Comparison of Thermal Performance between Direct Coil Cooling and Water Jacket Cooling for Electric Traction Motor based on Lumped Parameter Thermal Network and Experimentation

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Abstract
This paper focuses on analyzing a novel direct coil cooling approach for electric traction motor. Its thermal performance is compared with conventional water jacket cooling concept by using analytical and experimental methods. Results show, the direct coil cooling approach has significant advantage regarding thermal performance, which allows the electric traction motor more suitable for high load applications. This study is performed on an ODIN switched reluctance prototype machine. For a convincing comparison result, the ODIN prototype is equipped with dedicated cooling circuits for each cooling approach. Based on the design parameters of the prototype, a lumped parameter thermal network (LPTN) model is established for analytical studies. For an accurate representation of heat transfer in the direct coil cooled motor through fluid flow, the key convective boundary is modeled based on the results of computational fluid dynamics (CFD). Studies with the developed LPTN model and experiments for validation are conducted. The results of the model analysis and the experiments both indicate that, through cooling coils directly in the stator slots with oil flows, direct coil cooled motor can effectively dissipate heat in the thermal critical winding areas. Current density in the ODIN prototype can be significantly increased. Thermal resistance from hotspots to coolant can be reduced by up to 80%. Direct coil cooling can increase the continuous torque output of ODIN machine to approx. 300%.

Keywords: direct coil cooling, CFD, LPTN, electric machine, oil cooling

Nomenclature
\begin{itemize}
  \item $\mu_b$: Dynamic viscosity of fluid bulk
  \item $\mu_w$: Dynamic viscosity near wall
  \item $A$: Surface area of heat transfer
  \item $C$: Matrix of thermal capacity
  \item $D$: Hydraulic diameter
  \item $G$: Matrix of thermal conductance
  \item $h$: Heat transfer coefficient
  \item $k$: Thermal conductivity
  \item $L$: Characteristic length
  \item $Nu$: Nusselt number
  \item $P$: Vector of thermal energy
  \item $Pe$: Peclet number
\end{itemize}
In the recent years, electric machine gains more and more importance as traction machine in the automotive applications. Compare to combustion engine, electric machine is advantageous regarding torque output, efficiency, emission-free operation, etc. And it also provides possibility to recuperate kinetic and potential energy from the vehicle and in further reduces energy expense. Other than in the industrial applications, power density has a high relevance for traction machine, because space and weight are always limited in the vehicles. Therefore, during the development of traction machine, additional attentions to the thermal aspects are required. In all, it is the component temperature which determines the rated power of the machine. The winding area is one of the most sensitive positions, overheating can result in insulation breakdown and fatal damage. Besides, for permanent magnet synchronous machine (PMSM), the permanent magnets can also suffer from overheating [1].

There are in general following ways to improve machine thermal performance: reduce losses in the machine, improve heat dissipation, reduce coolant inlet temperature and raise component temperature limit. Previous study proposed a direct coil cooling approach, in which the improvement of heat dissipation is in the focus [2]. Figure 1 presents this cooling concept. The machine is cooled mainly in the stator slots by transmission oil flow.

![Figure 1. Concept of direct coil cooling](image)

The advantage of using oil for cooling is due to its dielectric characteristics. The oil can be directly applied to the electric winding areas where significant internal heat is generated. This configuration prevents extra thermal resistance that is built up by transmitting thermal energy from winding area to coolant through interjacent components, i.e. stator stack. However, oil is a medium with low thermal conductivity and capacity. Thus, fluid guiding structure, called baffle, is designed in the direct coil cooling concept to compensate the disadvantage.

To utilize the thermal design improvements and convert them into load capability of the electric traction machines, the knowledge of temperature distribution in the machine components during operation can be crucial. To analyze the thermal behavior of direct coil cooled machine, this paper employs the lumped parameter thermal network (LPTN) approach [3] and combines it with modified Nusselt number correlation based on CFD results. Finally the thermal performance between direct coil cooling and standard water jacket cooling is compared through experiment and simulation.

