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DOCUMENTATION OF CALCULATION OF THERMAL INSULATION RESISTANCE IN THE SLOT OF ELECTRIC MACHINES

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1 Objective

DuPont (Circuit & Imaging Technologies Division) would like to compare different insulation systems, especially with regard to their ability to drain heat from electric machines. The aim is to drain away the heat from the coil via the stator slot insulation to the cooled Laminate. For this objective, DuPont would like to compare the heat-draining performance of DuPont's insulations foils on uninsulated wire with the performance of different types of enamelled wires.

2 Lumped parameter model and boundary conditions

The lumped parameter model (also called lumped element model, or lumped component model) simplifies the description of the behavior of spatially distributed physical systems into a topology consisting of discrete entities that approximate the behavior of the distributed system under certain assumptions. For thermal modelling the lumped parameter model transfers the thermal behavior of a system to an electrical network consisting of resistances, sources and sinks for stationary calculations. By also using capacities it is possible to analyze the transient behavior. The lumped parameter model reduces a thermal system to a number of discrete "lumps" and assumes that the temperature difference inside each lump is negligible. With the help of the calculated thermal resistances of every subcomponent like insulation, tooth, wire etc. as well as fluid (air) the lumped parameter model returns the temperature within the subcomponent as a result.

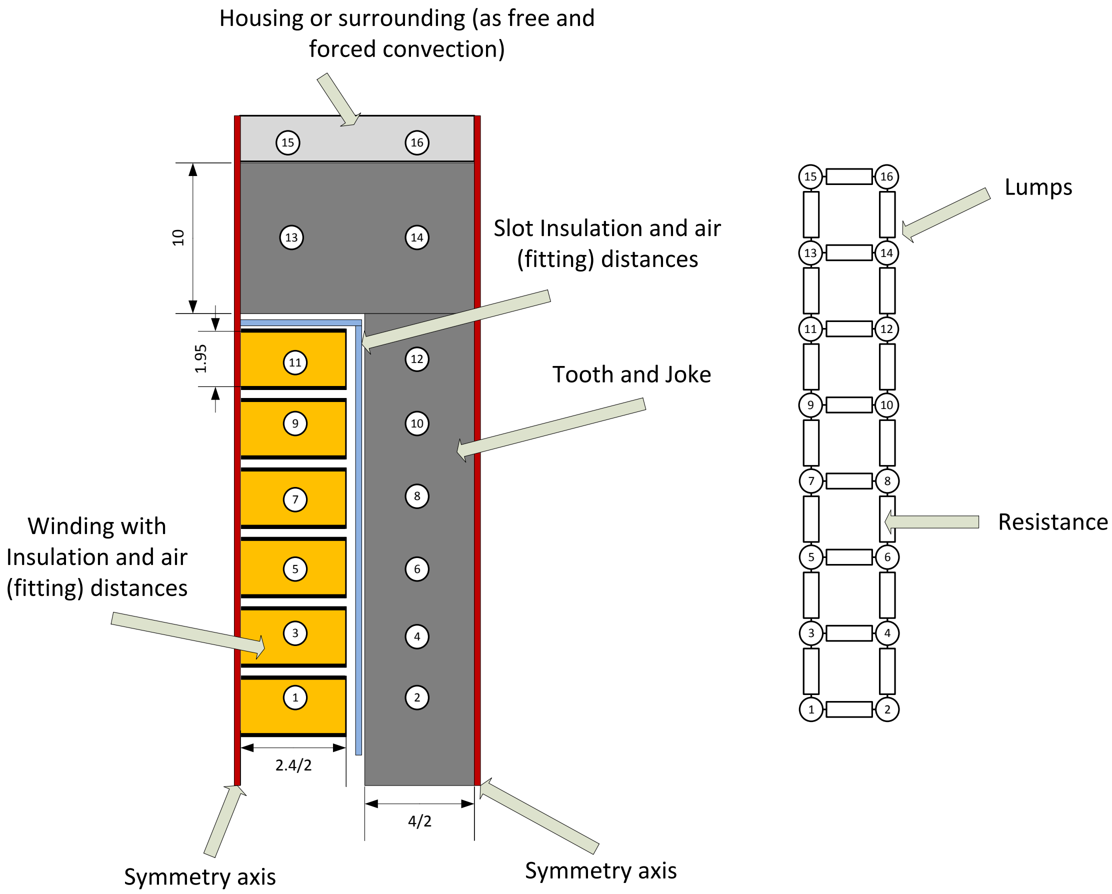

Figure 1: Lumped parameter model of a slot-tooth-symmetry unit of an electrical machine

For this approach Figure 1 shows a schematically lumped parameter model of a slot of an electrical machine. The following boundary conditions are applied:

