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Thermal management of electrical machines for propulsion – challenges and future trends

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Abstract: The continuous drive towards electrified propulsion systems has been imposing ever more demanding performance and cost targets for the future power electronics, machines and drives (PEMDs). This is particularly evident when exploring various technology road mapping documents both for automotive and aerospace industries, e.g. Advanced Propulsion Centre (APC) UK, Aerospace Technology Institute (ATI) UK, National Aeronautics and Space Administration (NASA) USA and others. In that context, a significant improvement of the specific performance and cost measures, e.g. power density increase by a factor of 10 or more and/or cost per power unit reduction by 50% or better, is forecasted for the next 5 to 15 years. However, the existing PEMD solutions are already at their technological limits to some degree. Consequently, meeting the performance and cost step change would require a considerable development effort. This paper is focused on electrical machines and their thermal management, which has been recognised as one of key enabling factors for delivering high specific output solutions. The challenges associated with heat removal in electrical machines are discussed in detail, alongside with new concepts of thermal management systems. Several examples from the available literature are presented. These include manufacturing techniques, new materials and novel integrated designs in application to electrical machines.

Key words: future technology trends, high specific output electrical machines, new manufacturing techniques and materials, thermal management

1. Introduction

The global efforts to reduce greenhouse gas emissions, like CO2 and NOx, resulted in environmental legislation, with stringent emission targets for the upcoming years. An example here is the UK government, which announced a long-term plan to bring all greenhouse gas emissions to net zero by 2050 [1]. In that context, the transportation industry is considered as one of the major contributors among power and heat generation, chemical, metallurgical and mineral industry sectors [2].

The ongoing, transformative change to the automotive industry is one of the examples, where the well-established propulsion technology, fossil fuel-based internal combustion (IC) engines, is being replaced with "new" zero/low-emission electrified solutions [3]. Similar trends can also be observed when analysing technology forecasts for the aerospace industry [4, 5].

However, to make any of the new electrified concepts a viable solution, further research and development work is needed. This is particularly prominent when reviewing various road mapping and technology review documents related to the advance of electric motor drives for propulsion [3–6]. Both the performance and cost targets for the future power electronics, machines and drives (PEMDs) are very challenging indeed.

Table 1 lists an example of forecasts of continuous power density for the future propulsion/on-board power generation electrical machines. It is important to note that the significant increase of power density is accompanied by considerably increased power output per machine unit, improved efficiency and reduced cost. Here, the performance targets suggest increase in power density of propulsion motors (for passenger cars) by a factor of 4 and cost per unit reduction by 50% by 2035 [3]. It is unsurprising that the specific performance/cost measures are even more demanding, when considering aerospace applications. Note that electrical machines with an output power of tens to hundreds of kW are typically envisaged for automotive applications, whereas future aircrafts call for machines with an output power of up to tens of MW [3–5].

Table 1. Forecasts of continuous power density for the future propulsion/on-board power generation electrical machines

Year	**2017/2018**	**2025**	**2030**	**+2035**
[kW/kg]				
APC[1)]	2.5	7.0	–	9.0
ATI[2)]	3.0	7.5	12.0	20.0
NASA[3)]	6.6	16.5	19.7/33.0[4)]	41.1[4)]

[1)] Advanced Propulsion Centre (APC) UK – [3]
[2)] Aerospace Technology Institute (ATI) UK – [4]
[3)] National Aeronautics and Space Administration (NASA) USA – [5]
[4)] Cryogenically cooled/superconducting electrical machines

The existing electrical machines for propulsion are designed to meet frequently conflicting design targets, like performance versus cost for in-volume manufacture, and well utilise the current array of materials and manufacturing processes. All these have been developing over several decades and are at high technology/process maturity, often with limited scope for further improvements.

Figure 1 presents a schematic highlighting complexity of the "design for application" process of a new electrical machine. Clearly, "design for performance" is just one of the elements of the multidisciplinary development process, where the material/component cost – "design for cost", manufacturability – "design for manufacture", and exploitation and life cycle – "design for life" aspects are also considered. Note that the application driven design process requires in-depth understanding of the intended operating conditions (like working envelope/duty and environmental factors). Usually, a "successful" commercial design is a compromise amongst multiple targets from the design landscape, Fig. 1.

