0	–	0	0	1	1	**0.05**
	Additional Mass	**AM**	0	2	–	1	2	5	**0.25**
	Safety & Reliability	**SR**	0	2	1	–	2	5	**0.25**
	Cost & Durability	**CD**	0	1	0	0	–	1	**0.05**
	Sum	$\sum$						20	1.0

TAB 3. Results of the weighted evaluation of cooling concepts. Allocated assignment value symbols for each cooling concept regarding each criterion and obtained evaluation scores.

			Criterion i					Evaluation			
			Cooling Effectivity	Energy Efficiency	Additional Mass	Safety & Reliability	Cost & Durability	Absolute Score	Relative Score	Abs. Weighted Score	**Rel. Weighted Score**
			CE	EE	AM	SR	CD	R_k	r_k	$R_{k,weighted}$	$\boldsymbol{r_{k,weighted}}$
	Relative Weight	w_i [−]	0.4	0.05	0.25	0.25	0.05	[−]	[%]	[−]	[%]
Cooling Concept k	Surrounding Flow Cooling	**SFC**	−−	+	++	±	++	13	65	1.85	**46.25**
	Jacket Cooling	**JC**	−	+	−−	±	±	8	40	1.15	**28.75**
	Annular Gap Cooling	**AGC**	±	+	±	±	++	13	65	2.15	**53.75**
	Flooding Cooling	**FC**	+	+	−	−	+	11	55	2.00	**50.00**
	Channel Cooling	**CC**	++	±	±	±	±	12	60	2.80	**70.00**
	Heat Pipe Cooling	**HPC**	++	++	±	−−	−−	10	50	2.30	**57.50**
	Hollow Conductor Cooling	**HCC**	++	−	+	−−	±	10	50	2.50	**62.50**
	Spray & Impingement C.	**SIC**	+	−	±	−	±	9	45	2.10	**52.50**
	Filling & Potting Cooling	**FPC**	−	++	±	−	+	11	55	1.50	**37.50**
	Insertion Cooling	**ISC**	±	++	±	−	+	12	60	1.90	**47.50**
	Immersion Cooling	**IMC**	−−	−−	±	±	++	8	40	1.20	**30.00**
	Hollow Shaft Cooling	**HSC**	+	+	±	−	±	11	55	2.20	**55.00**