1. Calculations are stationary (without capacities) in 2D at room temperature (20 °C)
2. The heat sink is the housing with
    a. α=5 W/m²K, which represents free convection (naturally ventilated)
    b. α=1000 W/m²K, which represents forced convection (e.g. liquid cooling)
3. Due to symmetry of an electrical machine the width of wire and slot are cut in half
4. Each layer to its adjacent layer has an assembly gap of a) 0 µm and b) 25 µm

5. Each layer to its adjacent tooth flank has an assembly gap of a) 0 µm and b) 50 µm
6. Each turn get the same DC-loss, that are not temperature dependent
7. The DC-losses are modified to receive a temperature level of a) 100 °C and b) 200 °C by using an assembly gap
8. The calculations with and without assembly gap based on equal power losses within the same temperature class to see the influence of an assembly gap
9. Calculations without assembly gap represent ideal case while the 50 µm assembly gap would be worst case airgap (no resin). Reality will be in between these extremes, gap filled with resin leaving minor gap. Thermal conductivity of resin and fill quality will impact on result, though is left out of this study.

The following Table 1 and Table 2 list the received data from DuPont for the calculations of the wire and slot insulation.

Table 1: Received Data from DuPont for the insulation of the wires

Typ	Type of insulation	Material	Thickness of insulation (µm)	Thermal conductivity (W/mK)
Wire1	Enamelled wire	PAI-PI coating Grade 2	70-80	0.2
Wire2	Winding wire	Film A (Kapton® FWN), foil thickness 33 µm, 1 foil with 50 % overlap	66	0.19
Wire3	Winding wire	Film B (Kapton® MT+ with Fluoropolymer), foil thickness 33 µm, 1 foil with 50 % overlap.	66	0.43

Table 2: Received Data from DuPont for the insulation of the slot

Typ	Type of insulation	Material	Thickness of insulation (mm)	Thermal conductivity (W/mK)
SlotA	Nomex® Paper	Nomex® 410	0.18	0.12
SlotB	NKN Laminate	Laminate A, (2-2-2, Kapton® HN Film)	0.17	0.14
SlotC	NKN Laminate	Laminate B, (1.5-5-1.5, Kapton® MT+ Film)	0.22	0.35

There are nine possible material combinations referring to Table 1 and Table 2. They can be grouped into pairings of a specific wire with the three kinds of slot insulations. Table 3 summarizes the different combinations.

Table 3: Wire and slot insulation combinations

	SlotA	SlotB	SlotC
Wire1	X	X	X
Wire2	X	X	X
Wire3	X	X	X

The next figures show the resulting stationary temperature of each turn layer.

3 Results of the lumped parameter model

Free convection

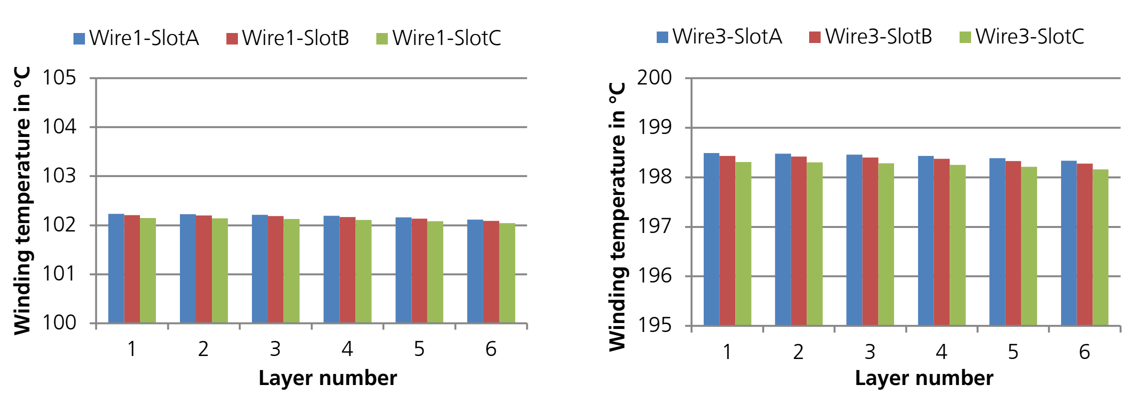

Figure 2: Winding temperatures at free convection at different end temperatures without assembly gap

Figure 2 represents the thermal distribution of each coil winding for all material combinations without assembly gap at 200 °C without forced convection. It is obvious that the effect of better thermal conductivity of the insulation materials has only a small influence on the heat flow. Within the thermal network the thermal resistance of the housing to the surrounding is very high due to the low thermal conductivity because of the poor heat transfer coefficient (alpha). The housing is not able to dissipate the heat resulting in a heat accumulation inside of the system. Therefore, it is anticipated that electrical machines with these kinds of insulations need a forced convection to achieve better heat transfer.