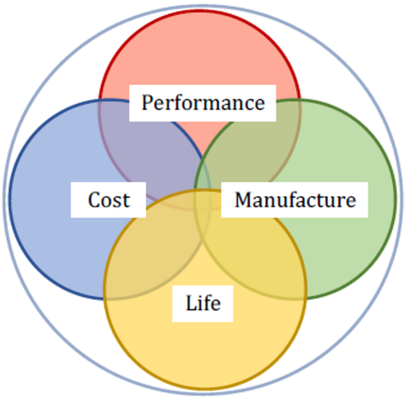


Fig. 1. Elements of "design for application" of an electrical machine

It is evident that delivery of a step-change in the performance of electrical machines for propulsion, would require a comprehensive approach combining state of the art in electrical machine "design for application", possibly with new materials and manufacturing techniques in mind. At the moment, there is no specific/single technology contender, which could enable such advancement. However, it has been recognised that more effective thermal management alongside with new low-power-loss active materials [7–10], light-weight composite structural parts and new manufacturing techniques [11–13] might bring the electrical machines for propulsion/on-board power generation closer to the targets for the future automotive and aerospace applications.

This paper introduces the key challenges associated with effective heat removal from electrical machines. Several examples of thermal management concepts in application to high-specific output electrical machines are presented. Some information on new low-power-loss active materials is also provided. The author's view on how the thermal management might evolve in the near future is given in final remarks to the paper.

2. Thermal management – challenges

In general, an electrical machine body can be treated as a heat source, with multiple/distributed power loss components. The electromagnetic power losses are associated with the windings, core packs and permanent magnets (PMs), whereas mechanical heat sources (frictional/drag power losses) are related to bearings and rotor subassemblies [14]. Note that some of the structural or thermal management parts of the machine assembly can also introduce additional power losses [14]. Further to these, the power loss distribution within the complete machine and/or per subassembly is inhomogeneous and strongly depends on the machine's operating point and conditions.

The generated heat is removed from the machine's body mainly by the conductive and convective heat transfer mechanisms. The radiation effect is usually of lesser importance, when considering high-specific-output machine designs. All the machine's active subassemblies are made of multiple materials/composites, making the heat removal particularly challenging. Figure 2 presents a typical stator winding construction, with focus being placed on the impregnated winding body. Although, the thermal conductivity of copper (Cu) or aluminium (Al) conductors is relatively high, Cu: 398 W/m·K and Al: 210 W/m·K, the electrical insulation system together with various manufacturing imperfections and subassembly contact thermal resistances make heat transfer from the winding body to the machine periphery/housing difficult [15–17]. Note that the equivalent thermal conductivity of impregnated windings is usually orders of magnitude lower than for the conductors themselves. A typical value of thermal conductivity for low-voltage, varnish impregnated windings is less than 1 W/m·K, whereas for epoxy impregnation up to 5 W/m·K, subject to specifics of the winding construction and insulation system [15–17]. Considering that the winding assembly is frequently the main heat source within the machine body [14], this clearly highlights the challenge associated with effective thermal management using solely conductive heat transfer. The heat conducted across multiple thermal paths (materials/machine's subassemblies) is then evacuated from the actively cooled machine's housing, e.g. motor housing with liquid jacket or finned housing with fan arrangement [7–10]. Such housing arrangement provides the mechanical encasing for active parts of the machine and acts as a heat exchanger. Consequently, a good housing design requires careful considerations, when designing high-specific-output electrical machines.