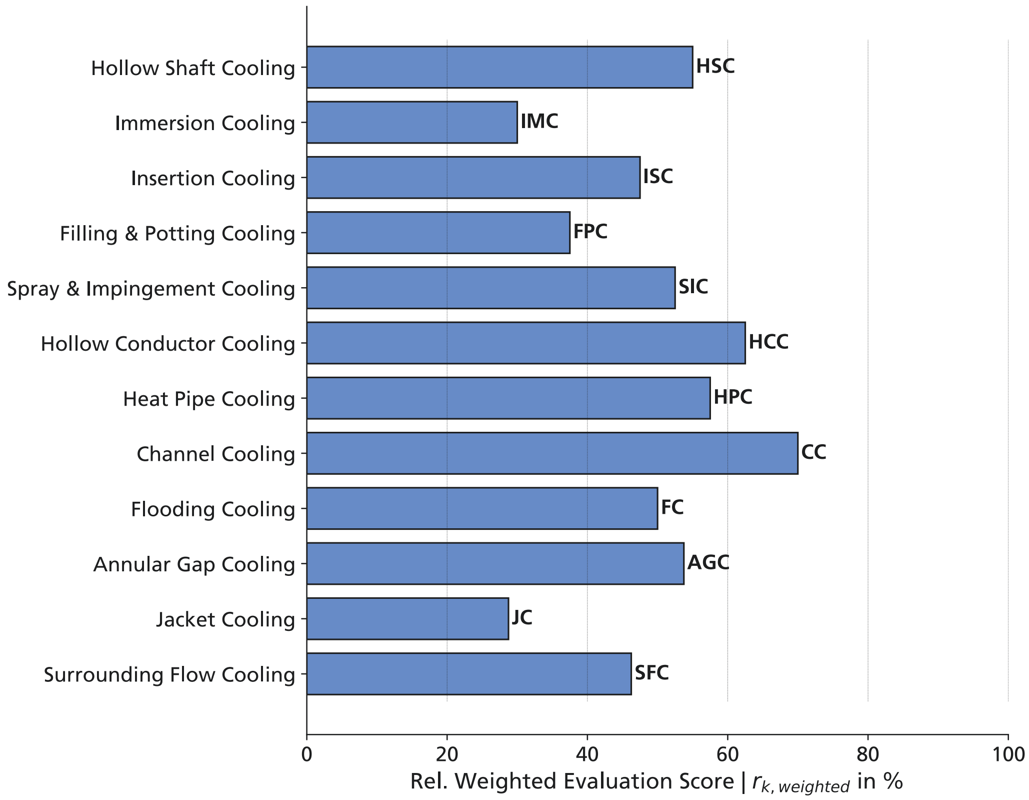


FIG 29. Results of the weighted evaluation of cooling concepts. Bar length corresponds to the Relative Weighted Evaluation Score in %, representing the potential of each cooling concept and its suitability for aviation purposes.

From TAB 3, TAB 4 and FIG 30, the following statements can be derived: the surrounding flow cooling has an unsatisfactory cooling effectivity but is low in additional mass and advantageous in costs and durability. As cooling effectivity is the most important criterion, the method's relative weighted evaluation score happens to be low to mediocre. The jacket cooling has a better effectivity but is unfavorable concerning its additional mass. Its rating is low due to weaknesses in important criteria. The annular gap cooling performs at an average level, but is strong in terms of cost and durability. As this criterion is weighted very low, the overall score of this approach remains average. The flooding cooling is evaluated positively in effectivity, efficiency and costs, but is weak in terms of safety, reliability and additional mass. Due to the mixed evaluation, its score turns out to be average as well. The channel cooling is very strong in cooling effectivity and shows medium abilities in the other criteria. The highest overall score results. The heat pipe cooling performs very well in terms of cooling ability and does not consume additional energy but the technology's immaturity leads to very low safety and reliability, as well as disadvantageous costs and durability. In total, it is evaluated medium to high. The hollow conductor cooling performs very well in cooling, but weak in terms of safety and reliability. The second highest score results. The spray and impingement cooling has good cooling capabilities but has rather high energy consumption and scores unfavorably in terms of safety and reliability. It is thus rated average. The filling and potting cooling has little cooling effectivity but does not require additional energy. Due to efficiency having little importance, it is rated low to medium. The insertion cooling shows mediocre cooling abilities, while the remaining criteria are coherent with the previous concept. The method's score is consequently mediocre. The immersion cooling performs very strong in costs and durability but very weak in cooling and efficiency. A low rating follows. The hollow shaft cooling performs medium to well overall except for its safety and reliability. This leads to an evaluation slightly above average.

Analyzing the relative weighted evaluation scores, resulting from the performed assessment and presented in FIG 29, the channel cooling stands out with the highest overall rating of 70 % and is therefore the preferable cooling concept. Additionally, it is universally applicable for every heat-generating component of electric machines. Slightly worse but still very favorable is the hollow conductor cooling with a rating of 62.5 %. Less beneficial than the previously discussed concepts but advantageous in terms of passive operation without the necessity of external energy is the heat pipe cooling with an overall result of 57.5 %. The forementioned outcomes suggest that cooling systems of high power electric machines for aircraft propulsion purposes should be based on one or multiple of the three presented preferred options. As the channel cooling's strength is the direct cooling of iron cores and the hollow conductor cooling is the most direct and capable winding cooling approach, a combination of both seems advantageous.

6. CONCLUSIONS

To obtain a general idea and broad outline of established and promising existing cooling technologies for high power electric motors for aviation propulsion purposes, an overview of cooling concepts was provided initially. Afterwards, the extracted technologies were summarized and classified uniting two competing categorization methodologies and subsequentially condensing the previously established overview of cooling concepts. In the following core element of this work, a weighting of rating criteria by pairwise comparison was performed to enable an expedient assessment of cooling concepts appropriate to the purpose of aviation operation. These weighted criteria were finally used for an evaluation of all extracted cooling concepts, leading to numerical parameters serving as performance indicators and enabling an objective comparison of the assessed cooling technologies.

