Modern Heat Extraction Systems for Electrical Machines – A Review

Mircea Popescu, Fellow, IEEE, Dave Staton, Member, IEEE, Aldo Boglietti, Fellow, IEEE, Andrea Cavagnino, Senior Member, IEEE, Douglas Hawkins and James Goss

Abstract—This paper presents a review of modern cooling system employed for the thermal management of electrical machines. Various solutions for heat extractions are described: high thermal conductivity insulation materials, spray cooling, high thermal conductivity fluids, combined liquid and air forced convection, loss mitigation techniques.

Index Terms—Thermal management, thermal analysis, cooling system, convection, radiation, conduction, AC losses, core losses, magnet losses, spray cooling, high thermal conductivity

I. INTRODUCTION

The thermal stress on the electrical machines is created by the losses dissipated in the system which will heat different components of the machine, like windings, rotor cages, magnets, and needs to be dissipated. One can thermally protect the electrical machines by reducing the local losses, i.e., the induced eddy-current losses in the electrical conducting regions, iron cores, magnets, retaining sleeves, and/or using an efficient cooling system. Depending on the application, cooling systems can be employed with natural convection (totally enclosed non-ventilated), forced convection (air or liquid cooling), or radiation cooling (in the case of electrical machines, operating in vacuum environment), [1].

The thermal analysis of an electric motor is generally regarded as a more challenging compared to the electromagnetic analysis in terms of the ease of construction of a model and achieving good accuracy. This is because it is highly dependent not only on the design but on the manufacturing tolerances.

Heat can be extracted through conduction, convection (natural and forced) and radiation.

The thermal management of electrical machines is a 3-dimensional problem which requires complex heat extraction phenomena to be addressed; e.g., heat transfer through complex composite components such as the wound slot, temperature drop across interfaces between components and complex turbulent air flow within the end-caps.

This study presents modern various solutions for an efficient heat extraction or thermal management of the electrical machines.

II. HEAT EXTRACTION THROUGH CONDUCTION

Conduction heat transfer mode is created by the molecule vibration in a certain material. Typically, a material with good electrical conductivity is also characterized by a good thermal conductivity. In an electrical machine it would be desirable to have also materials that are good electrical insulators and have good thermal conductivity.

Conduction will depend on the thermal conductivity and dimensions (length $L$ and area $A$) of the region, with the thermal resistance given by:

$$R_h = \frac{L}{kA} \quad (1)$$

Eq. (1) shows that a good heat extraction through conduction, i.e. low thermal resistance of a motor component, is achieved either if the material has a high thermal conductivity or if the ratio area vs length is maximized. The latter is translated for example by having a high slot fill factor, or packing as much wire as technological possible in the slots of the electrical machines.

Metals, i.e. copper, aluminum, steel, have high thermal conductivity due to their well-ordered crystalline structure. The thermal conductivity for metals, $k$, is usually in the range 15 – 400 W/m/K. Solid insulator materials, i.e. resins, paper, do not have a well ordered crystalline structure and often porous. Thus, the energy transfer between molecules is impeded. The thermal conductivity for insulators is typically in the range 0.1 – 1W/m/K. For comparison, air has an average thermal conductivity of 0.026W/m/K.

In the last decade, significant research efforts lead to the development of insulation materials that have a higher thermal conductivity value. Table I summarizes the actual standard insulation classes as approved by IEC and NEMA.

Notice that an existing insulation class at 300 °C is not part of the standard.