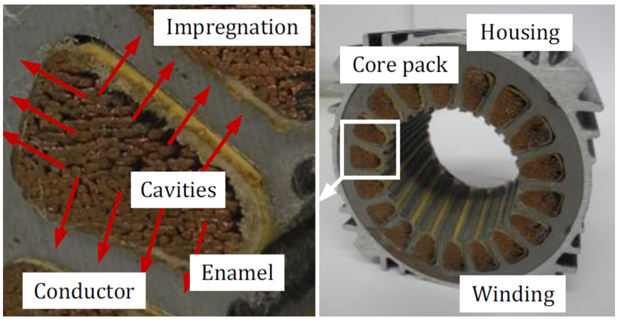


Fig. 2. An example of typical low-voltage stator winding assembly (red arrows indicate schematically heat transfer path from the winding body to the machine periphery/housing)

Clearly, the use of conductive heat removal is limited by the materials and manufacturing techniques used. Direct fluid cooling, which is common in high-power large machines for power generation, provides a more effective means of extracting the generated power losses [7–10]. However, such an approach usually requires a more complex machine design, where the fluid cooling system is incorporated in the machine body. The cooling fluid is frequently in direct contact with the machine's active parts, e.g. direct gas or liquid cooling of stator and/or rotor subassemblies [7–10]. Note that the indirect fluid heat removal by the introduction of appropriate cooling features like channels is also used. Although the direct cooling approach might seem easy to implement, several design challenges need to be considered, e.g. additional power losses (electromagnetic and mechanical), increased complexity, need for more frequent maintenance checks and cost are some of the factors. However, some of the drawbacks can be offset by the overall machine/system performance gains.

The high-speed/frequency operation, often associated with electrical machines for propulsion/on-board power generation, imposes several challenges including the rotor mechanical integrity, power losses and thermal management. The rotor subassembly, which is mechanically suspended using appropriate bearing arrangement, has an inherently limited dissipative thermal path into the surrounding structures. To improve heat removal from the rotor body, a variety of techniques are used, with direct air and or oil cooling being the most common [7–10]. It is important to note here, that increase of the rotational speed in order to reduce the overall machine's mechanical envelope (increased power density) has its limitations. In [6], the authors surveyed electrical machines by application accounting for the rated output power and rotational speed, and indicated a technology limit set by the current materials and manufacturing techniques. In that context, the rotor tip speed is used as an indication of the mechanical design limits, e.g. high-specific-output electrical machines with a rotor tip speed of up to 200 m/s have been reported in the literature [18–20].