## 2 Modeling of Direct Coil Cooled Electric Machine

In the LPTN approach for modeling electric machine, the cooling medium, such as air and water, is considered as a boundary condition. Thus, the convective heat transfer is usually referred as film coefficient and is calculated based on the standard analytical correlations [4]. However, the correlations are established on studies of simplified channel geometries. Directly applying standard correlation on the application specified cooling channels could cause error in machine temperature estimation. For water jacket cooled machine the error is marginal. The heat transfer coefficient between water flow and surface is considerably higher compare to the thermal resistances in the machine structure. By direct coil cooled machine, the errors could be significant. Since, this cooling concept aims at bypassing thermal resistances in the machine structure. In addition, the heat transfer between oil flow and surface is much lower than that of water. Table 1 presents the influence of convective flow boundary on machine temperature.

To correctly represent the machine model with fluid boundary, the author proposes to combine LPTN with computational fluid dynamic (CFD) analysis.
Table 1. Influence of convection flow boundary

<table>
<thead>
<tr>
<th>Heat transfer coefficient offset [W/m²K]</th>
<th>Hotspot temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct coil cooled</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>T_{ref}+18</td>
</tr>
<tr>
<td>1300</td>
<td>T_{ref}</td>
</tr>
<tr>
<td>1700</td>
<td>T_{ref}-10</td>
</tr>
<tr>
<td>Water jacket cooled</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>T_{ref,w}</td>
</tr>
<tr>
<td>12000</td>
<td>T_{ref,w}-6</td>
</tr>
</tbody>
</table>

2.1 Modeling Approach

By developing thermal model for direct coil cooled machine, lumped parameter approach is used as a basis. Within this approach the machine can be discretized into connected physical lumps, and represented by thermal nodes in the network model. The nodes include thermal capacity of the associated lumps, and are connected with each other through the thermal resistance between. By lumps which can generate internal heat energy, e.g. winding or stator, the thermal nodes are also connected with a heat source. The parameters of the LPTN can be entirely derived from machine design parameters and thermal properties of the materials that are used in the machine. Compare to FEA, analysis with LPTN is less accurate, but regarding computational time and adaption to system model the advantage is evident. This thermal network model principle can be also represented in a mathematical way through differential equation:

\[
C \frac{dT}{dt} = P - GT
\]

The cooling fluid takes away heat in the electric machine, and is considered in the model as a boundary condition for solving the equation system. The temperature of the cooling fluid is set as constant, and its thermal resistance to the machine can be described with the following equation:

\[
R = \frac{1}{hA}
\]

In the conventional LPTN model this thermal resistance between fluid and wall is either estimated empirically [5] or calculated based on Nusselt correlation for idealized flow patterns [6] [7]. Limited correlations are specified for electric machines. In the Nusselt correlations, the Reynolds number, Prandlt number etc. can be used for calculating Nusselt number. The Nusselt number is a dimensionless quantity, which presents the ratio of convective to conductive heat transfer across the fluid-solid boundary. By solving the following equation with Nusselt number, the thermal resistance to the flow boundary in the thermal network model can be solved.

\[
Nu = \frac{hL}{k}
\]

However, due to the complexity of thermal flow the Nusselt correlations are experimentally determined. By different flow channel geometries or even different flow speeds, the equation can be entirely different.

In this paper by calculating the oil flow in the slot channel with CFD, a modified Nusselt correlation specifically for the studied channel is generated. In this way, the temperature calculation for direct coil cooled machine can be more precise. This modeling procedure is described in Figure 2.

![Figure 2. Modeling procedure of thermal analysis of direct coil cooled machine](image)

2.2 Modeling of machine with LPTN

A direct coil cooled switched reluctance machine is proposed for the investigation. The machine has an 18/12 tooth combination and can deliver up to 70 kW power. The maximal speed is larger than 18,000 rpm. For modeling, the thermal behavior of the machine in the circumferential direction is assumed to be periodically symmetric. Thus in the cross section plane 1/36 of the stator, shown in Figure 3(a), and 1/24 of the rotor is considered in the thermal model. The stator and rotor are both divided into yoke and tooth. Due to the large thermal resistance of winding insulation, the coils are discretized into 6 segments. The oil flow has contact with winding segments and stator yoke. In the axial direction, the temperature rise of oil flow
along the machine is regarded, because the oil have relatively low thermal capacity compare to water. End-windings are modeled on both front ends of the motor. These end windings are completely submerged in oil, and modeled according to the thermal behavior described in Figure 3(b). With this configuration the temperature gradient caused by oil flow, see Figure 1, can be included.