In Table II, some of the latest high thermal conductivity materials/ high volume electric resistivity are reported.
### Table I. Standard Insulation Classes [6]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>Y</td>
<td>90°C</td>
<td></td>
<td></td>
<td>Un-impregnated paper, silk, cotton, vulcanized natural rubber, thermoplastics that soften above 90°C [4]</td>
</tr>
<tr>
<td>105</td>
<td>A</td>
<td>105°C</td>
<td></td>
<td></td>
<td>Organic materials such as cotton, silk, paper, some synthetic fibers [5]</td>
</tr>
<tr>
<td>120</td>
<td>E</td>
<td>120°C</td>
<td></td>
<td></td>
<td>Polyurethane, epoxy resins, polyethylene terephthalate, and other materials that have shown usable lifetime at this temperature</td>
</tr>
<tr>
<td>130</td>
<td>B</td>
<td>130°C</td>
<td></td>
<td></td>
<td>Un-organic materials such as mica, glass fibers, asbestos, with high-temperature binders, or others with usable lifetime at this temperature</td>
</tr>
<tr>
<td>155</td>
<td>F</td>
<td>155°C</td>
<td></td>
<td></td>
<td>Class 130 materials with binders stable at the higher temperature, or other materials with usable lifetime at this temperature</td>
</tr>
<tr>
<td>180</td>
<td>H</td>
<td>180°C</td>
<td></td>
<td></td>
<td>Silicone elastomers, and Class 130 un-organic materials with high-temperature binders, or other materials with usable lifetime at this temperature</td>
</tr>
<tr>
<td>200</td>
<td>N</td>
<td>200°C</td>
<td></td>
<td></td>
<td>As for Class B and including Teflon</td>
</tr>
<tr>
<td>220</td>
<td>R</td>
<td>220°C</td>
<td></td>
<td></td>
<td>As for IEC class 200</td>
</tr>
<tr>
<td>240</td>
<td>S</td>
<td>240°C</td>
<td></td>
<td></td>
<td>Polymide enamel (Pyre-ML) or Polymide films (Kapton and Alconex GOLD)</td>
</tr>
<tr>
<td>250</td>
<td></td>
<td>250°C</td>
<td></td>
<td></td>
<td>As for IEC class 200. Further IEC classes designated numerically at 25 °C increments.</td>
</tr>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>300</td>
<td>Newly developed polymer (NeoTem™) at Zeus Inc.</td>
</tr>
</tbody>
</table>

### Table II Insulation Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity [W/m/K]</th>
<th>Electric resistivity [ohm x cm]</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC4260</td>
<td>0.60-0.70</td>
<td>8 x 10⁻¹⁴</td>
<td>Elantas</td>
</tr>
<tr>
<td>Kapton FN</td>
<td>0.12</td>
<td>1.4 – 2.3 x 10⁻¹⁷</td>
<td>DuPont</td>
</tr>
<tr>
<td>Nomex Paper</td>
<td>0.12 – 0.15</td>
<td>8 x 10⁻¹⁵ – 8 x 10⁻¹⁶</td>
<td>DuPont</td>
</tr>
<tr>
<td>PEEK 450G</td>
<td>0.25</td>
<td>4.9 x 10⁻¹⁸</td>
<td>Victrex</td>
</tr>
<tr>
<td>Circalok 6006</td>
<td>1.1</td>
<td>1 x 10⁻¹⁵</td>
<td>Lord</td>
</tr>
<tr>
<td>ECCTreme ECEA 3000</td>
<td>0.180</td>
<td>&gt; 10⁻¹⁸</td>
<td>DuPont</td>
</tr>
<tr>
<td>Teflon PTFE</td>
<td>0.22</td>
<td>&gt; 10⁻¹⁸</td>
<td>DuPont</td>
</tr>
</tbody>
</table>

Figs. 1, 2 [15, 16] show various solutions to achieve high winding slot fill factors. Most of these are suitable for brushless permanent magnet machines with concentrated fractional slots/pole configurations, e.g. Slots = Poles ± 2; Poles ± 3, etc. Such topologies can be built with pre-formed tooth wound coils. When the coils are pre-formed, various shapes can be considered and the conductors can subjected to a high pressure assembly method that would increase significantly the amount of conducting material, copper or aluminum, that can be packed in the machine’s slots.

Other AC machines types, as induction or synchronous wound field, cannot benefit from these solutions as they generally require a distributed winding configuration.