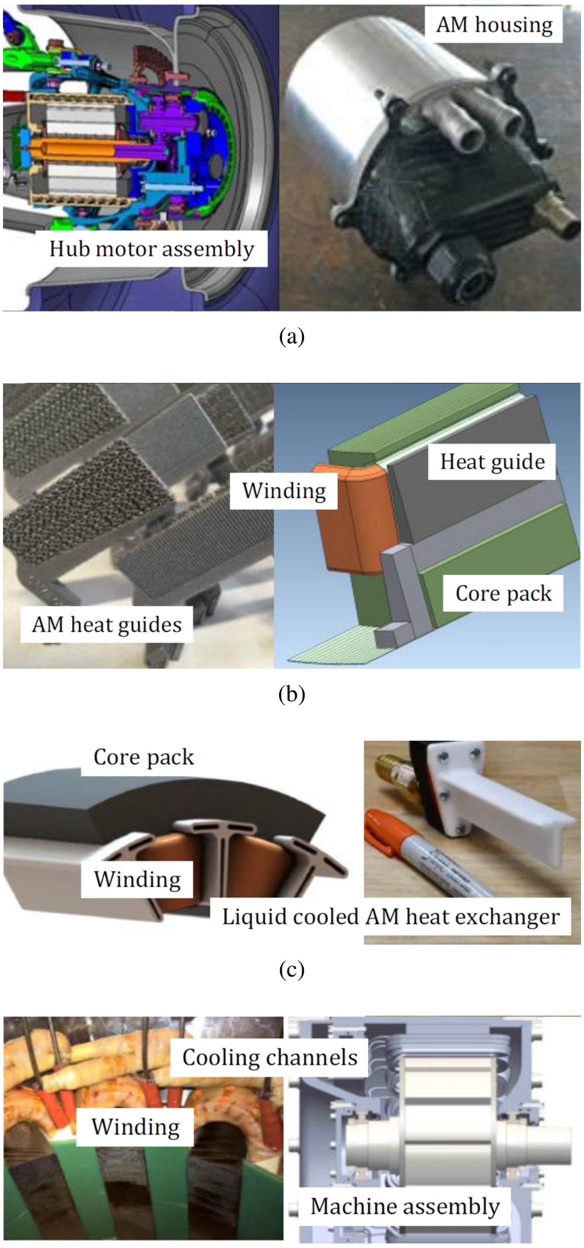
3. Thermal management – opportunities

This section reviews the recent developments related to the thermal management of electrical machines. The selected examples indicate some of the technology avenues, which might provide a more effective heat removal and consequently bridge the gap between the current and future technology targets for electrical machines for propulsion/on-board power generation.

3.1. Heat exchangers and cooling features

Figure 3 presents a number of heat exchangers and cooling features to provide/enhance heat removal from various parts of the electrical machine assembly. Figure 3(a) presents an example of additively manufactured (AM) machine housing for an electric vehicle (EV) application. Here, the use of metal AM (aluminium alloy – AlSi10Mg) enabled the integration of unique cooling channels design, which resulted in the reduction of the total number of housing parts and improvement of the overall thermal management performance [22]. The authors reported 31% higher total mass flow and 20% improvement in total heat conduction and efficiency of the cooling system as compared with a more conventional design [22]. Note that in-volume fabrication of liquid-cooled motor housings relies on casting. Consequently, the motor housing design is restricted to some degree by the use of such a manufacturing process.

Figure 3(b) shows a family of heat guides (HGs) developed to enhance heat removal directly from the winding body [23]. AM has been used here to enable design solutions with high thermal conductivity and minimal additional power loss. As the HGs were designed to be placed in the stator slots, and consequently to be in direct contact with the winding body, providing a good balance between thermal and electrical properties of such an assembly was essential. It has been shown that the supplementary heat path between winding and the actively cooled machine



(a)

(b)

(c)

(d)

Fig. 3. Heat exchangers and cooling features: (a) AM motor housing with integrated cooling channels – Technical University of Munich, TUfast Racing Team Formula Student [22]; (b) set of AM HGs for enhanced heat transfer in electrical machines – Newcastle University [23]; (c) AM integrated liquid cooled HE – University of Wisconsin-Madison [25]; (d) winding with custom Litz wire, with embedded cooling channel – Lappeenranta University of Technology [26]

housing (path introduced by HGs) results in 20% to 40% improvement in dissipation of the generated power loss from the stator/winding assembly [23]. Here, the lower improvement bound corresponds with a higher operating frequency, whereas the higher performance increase is at low frequency.

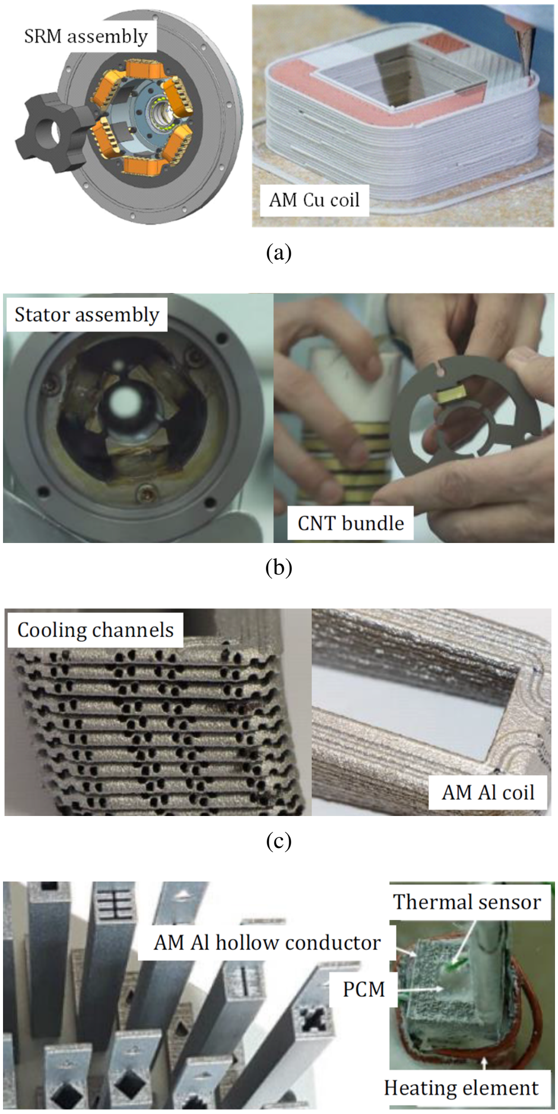
Figure 3(c) presents a liquid-cooled heat exchanger (HE) for direct heat evacuation from the winding body [24, 25]. Here, the HE is sharing the stator slot together with the winding assembly. To assess the HE concept, the authors evaluated a number of alternative plastic and ceramic materials, with Al-PC (plastic) and Ceramco 3D (printable Alumina ceramic) being the preferred choices here. A 44% reduction in winding operating temperature as compared with no HE alternative stator/winding assembly has been reported for the initial work with Al-PC [24]. Further development of the cooling concept using the ceramic material showed additional improvements, with winding current density up to 30 A/mm^2 for continuous operation [25].