The results of the performed weighted evaluation reveal the favorable potential of three cooling concepts: the cooling through cooling channels emerges as the most promising approach providing very high cooling capabilities and advantageous universal applicability resulting in a relative weighted evaluation score of 70 %. The winding cooling by hollow conductors follows with a rating of 62.5 % due to a very high winding cooling effectivity and low additional mass, showing weaknesses in safety and reliability owing to the technology's immaturity. These problems are shared by the heat pipe cooling, also being disadvantageous in terms of costs and durability but not requiring any additional energy to provide its very high passive cooling ability. This leads to a score of 57.5 %. In general, direct cooling technologies with close proximity of heat source – the loss-generating machine component – and heat sink – the cooling component absorbing and dissipating the heat loss – appear to have the most promising potential.

In summary, the most capable and therefore preferred variants are channel cooling, hollow conductor cooling and heat pipe cooling. As all of these techniques have their strengths and weaknesses, a combination of technologies seems advisable to obtain a capable cooling system for high power electric machines, suitable for aviation purposes. Consequently, the operation of direct channel cooling for effective heat dissipation from the stator and rotor core in combination with the hollow conductor cooling for most direct heat removal from the stator windings is suggested, both being sufficiently expedient in terms of additional mass and operational safety.

Uncertainties in the weighted evaluation performed in this study arise from a potentially incomplete information base, imponderabilities and ambiguities in assigning criteria abilities to certain technologies. Additionally, the assessment approach is rather coarse due to the limited number of weighting options in pairwise comparison and the amount of criteria fulfillment levels used for rating the cooling concept within each criterion.

To consolidate the findings of this work, a more profound literature overview and a more detailed and precise evaluation of cooling concepts are indicated. Additionally, the analytical modeling of cooling concepts and their objective, reproductive and quantitaive evaluation by the derived numerical parameters will enable a well-founded selection of cooling technologies, converging towards one expedient approach to be designed. The literature-based weighted evaluation as well as the analytical calculations then certainly require validation through numerical simulations and/or experimental testing.

In consequence, this could potentially lead to an increase in power density, efficiency and durability of high power electric machines, enabling the realization of electric aircraft propulsion systems and therefore mitigating CO_2 emissions and adverse climate impacts of aviation.

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APPENDIX

TAB 4. Detailed evaluation of cooling concepts. Assessment of the criteria fulfillment level of each cooling concept in each criterion based on specific positive and negative properties.

Criterion		Cooling Concept: Surround. Flow Cooling **SFC**	Jacket Cooling **JC**	Annular Gap Cooling **AGC**	Flooding Cooling **FC**	Channel Cooling **CC**	Heat Pipe Cooling **HPC**
Cooling Effectivity **CE**	w_i = 0.4	− Low effectivity − Long heat path − Performance directly depending on ambient conditions	± Medium effectivity − Long heat path	± Medium effectivity ± Medium long heat path	± Medium effectivity ± Medium long heat path + Large heat transferring area	+ High effectivity + Short heat path	+ Very high effectivity + Very high thermal conductivity + Short heat path − No heat dissipation to outside the machine
		−−	−	±	+	++	++
Energy Efficiency **EE**	w_i = 0.05	+ No additional power consumption − Potential additional drag	+ Low power consumption	+ Low power consumption	+ Low power consumption	± Medium power consumption	+ No additional power consuption
		+	+	+	+	±	++
Additional Mass **AM**	w_i = 0.25	+ No additional weight (except cooling fins) + No cooling circuit component weight	− Jacket and coolant volume weight − Weight of cooling circuit components	+ No additional weight − Weight of cooling circuit components	− Reservoir and coolant weight − Weight of cooling circuit components	+ No additional weight − Weight of cooling circuit components	− Heat pipe weight + No cooling circuit component weight
		++	−−	±	−	±	±
Safety & Reliability **SR**	w_i = 0.25	+ High reliability + No moving parts − Potential particle accumulation − Potential abbrasion by particles	+ Mature technology + High reliability − Moving parts − Potential corrosion in cooling circuit − Potential leakage	+ High reliability − Moving parts − Potential corrosion in cooling circuit	+ High reliability − Moving parts − Potential corrosion in cooling circuit − Potential leakage	+ High reliability − Moving parts − Potential corrosion in cooling circuit	− Unmature technology + No moving parts − High temperature and pressure loads − Potential leakage − Potential deformation
		±	±	±	−	±	−−
Cost & Durability **CD**	w_i = 0.05	± Medium material costs + Low manufacturing costs + Low maintenance costs + Long service life	± Medium material costs ± Medium manufacturing costs ± Medium maintenance costs + Long service life	+ Low material costs + Low manufacturing costs ± Medium maintenance costs + Long service life	+ Low material costs ± Medium manufacturing costs − High maintenance costs + Long service life	+ Low material costs − High manufacturing costs − High maintenance costs + Long service life	− High material costs ± Medium manufacturing costs − High maintenance costs − Short service life
		++	±	++	+	±	−−