All AC machine types can benefit from using aluminum magnet wire in special applications like automotive and aerospace, where a high rotational speed (> 10krpm) might be required and a highly transient duty cycle.
TABLE III COPPER AND ALUMINIUM WIRE PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>Electric resistivity @ 20°C (ohm x m)</th>
<th>Thermal conductivity (W/m/K)</th>
<th>Density (kg/m³)</th>
<th>Specific heat (kJ/kg/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper 99.9%</td>
<td>1.724 x 10⁻⁸</td>
<td>386</td>
<td>8890</td>
<td>0.385</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2.826 X 10⁻⁸</td>
<td>205</td>
<td>2700</td>
<td>0.833</td>
</tr>
</tbody>
</table>

For comparison the two material properties are given in Table III.
In high speed applications, the winding losses will comprise a DC component and an AC component. As observed from the simplified formulations to calculate AC losses in windings (2-3), and assuming that the induced current is resistance limited and the magnetic field generated by the eddy currents is negligible compared to the external field, the copper windings will exhibit higher AC losses than aluminium winding for the same dimensions, and load. Notice that the inductance of the eddy current path and the mutual interactions between neighbouring conductors are not catered for. The approach is accurate were the conductor dimension is small relative to the field variation and has been successfully applied to evaluating eddy current losses in randomly disposed, multi-stranded electrical machine windings [3], \(\rho\) electrical resistivity, \(l\) is the conductor active length, \(B\) is the average value of a sinusoidal external field and \(\omega\) is the electrical pulsation. The rectangular conductor cross section is defined by its height \(h\), and width \(w_c\), and the circular conductor by its diameter \(d_c\).

Round conductors:
\[
P_w = \frac{\pi d_c^4 (\omega B)}{64 \rho} \tag{2}
\]
Rectangular conductors:
\[
P_w = \frac{lh w_c^3 (\omega B)^2}{12 \rho} \tag{3}
\]

III. HEAT EXTRACTION THROUGH CONVECTION

Convection heat transfer mode appears between a surface and a fluid due to intermingling of the fluid immediately adjacent to the surface where a conduction transfer mode will occur, with the remainder of the fluid due to the molecules motion. Generically, we distinct between: (a) natural convection when the fluid motion is due to buoyancy forces that arise from the change in density of the fluid in the vicinity of a surface; and (b) forced convection when the fluid motion is due to an external force created by a special device, e.g. fans, pumps. Based on the fluid flow type, it is possible to have laminar flow, that is a streamlined flow and occurs at lower velocity and turbulent flow that is created by the eddies at higher velocities when an enhanced heat transfer happens by comparison with the laminar flow case, but with a larger pressure drop.

Convection depends on the heat transfer coefficient \(h\) that is determined empirically from test data or from CFD analysis.

\[
R_h = \frac{1}{hA} \tag{4}
\]

Modern applications where electrical machines are employed rely frequently on forced convection cooling systems that use air or liquid, i.e., water, oil and their combinations. Based on the convection technique we can have: air natural convection (\(h = 5 \text{ to } 10 \text{ W/m}^2\text{K}\)), air forced convection (\(h = 10 \text{ to } 300 \text{ W/m}^2\text{K}\)) and liquid forced convection (\(h = 50 \text{ to } 20000 \text{ W/m}^2\text{K}\)).

Forced convection can be achieved using configurations of channels, ducts, water jackets, spray cooling and axle cooling [9]: Natural Convection (TENV) with various housing design types; Forced Convection – (TEFC) where the fin channel design is essential; Through Ventilation with rotor and stator cooling ducts; Open end-shield cooling; Water Jackets with various design types (axial and circumferential ducts) and stator and rotor water jackets; Submersible cooling; Wet Rotor & Wet Stator cooling; Spray Cooling; Direct conductor cooling; e.g., slot water jacket;