Figure 3(d) shows a similar concept, of direct heat removal from the winding body by introduction of appropriate cooling channels (liquid-cooled heat exchanger), to that discussed in the previous section. Here, however, more conventional techniques were adopted to fabricate a Litz wire incorporating stainless steel cooling channel. Consequently, a fully formed winding contains direct heat extraction from the individual coils/turns. Such an approach is allowed for a winding current density of up to 18 A/mm^2 to be continuously sustained [26]. Interestingly, the complete prototype machine was fabricated and tested both in the lab and heavy-duty electrical-bus application, proving the machine design with direct winding cooling. Although similar thermal management concepts can be found in high-power large machines for power generation, successful implementation of such design concepts on a lower scale is very challenging.

3.2. Winding fabrication and integrated cooling

Figure 4(a) shows an example of a concentrated winding/coil for a switched reluctance machine (SRM) application. The AM employed by the authors used both copper alloy and a ceramic material with an appropriate binding agent [27]. Such an approach enables complex geometries to be formed. An appropriate thermal treatment, during which built parts are sintered, has been used to achieve the required material physical properties. The electrical conductivity of the fabricated coils was lower than the conventional copper wire (41.9 MS/m, 72% of International Annealed Copper Standard (IACS)), which is attributed here to the material porosity [27]. Further to this, the authors investigated thermal expansion of the multi-material parts showing no mechanical defects after an initial thermal cycling of up to 300°. The high conductor fill factor, achievable when using AM, together with the elevated operating temperature of the winding might allow for the increased power density of the analysed machine. This, however, would need further improvements of material physical properties, e.g. electrical conductivity, for AM Cu.

Figure 4(b) presents an electrical machine demonstrator with a carbon nanotube (CNT) winding [28]. Here, the authors fabricated the complete wire (bundle of conductors) by gluing individual CNTs to an aramid (Twaron) yarn. The use of a CNT in the construction of electrical windings offers potentially several interesting performance gains like increased electrical and thermal conductivity (100.0 MS/m^2, 3000 W/m·K) and reduced mass by a factor of 6 as compared to Cu equivalent. All these are very desirable in the context of future electrical machines for propulsion/on-board power generation. The measured data gathered from tests on the prototype machine with alternative winding/conductor materials (Cu, CNT) showed that the electrical properties of commercially available CNTs would require further improvements to match or exceed the performance of commonly used Cu or Al conductors. However, it was successfully demonstrated that a CNT can be effectively implemented in the construction of electrical windings.



(a)

(b)

(c)

(d)

Fig. 4. Alternative winding variants: (a) AM Cu coil with ceramic insulation for SRM – Chemnitz University of Technology [27]; (b) carbon nanotube [28]; (c) AM Al alloy coil with integrated cooling channels – Leibnitz University Hannover [29]; (d) AM Al conductors with PCM phase change material – Safran Tech [30]

An interesting concept of a concentrated coil/winding with integrated cooling channels is shown in Fig. 4(c). Here, the coil geometry was designed to reduce the winding ac power losses as well as to provide a high heat removal capability [29]. The authors used aluminium alloy (AlSi10Mg) in the construction of the coil [29]. Interestingly, the cooling channels are designed to reduce the overall winding power loss generated at ac operation. It was experimentally demonstrated that the proposed approach allows for direct heat extraction from the winding, with a conductor current density of 100 A/mm^2. This is well beyond the existing figure of merit for the windings with direct liquid cooling, Table 2.