2.3 CFD study of cooling channel

In the direct coil cooled machine, the slot channels are formed by electric windings, and can have large aspect ratio in the cross section. The fluid guiding structure further increases heat transfer along the cooling channel periodically. These effects cannot be precisely represented by using classical Nusselt number correlations.

A variety of Nusselt correlations can be used for solving heat transfer issues in laminar flow regime [7], most of the correlations can be written in the following form:

\[ \text{Nu} = f(Re, Pr, ...) \]

The oil flow in the machine slot is in the laminar flow regime and has thermal entrancing effect. A correlation considering the thermal entrancing effect was provided by Sieder & Tate [8].

\[ \text{Nu} = 1.86(RePr)^{1/3} \left( \frac{D}{L} \right)^{1/3} \left( \frac{\mu_w}{\mu_b} \right)^{0.14} \]

This equation is valid for flow in short channels, where the thermal entrancing effect is dominant. In the equation the basic influence factors, e.g. Reynolds number and Prandtl number on heat transfer are taken into account. The term D/L implies that the shorter the channel is, the larger the thermal entrancing effect can be. The effect of the term \( \mu_w/\mu_b \) is limited due to the power, however, it represent the influence of temperature gradient in the fluid flow. The fluid near a heated wall has higher temperature and hence lower viscosity.

In the laminar channel flow with fluid guiding structure, the flow in the channel is reflected by the guiding structure and forming a 3-dimentional velocity field, which is presented in Figure 4(a). This effect prevents the thermal development along the channel and enhances heat transfer to wall periodically. Figure 4(b) present the wall temperature of a slot cooling channel with guiding structure.

\[ \text{Nu} = a(RePr)^b \left( \frac{\mu_w}{\mu_b} \right)^c \]

Since the discussed slot channel has a constant D/L ratio, the D/L term is then taken out of the equation.

In CFD analysis the flow rate \( v \) and inlet temperature \( T_{in} \) are considered as input variables. The Nusselt number \( Nu \), and all other variables e.g. \( Re, Pr, \) viscosities \( \mu_w \) and \( \mu_b \) can all be calculated. In the end, through regression analysis the parameters \( a, b, c \) in the equation can be evaluated.
After these parameters are solved, the new correlation can represent the heat transfer of stator slot channels and then be transferred into LPTN model for machine thermal study. The solver for the analysis is chosen based on Reynolds-averaged Navier-Stokes (RANS) governing equations. With the RANS equations the Reynolds stress term in Navier-Stokes equations is averaged, which resulted in a flow and heat transfer with suppressed fluctuation. Commercial CFD software ANSYS FLUENT® is utilized for the calculation. The analysis setup is shown in Table 2. The fluid for the study is a special developed type of transmission oil.

Table 2. Setup of the CFD analysis

<table>
<thead>
<tr>
<th>Fluid</th>
<th>TYPE-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Temperature</td>
<td>-30 – 100 °C</td>
</tr>
<tr>
<td>Inlet Flow Speed</td>
<td>0.001 – 0.3 m/s</td>
</tr>
<tr>
<td>Heat Flux on Wall</td>
<td>51 kW/m²</td>
</tr>
</tbody>
</table>

Figure 5 plots the CFD calculated correlation between the \( Nu \) and \( Re, Pr, \mu_w/\mu_b \). The \( Re \) and \( Pr \) is combined and presented by the non dimensional Peclet number \( (Pe) \). The Peclet number have the major influence on Nusselt number, and the \( \mu_w/\mu_b \) ratio further illustrate the temperature influence on the viscosity gradient. The viscosity of oil rises exponentially as the temperature decreases. At low inlet temperature the heat transfer reduces while the viscosity ratio between wall and bulk rises.

![Figure 5](image_url)  
Figure 5. Result of CFD analysis

A comparison to standard Sieder-Tate correlation is plotted in Figure 6. The derived correlation agrees well with the CFD simulation for channel with fluid guiding structure. The standard Sieder-Tate correlation is calculated for a channel with the same hydraulic diameter and length. The wall temperature is overestimated, which implies the thermal effect of fluid guiding structure cannot be captured by this standard correlation.