TABLE IV COOLING FLUIDS PROPERTIES – AVERAGE VALUES @ 0°C – 40°C

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Thermal conductivity (W/m²K)</th>
<th>Specific heat (kJ/kg/K)</th>
<th>Density (kg/m³)</th>
<th>Kinematic viscosity (m²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (sea level)</td>
<td>0.0264</td>
<td>1.0057</td>
<td>1.1174</td>
<td>1.57 x 10⁻⁵</td>
</tr>
<tr>
<td>Brayco Micronic</td>
<td>0.1344</td>
<td>1.897</td>
<td>835</td>
<td>1.35 x 10⁻⁵</td>
</tr>
<tr>
<td>Dynalene HF-LO</td>
<td>0.1126</td>
<td>2.019</td>
<td>778</td>
<td>3.2 x 10⁻⁵</td>
</tr>
<tr>
<td>EGW 50/50</td>
<td>0.37</td>
<td>3.0</td>
<td>1088</td>
<td>7.81 x 10⁻⁶</td>
</tr>
<tr>
<td>EGW 60/40</td>
<td>0.34</td>
<td>3.2</td>
<td>1100</td>
<td>1.36 x 10⁻⁵</td>
</tr>
<tr>
<td>Engine Oil</td>
<td>0.147</td>
<td>1.796</td>
<td>899</td>
<td>4.28 x 10⁻⁵</td>
</tr>
<tr>
<td>Mobil Jet Oil</td>
<td>0.149</td>
<td>1.926</td>
<td>1014</td>
<td>1.88 x 10⁻⁴</td>
</tr>
<tr>
<td>Paratherm LR</td>
<td>0.1532</td>
<td>1.925</td>
<td>778</td>
<td>3.43 x 10⁻⁶</td>
</tr>
<tr>
<td>PGW 50/50</td>
<td>0.35</td>
<td>3.5</td>
<td>1050</td>
<td>1.9 x 10⁻⁵</td>
</tr>
<tr>
<td>PGW 60/40</td>
<td>0.28</td>
<td>3.25</td>
<td>1057</td>
<td>3.31 x 10⁻⁵</td>
</tr>
<tr>
<td>RF 245 FA</td>
<td>0.014</td>
<td>0.9749</td>
<td>10.51</td>
<td>1.027 x 10⁻⁶</td>
</tr>
<tr>
<td>Silicone KP96</td>
<td>0.15</td>
<td>1.5</td>
<td>1000</td>
<td>8 x 10⁻⁷</td>
</tr>
<tr>
<td>Skydrol 500-4</td>
<td>0.1317</td>
<td>1.75</td>
<td>1000</td>
<td>3.5 x 10⁻⁷</td>
</tr>
<tr>
<td>Water</td>
<td>0.56</td>
<td>4.217</td>
<td>1000</td>
<td>1.78 x 10⁻⁸</td>
</tr>
</tbody>
</table>

Fig. 3 shows a TENV servo-motor that has an improved heat extraction by optimizing the space and shape of the housing fins.
In Fig. 4, an in-wheel motor with natural convection air cooled rotor and axle water jacket, EWG50/50 cooling fluid [17] is presented. The central axle of the wheel acts also as a large heat sink.
Fig. 5a illustrates the Nissan Leaf electric motor assembly [18]. This is a brushless permanent magnet motor that is cooled via a water jacket with 3 parallel paths and using as cooling fluid EGW 50/50, with 6 l/min flow rate
and 65°C inlet temperature. In Fig. 5b, the modelled temperature distribution in the water jacket is given.

Fig. 3 (a) Servo-motor with optimised fins for natural convection; (b) Influence of the gap between fins on motor thermal response

Fig. 4 In-wheel electric motor, air-cooled and axle water jacket [17]

Fig. 5 (a) Nissan-leaf electric motor; (b) CFD analysis of the cooling system [18]

Fig. 6 High torque density BPM for electric racing cars [20]

Fig. 7 Axial cross-section for high torque density BPM with dual cooling system: oil through the slots and air through the rotor [20]

Fig. 8 YASA motor cooling system (a) axial cross-section, (b) 3D view of the motor – US 20130187492 A1