Table 2. Current density in windings for alternative cooling techniques – [21]

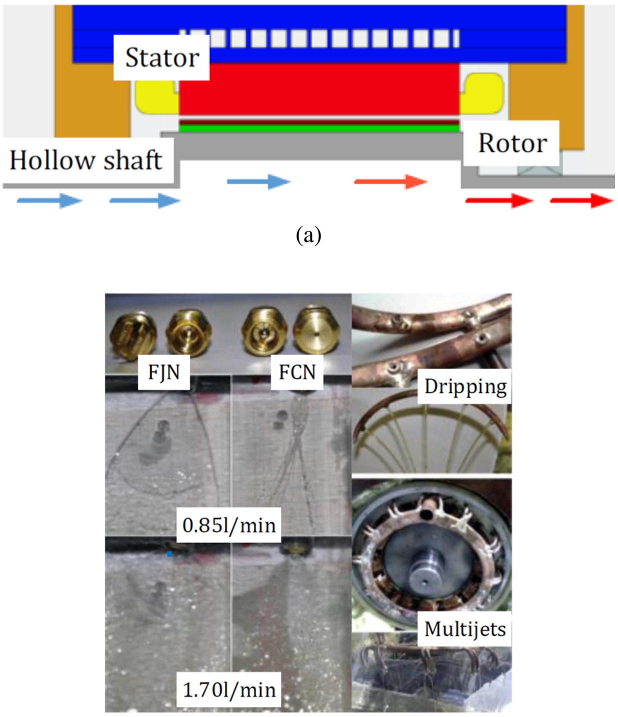
Cooling type	**[A/mm^2]**
Housing with fins and heat sinks	5–8
Housing with water or oil jacket	10–15
Direct winding liquid cooling	30
Direct end-winding spray oil cooling	28

Phase change materials (PCMs) offer an interesting design avenue when considering winding designs with an extended overload capability. Figure 4(d) shows a family of AM conductors with different channel profiles to accommodate for PCM. Here the authors used paraffin (RT70HT) as PCM [30]. The benefit of the improved thermal transient response was experimentally demonstrated. Here, approximately 60% reduction of the winding temperature rise was achieved for the PCM-based winding concept as compared to a conventional alternative. However, further work is required to gain a better understanding of the thermal and power loss effects, when developing the complete winding/coil demonstrator.

3.3. Rotor and end-winding cooling

As discussed before, effective heat removal from the rotor assembly is particularly difficult due to multiple, frequently conflicting, design requirements. One of the solutions, which was successfully implemented in several vehicle applications, employs a liquid-cooled hollow shaft. An example of such a rotor cooling approach is shown in Fig. 5(a). Here, liquid coolant (water or oil) is passed through the hollow shaft, which is interfaced with an external cooling system via rotary seals on both inlet and outlet sides of the rotor assembly. Although the fundamentals of heat removal via circular, stationary channels (with no rotation) are well known, the overall effects of rotation on the thermal behaviour of such a solution were unclear. In [31] the authors showed that the hollow shaft rotation has a positive impact on the hollow shaft rotor cooling, with the dissipative heat transfer increased by a factor of 4 at high-speed operation (30 000 rpm) as compared with the stationary or low-speed operation.