TAB 4. (cont.) Detailed evaluation of cooling concepts. Assessment of the criteria fulfillment level of each cooling concept in each criterion based on specific positive and negative properties.

Criterion			Cooling Concept Hollow Conductor Cooling **HCC**	Spray & Impingement C. **SIC**	Filling & Potting Cooling **FPC**	Insertion Cooling **ISC**	Immersion Cooling **IMC**	Hollow Shaft Cooling **HSC**
Cooling Effectivity	**CE**	$w_i = 0.4$	+ Very high effectivity + Very short heat path	+ Intense heat transfer – Long heat path + Very high heat path thermal conductivity	+ Increased heat path thermal conductivity – Influence on small part of heat path only – No heat dissipation to outside the machine	+ Strongly increased heat path conductivity – Influence on small part of heat path only – No heat dissipation to outside the machine	+ Use of whole surface for heat transfer – Low heat transfer – Long heat paths – No heat dissipation to outside the machine	+ High heat transfer + High heat absorption ability – Long heat path
			++	+	–	±	– –	+
Energy Efficiency	**EE**	$w_i = 0.05$	– High power consumption	± Medium power consumption – Additional rotor drag	+ No additional power consumption	+ No additional power consumption	– High additional rotor drag – High fluid friction losses	+ Low power consumption
			–	–	++	++	– –	+
Additional Mass	**AM**	$w_i = 0.25$	+ Few additional weight + Saved conductor material weight – Weight of cooling circuit components	+ No additional weight – Weight of cooling circuit components	– Filling/potting material weight + No cooling circuit component weight	– Heat guide weight + No cooling circuit component weight	– Coolant weight + No cooling circuit component weight	+ Saved shaft weight – Weight of cooling circuit components
			+	±	±	±	±	±
Safety & Reliability	**SR**	$w_i = 0.25$	– Unmature technology – Moving parts – High pressure loads – Potential corrosion in cooling circuit – Potential channel obstruction by impurities – Potential leakage	+ Mature technology + High reliability – Moving parts – Potential corrosion in cooling circuit – Potential nozzle obstruction by impurities	+ No moving parts – Potential short circuit failure – Potential material rupture/deformation	+ No moving parts – Potential short circuit failure – Potential partial discharge	+ No moving parts – Potential coolant overheating	+ High reliability – Moving parts – Potential corrosion in cooling circuit – Potential leakage
			– –	–	–	–	±	–
Cost & Durability	**CD**	$w_i = 0.05$	± Medium material costs ± Medium manufacturing costs ± Medium maintenance costs ± Medium service life	± Medium material costs ± Medium manufacturing costs – High maintenance costs + Long service life	– High material costs ± Medium manufacturing costs + Low maintenance costs + Long service life	± Medium material costs ± Medium manufacturing costs + Low maintenance costs + Long service life	+ Low material costs + Low manufacturing costs + Low maintenance costs + Long service life	± Medium material costs – High manufacturing costs + Low maintenance costs ± Medium service life
			±	±	+	+	++	±