Fig. 6 and 7 are presenting a new high torque density motor for electric racing cars [20]. With all the electromagnetic loss components minimized, an extremely efficient cooling system is still required for the heat extraction from the motor without compromising the overall system performance. The stator winding is cooled with forced liquid – Paratherm LR, Table IV– through the slot. The fluid is retained in the stator slots region with a carbon fibre tube, whilst the end-windings are potted. The volume flow rate is variable between 5 and 15l/min allowing a winding temperature below 120°C in all cases. In the airgap, a constant air volume flow rate of 1000l/min helps with maintaining the rotor surface and magnets temperature less than 160°C. Inlet temperatures are between 40°C and 50°C.
Fig. 8 shows YASA cooling system [21]: a wheel-hub motor comprises a rotor having permanent magnets, although other field generation means are available, and a stator. The stator has coils wound on stator teeth (bars). The stator forms a housing of a chamber containing refrigerant. The stator housing has heat dissipating fins accessible by the open environment whereby air movement relative to the housing caused at least by rotation of the rotor absorbs heat from the fins. The motor may be an axial flux machine, the coils being wound on bars that are disposed circumferentially spaced around a rotation axis of the rotor. The wheel of the vehicle is mounted directly on the rotor housing.

Another recently popular and efficient cooling system is to implement oil spray cooling, with or without the use of nozzles. A typical arrangement is to fill the motor partially with oil such that the oil in contact with the rotor splashes around the end space and cools the surfaces that it splashes over. Such a method is used in the Toyota Prius traction electric motor. The level of oil fill is important in this case. Too little oil and there will be no pick up of oil from the rotor and so no splashing. Too much oil will hinder the splashing and also increase the windage loss due to oil in the airgap.

Another arrangement is to feed oil onto the rotor such that it is thrown off the axial ends by rotation so hitting the end-windings and other surfaces in the end-space. A good cooling fluid for electrical machines using the spray method should have acceptable properties as listed in [27]: chemically stable and inert; non-toxic; non-flammable; low dielectric constant; high dielectric strength; high electric resistivity. Obviously, the water is not suitable due to its properties: electrical conductive, corrosive, etc.

In [27] it is recommended the use of “Perfluorinated inert liquids, such as the Fluorinert liquids, made by the 3M Company, are suited for direct liquid cooling because they fulfill the conditions mentioned above. However, some of their thermal properties (e.g., viscosity) are highly dependent on temperature”.

Two working liquids are considered for the submerged double-heat impingement (SDJI) method: Baysilone silicon oils manufactured by BAYER.

In [27] it is recommended as selection criteria for the cooling fluids the minimization of the external case-to-fluid thermal resistance. A fluid thermal figure-of-merit (FOM) is introduced. This figure has an empirical form and strictly determined based on measurements.

“Higher values of FOM means better cooling characteristics and, thus, lower external thermal resistance for the heat extraction path. For small ratio axial length/diameter of the machine, heat transfer predominantly occurs in the impingement region, represented by the following figure-of-merit:

\[
FOM_i = \frac{D^{0.5}k^{0.6}c^{0.4}}{\mu^{0.1}}
\]  

(5)

For large ratio axial length/diameter, the wall jet region dominates the heat transfer:

\[
FOM_{wj} = \frac{D^{0.4}k^{0.6}c^{0.4}}{\mu^{0.4}}
\]  

(6)

where \( \rho \) = density (kg/m\(^3\)); \( k \) = thermal conductivity (W/mK); \( c \) = specific heat capacity (J/kg°C); \( \mu \) = dynamic viscosity (kg/m\(^2\)s).

From Table IV, it can be concluded that the heat transfer in the impingement region (denoted by FOM\(_i\)) is not very sensitive to the liquid type. However, when the wall jet region dominates heat transfer (FOM\(_{wj}\)), a significant difference is observed with the candidate liquids. In the actual SDJI cooling application, the impingement and the wall jet region both dominate the heat transfer. Therefore the geometry of the nozzles has to be taken into account to select the optimal cooling fluid”.[27]

Fig. 9 shows a 3D schematic representation of a brushless permanent motor with spray cooling system. The fluid flow directions coming from various nozzles mounted on the shaft, rotor poles or end-winding to outer cap and stator bore are modelled via symbolic arrows.