The spray oil cooling of the machine's end regions, including the end-winding and/or rotor, was shown to be very effective [32], Table 2. Figure 5(b) presents examples of end-winding oil cooling with alternative types of spray, namely mist, dripping and multi-jets. Also, alternative jet types with a flat jet nozzle (FJN) and a full cone nozzle (FCN) were investigated. The experimental



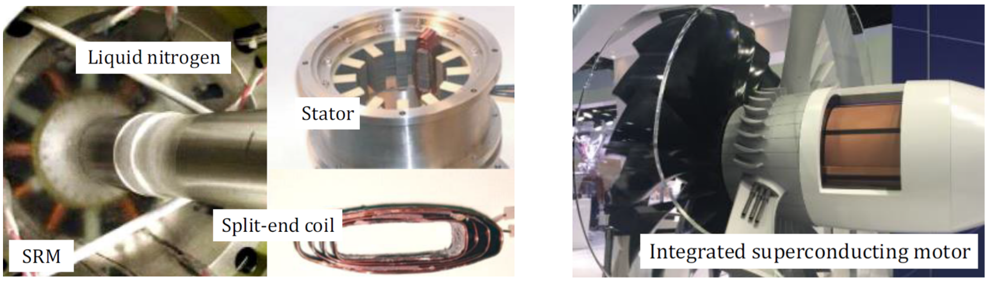
(b)

Fig. 5. Examples of direct liquid-cooling: (a) hollow shaft oil rotor cooling – Newcastle University [31]; (b) end-winding oil cooling – University of Lille North of France, University of Valenciennes, Renault [32]

results showed that the dripping spray cooling is the most effective, with the heat removal increased up to 5 times. Note that relatively low flow rates of oil allowed for significant improvement in dissipated power loss as compared to machine assembly without spray oil cooling in place. This clearly shows the potential of the targeted liquid cooling of the machine's subassemblies, which are susceptible to high-power loss and simultaneously are difficult to remove the generated heat from.

3.4. Cryogenic cooling and superconducting machines

Cryogenic cooling is commonly associated with superconducting machines. However, it is important to note that such a cooling approach is not exclusive to superconductive windings. Some attempts were made to use cryogenic-based thermal management for machines with conventional windings. Figure 6(a) shows an example of an SRM, which was cryogenically cooled using liquid nitrogen [33]. Here, the authors managed to significantly increase the winding current density from 11 A/mm^2 for conventional cooling to approximately 100 A/mm^2 for a cryogenically cooled machine, with the 50% duty-cycle of the excitation. Note that such an increase of current density results from the reduced temperature of the winding material, i.e. reduced electrical resistivity, that is orders of magnitude lower (a factor of 100 or better) than at room temperature. Also, to further enhance heat removal from the winding body, the split-end coils/winding was employed, Fig. 6(a).



(a) (b)

Fig. 6. Examples of cryogenically-cooled machines: (a) SRM demonstrator with conventional Cu winding – NASA [33]; (b) integrated superconducting motor for aerospace propulsion – ASuMED project [35]

The superconducting machines for propulsion/on-board power generation have been undergoing dynamic advances [34]. Figure 6(b) presents an example of the latest development, an integrated superconducting machine for aerospace applications. This ambitious motor development is funded by the EU (advanced superconducting motor experimental demonstrator (ASuMED) project) [35]. Some of the motor performance targets include 99% efficiency, 1 MW output power, 6 000 rpm rated speed, 20 kW/kg power density, with windings constructed using second generation (2 G) high-temperature superconductor (HTS) tape (dc field magnets and ac windings). Some of the more detailed metrics include magnetic and electric loadings larger than 2.5 T and 450 kA/m, respectively. All these are well beyond what is achievable when using conventional machine technology and in line with the existing technology forecasts, Table 1.

4. Observations and final remarks

The technology targets for the future electrified propulsion/on-board power generation, for automotive and aerospace industries are very demanding, indeed. To meet such performance goals, a more comprehensive development process, i.e. “design for application” needs to be employed. Clearly, the thermal management of electrical machines is just one of the key design aspects enabling the next generation of high-specific-output electrical machines. When reviewing the existing literature devoted to cooling of electrical machines, it is evident that there are numerous design avenues allowing one to achieve a highly effective and well-integrated heat removal. It is the author’s opinion that a combination of new design concepts, materials and manufacturing techniques, rather than a single technology, is most likely to provide commercially viable solutions. It seems that the superconductive machine technology has a good promise to deliver the high specific performance targets, discussed in this review, first among the other possible solutions.

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