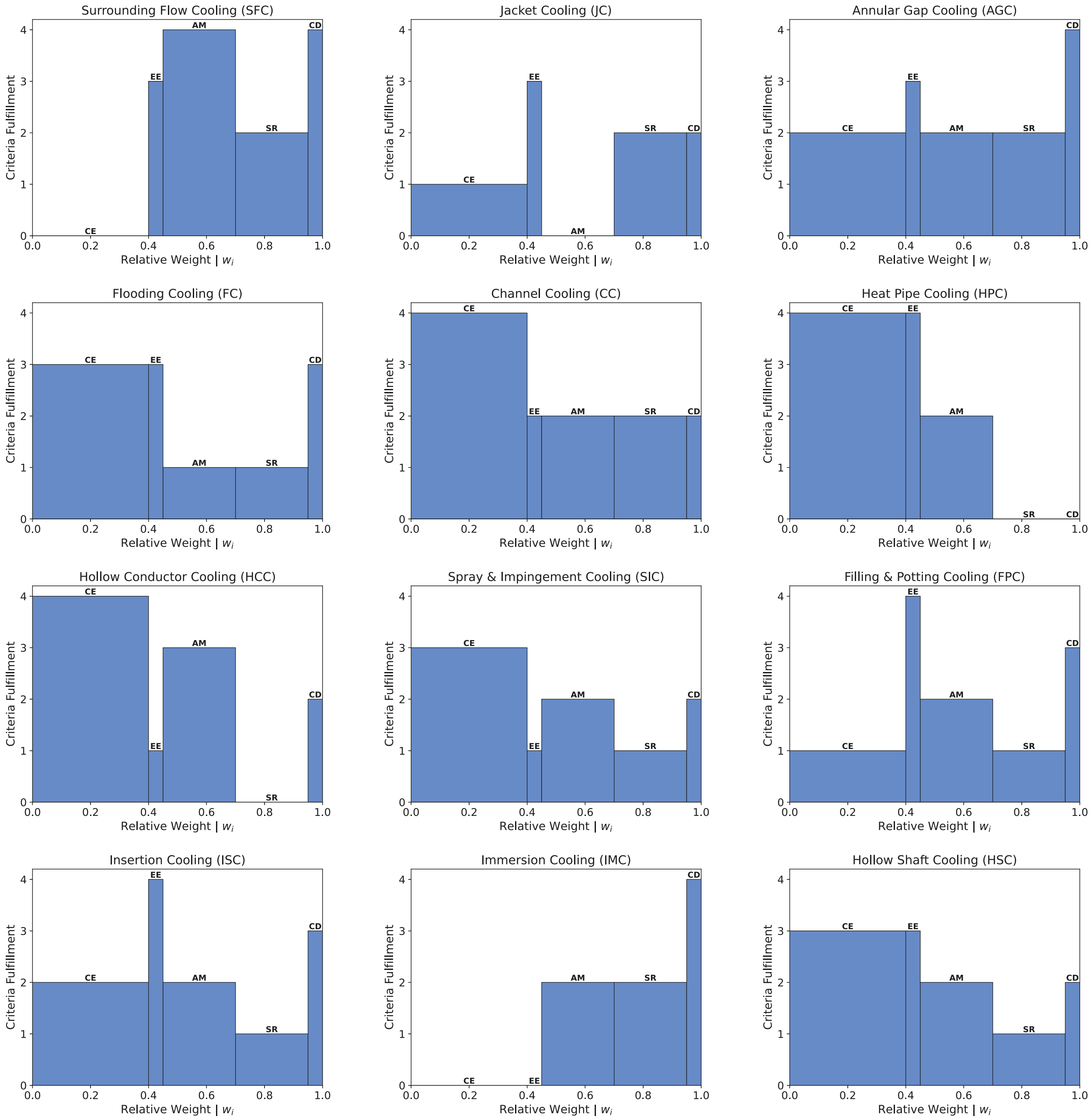

FIG 30. Characteristic utility diagrams for each cooling concept with the bar height correlating to the criteria fulfillment level and bar width corresponding to criteria weight. Assessment criteria: Cooling Effectivity (CE), Energy Efficiency (EE), Additional Mass (AM), Safety & Reliability (SR) and Cost & Durability (CD).