In Fig. 10, another combined cooling system [21] with stator water jacket - oil as cooling fluid - and forced air flow through the rotor assembly is presented.
Illustrated in Fig. 11 [23], the motor/generator may be in a cooling circuit with the transmission such that the cooling oil is provided from the transmission to the motor/generator (i.e., the same cooling oil used to cool transmission components cools the motor/generator). Alternatively, the motor/generator may be provided with cooling oil in a separate cooling circuit not shared with the transmission. A power inverter module operatively connected with the motor/generator for providing electrical power to the stator may be cooled within the same cooling circuit as the motor/generator, or may have a dedicated cooling circuit using oil, water-ethylene glycol, or air cooling.

In one embodiment of this solution, only a single oil feed is provided from the transmission to the motor/generator to deliver oil to cool the stator, the rotor and preferably bearings within the motor/generator. A flow control member, which may be a partial or complete ring, is cooperatively configured with the motor/housing to distribute the oil at desired flow rates to the stator and the rotor. A dam member may be connected or integrally formed with a rotor end ring to distribute the cooling oil circumferentially to the stator when the cooling oil is thrown outward toward the stator by centrifugal force. A feature may be provided on a bearing retainer to deliver some of the oil flowing from the flow control member to the bearing.

In Fig. 12 [24], an electric motor cooling system is provided in which at least one heat pipe is captured within at least one hollow region within the motor's rotor shaft. An end of the heat pipe that extends out and away from the end of the rotor shaft is coupled to a heat exchanger, for example a heat sink in which the fins of the heat sink are shaped as fan blades. During motor operation, as the rotor heats up thermal energy is absorbed by the heat pipe within the rotor shaft and transferred to the heat sink for efficient removal.

<table>
<thead>
<tr>
<th>Property (@ 25 °C)</th>
<th>DI-water</th>
<th>Fluorinert oils</th>
<th>Baysilone oils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC-72</td>
<td>FC-84</td>
<td>FC-77</td>
</tr>
<tr>
<td>Boiling point (°C)</td>
<td>100</td>
<td>56</td>
<td>80</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>0</td>
<td>-90</td>
<td>-95</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>998</td>
<td>1680</td>
<td>1730</td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>0.598</td>
<td>0.057</td>
<td>0.060</td>
</tr>
<tr>
<td>Specific heat capacity (J/kg°C)</td>
<td>4180</td>
<td>1046</td>
<td>1046</td>
</tr>
<tr>
<td>Dynamic viscosity (kg/m's)</td>
<td>10×10⁻⁴</td>
<td>6.7×10⁻⁴</td>
<td>9.5×10⁻⁴</td>
</tr>
<tr>
<td>Dielectric constant @ 1 kHz</td>
<td>78</td>
<td>1.76</td>
<td>1.81</td>
</tr>
<tr>
<td>Volume resistivity (ohm*cm)</td>
<td>18×10⁶</td>
<td>1×10⁴</td>
<td>1×10⁴</td>
</tr>
<tr>
<td>FOM₁</td>
<td>1300</td>
<td>246</td>
<td>249</td>
</tr>
<tr>
<td>FOM₂</td>
<td>82000</td>
<td>20472</td>
<td>18795</td>
</tr>
</tbody>
</table>
IV. HEAT EXTRACTION THROUGH RADIATION

Radiation heat transfer mode from a surface appears due to the energy transfer by electromagnetic waves. The energy is emitted by vibrating electrons in molecules of the material of the surface of the analyzed body. The amount of emitted energy depends upon the absolute temperature of the body and can occur also in vacuum environment.