![Figure 6](image_url)  
Figure 6. Comparison of wall temperature between classical Sieder-Tate and developed correlation

3 Experimental setup

The prototype machine is equipped with both direct coil cooling structure and conventional water cooling jacket, shown in Figure 7, which can be activated separately. With this configuration, the influence from machine manufacturing can be excluded during the experimental comparison.

![Figure 7](image_url)  
Figure 7. Cut view of prototype machine with both water jacket and direct coil cooling

The comparison is conducted on a test bench, shown in Figure 8, under room temperature with 6 l/min flow rate. The machine is connected both with a water temperature control unit and an oil temperature control unit. 29 type-K thermal couples are mounted in the stator stack, slot winding area, end-winding, rotor etc. In the slot winding area, thermal couples are mounted on the middle section of the coils. Since the slot winding area can have large temperature gradient, thermal couples are mounted on 3 different coils to compensate possible error due to sensor positioning. To present temperature gradient along
the axial direction of the machine, thermal couples are mounted on both ends of the coil.

Figure 8. Prototype machine on test bench

4 Comparison with water cooled machine

To exactly compare the cooling performance without influenced by high frequency uncertainties, e.g. eddy current due to skin effect and proximity, the prototype machine is applied with direct current.

At the beginning of the experiment, one cooling circuit is chosen to be activated. And a constant voltage of 2 V is applied to all of the three phases of the machine to generate power losses. By applying losses to the coils, the temperature in the machine structure will rise to an equilibrium level, at which the temperature in the machine no longer changes. As soon as no significant temperature changes can be observed in the machine, the power supply is then shut down and another voltage of 2.4 V is applied to the coils. With this test configuration the temperature behavior in the machine can be compared. Also in the coils, the variation of electric resistance regarding temperature change can be documented.

Figure 9 plots the temperature behavior of the machine with activated water jacket cooling. In the LPTN model, the boundary to oil is removed in this case and the heat transfer of water jacket is added to the model. The dashed lines are values from experiments, and solid lines are values from model simulation. The maximal temperature in coil swings into 120 °C, when the coils are applied with 2 V, and approx. 150 °C, when 2.4 V is applied. The average stator temperature stays low during the operation. Avg. stator temperature remains under 45 °C.

Figure 9. Temperature behavior in water jacket cooled machine

Figure 10 present the temperature behavior of the machine with activated direct coil cooling. The modeling approach with CFD, which is described in section 2, is deployed. The result from LPTN model agrees well with the values from experiment. The model slightly overestimates the temperatures in the machine for approx. 3 K, which is acceptable. The end-winding on the fluid inlet side have lower temperature than the end-winding on the fluid outlet side, approx. 10 K. In the machine with direct coil cooling, the temperature gradient is significantly lower. The maximal coil temperature is reduced by 90 K compare to water jacket cooling.

Figure 10. Temperature behavior in direct coil cooled machine

This thermal difference also influences the electric resistance of the machine. Making the direct coil cooled machine more energy efficient. The phase current in the experiments are presented in Figure 11. The coil resistance is reduced by 18.5 % when the direct coil cooling is activated.
In the test the thermal resistance from machine hotspot to fluid is reduced by 74% when the machine is cooled with direct coil cooling, although the applied losses are 20% higher. When comparing at the same losses level, the direct coil cooling shows a reduction of more than 80%.

Table 3 compares the effectiveness of cooling as the machine is operating. When the coil cooling is activated, the rated torque output can be raised to the peak torque level. At the same time, water jacket cooling provides much lower output.

Table 3. Rated torque output of the prototype machine

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>3000</td>
<td>110</td>
<td>29</td>
</tr>
<tr>
<td>6000</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

5 Conclusions

In this paper, an advanced LPTN modeling approach with CFD analysis is presented. Particular focus is put onto the thermal boundary to coolant flow. This is especially important for estimating the thermal behavior of the direct coil cooled machine. The proposed correlation with CFD analysis is compared with standard Sieder-Tate correlation. The developed LPTN model is then used in the comparison with water jacket cooling. To exclude the influences from high frequency, direct current experiment is conducted on the prototype machine. The simulation results agree well with the experiments. Direct coil cooling reduces hotspot thermal resistance by 80%. The continuous torque output can be raised to 300%. Also, the thermal influence on the electric resistance is compared and discussed.

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References


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