Radiation depends on emissivity $\varepsilon$ and the view factor $F$ of the analyzed surface, with the corresponding thermal resistance given by:

$$R_{\text{th}} = \frac{(T_1 - T_0)}{\sigma \varepsilon F (T_1^4 - T_0^4) A} \quad (7)$$

Expressions (1,4,7) show that an improved heat extraction from the system is achieved either by materials with higher thermal conductivity (1), or by having forced convection with high heat transfer coefficient (4) or using materials with high emissivity and a good view factor (7). Radiation phenomena occur both inside and outside the motor and in parallel with heat transfer through conduction and convection, natural or forced. [19]. It is possible to improve the motor cooling system through radiation by one or more of the following ways:

- Housing emissivity. The motor paint and its fin dimensions can be chosen to improve the motor apparent emissivity [8].
- Reduce the temperature of surroundings bodies. Hot devices, such as other motors working in the neighborhood, can transfer heat by convection, conduction, and radiation.
- Environment system absorptivity. When the motor is located in a small working environment, e.g., in a small box, a high wall absorptivity reduces the reflected radiation heat that strikes the motor.

Significant radiation thermal exchanges are not only present on the external frame but also at several surfaces inside the motor. In particular, the main radiation paths are between the copper wires inside the slot and the stator lamination and between the end winding and the external frame.

The latter can be reduced, for example, by means of a separator:
- Environment system absorptivity. When the motor is located in a small working environment, e.g., in a small box, a high wall absorptivity reduces the reflected radiation heat that strikes the motor.

Significant radiation thermal exchanges are not only present on the external frame but also at several surfaces inside the motor. In particular, the main radiation paths are between the copper wires inside the slot and the stator lamination and between the end winding and the external frame.

### Table V Total emissivity of various materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity</th>
<th>Material</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>0.09</td>
<td>Iron</td>
<td>0.74 – 0.89</td>
</tr>
<tr>
<td>Commercial sheet</td>
<td>0.03 – 0.1</td>
<td>Oxidized</td>
<td>0.74 – 0.89</td>
</tr>
<tr>
<td>Unoxidized</td>
<td>0.05</td>
<td>Unoxidized</td>
<td>0.05</td>
</tr>
<tr>
<td>Heavily oxidized</td>
<td>0.31 – 0.46</td>
<td>Nickel oxidized</td>
<td>0.31 – 0.46</td>
</tr>
<tr>
<td>Alloy A3003, oxidized</td>
<td>0.41</td>
<td>Paints</td>
<td>0.41</td>
</tr>
<tr>
<td>Alumina on Inconel</td>
<td>0.45 – 0.69</td>
<td>Black</td>
<td>0.92</td>
</tr>
<tr>
<td>Asbestos</td>
<td>0.96</td>
<td>White</td>
<td>0.91</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.95</td>
<td>Green</td>
<td>0.95</td>
</tr>
<tr>
<td>Chromium polished</td>
<td>0.06</td>
<td>Steel cold rolled</td>
<td>0.75 – 0.85</td>
</tr>
<tr>
<td>Copper</td>
<td>0.94</td>
<td>Rubber, hard</td>
<td>0.94</td>
</tr>
<tr>
<td>Polished</td>
<td>0.02 – 0.03</td>
<td>Silver, polished</td>
<td>0.02 – 0.03</td>
</tr>
<tr>
<td>Black oxidized</td>
<td>0.19 – 0.21</td>
<td>Inconel polished</td>
<td>0.19 – 0.21</td>
</tr>
<tr>
<td>Brass polished</td>
<td>0.04</td>
<td>Tin unoxidized</td>
<td>0.04</td>
</tr>
</tbody>
</table>

A cooling plate [25] including a plurality of plate members stacked on one another between an electric motor and a coupled body to which the electric motor is coupled, wherein at least one of the plurality of plate members has a penetration groove extending through the plate member in a thickness direction and extending in the plate member in a plane direction orthogonal to the thickness direction, the penetration groove defining a coolant supply channel for supplying a coolant.
V. CONCLUSIONS

A review for various modern cooling systems for electric motors is presented. Complex applications require an understanding of the loss mechanisms and these can be mitigated, while a cooling system gives the measure of how efficient the heat is extracted from the motor. High quality materials, as the insulation resins or cooling fluids are essential in improving the cooling of electrical motors. These have to be combined with various cooling configurations that make use of all heat extraction methods: conduction – pressed wire with high insulation class -, convection – spray cooling, liquid and air cooling or radiation – high emissivity material with increased areas.

VI. REFERENCES