Forced convection

Figure 3 and Figure 4 list the thermal distribution of each coil for all material combinations as well as with (right) or without (left) assembly gap at different thermal classes. In contrast to Figure 2 it is obvious that the effect of better thermal conductivity of the insulation materials has quite more influence on the heat flow. Due to the different distances of the heat source (every turn layer) to the heat sink (surrounding, cf. Figure 2) there is a temperature gradient within the coil. Beginning with the highest coil temperature in layer number 1 which is located in the temperature model at the end of the tooth, the temperature drops in the direction of the layer number 6 at the slot bottom. It is evident that the end temperature of each layer decreases by using the slot insulation "SlotB and SlotC" in comparison to the rather conventional insulation material "SlotA". Additionally the choice of the new wire insulation method "Wire2 and Wire3" leads to reduced end temperatures – especially "Wire3" because of the better thermal conductivity of these materials. These figures show furthermore that an assembly gap (right column) impairs the heat transfer. So, an assembly gap should be avoided. By infiltrating the assembly gap with compound this decrease can be reduced.

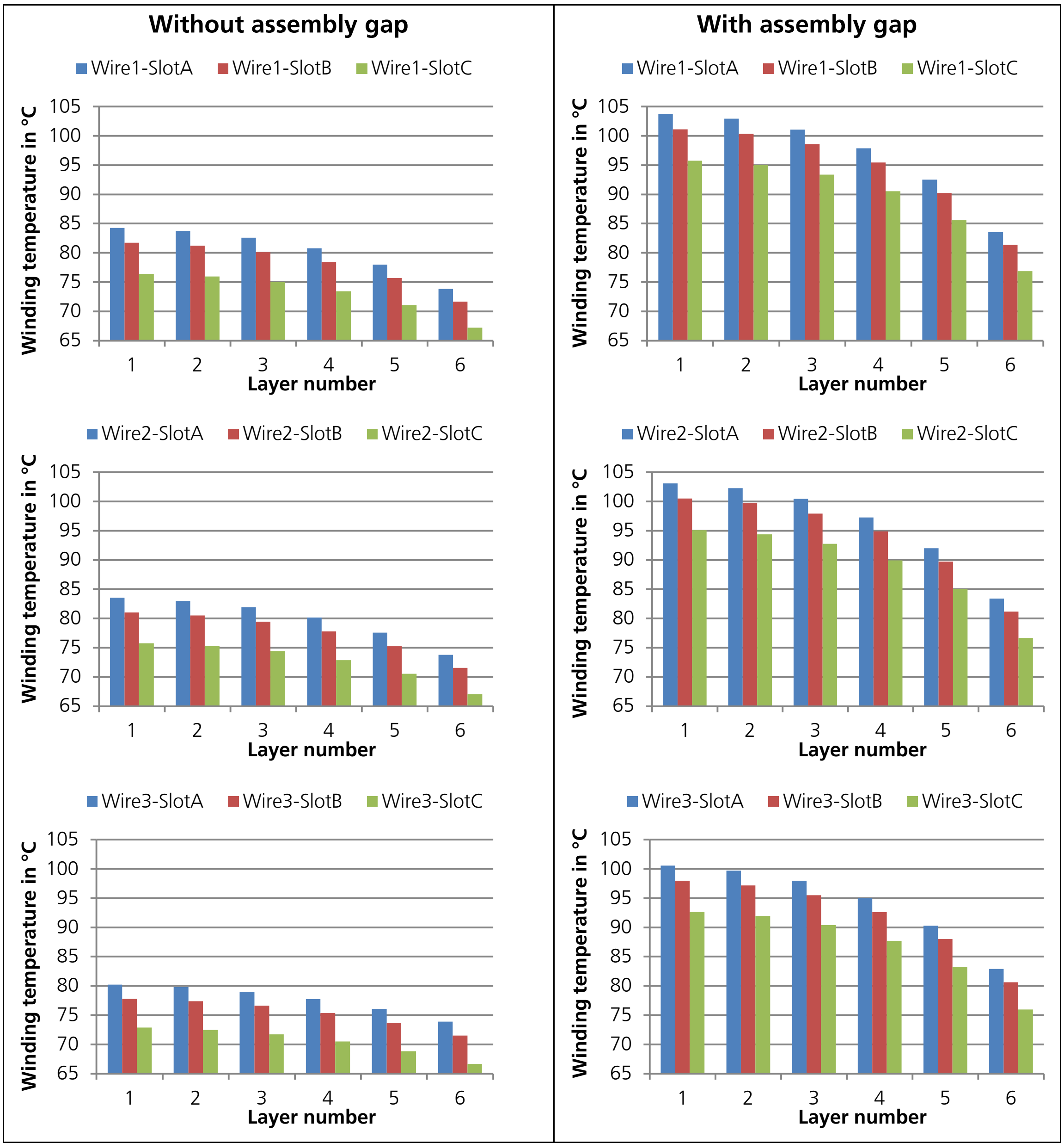

Figure 3: Winding temperatures at forced convection at 105 °C

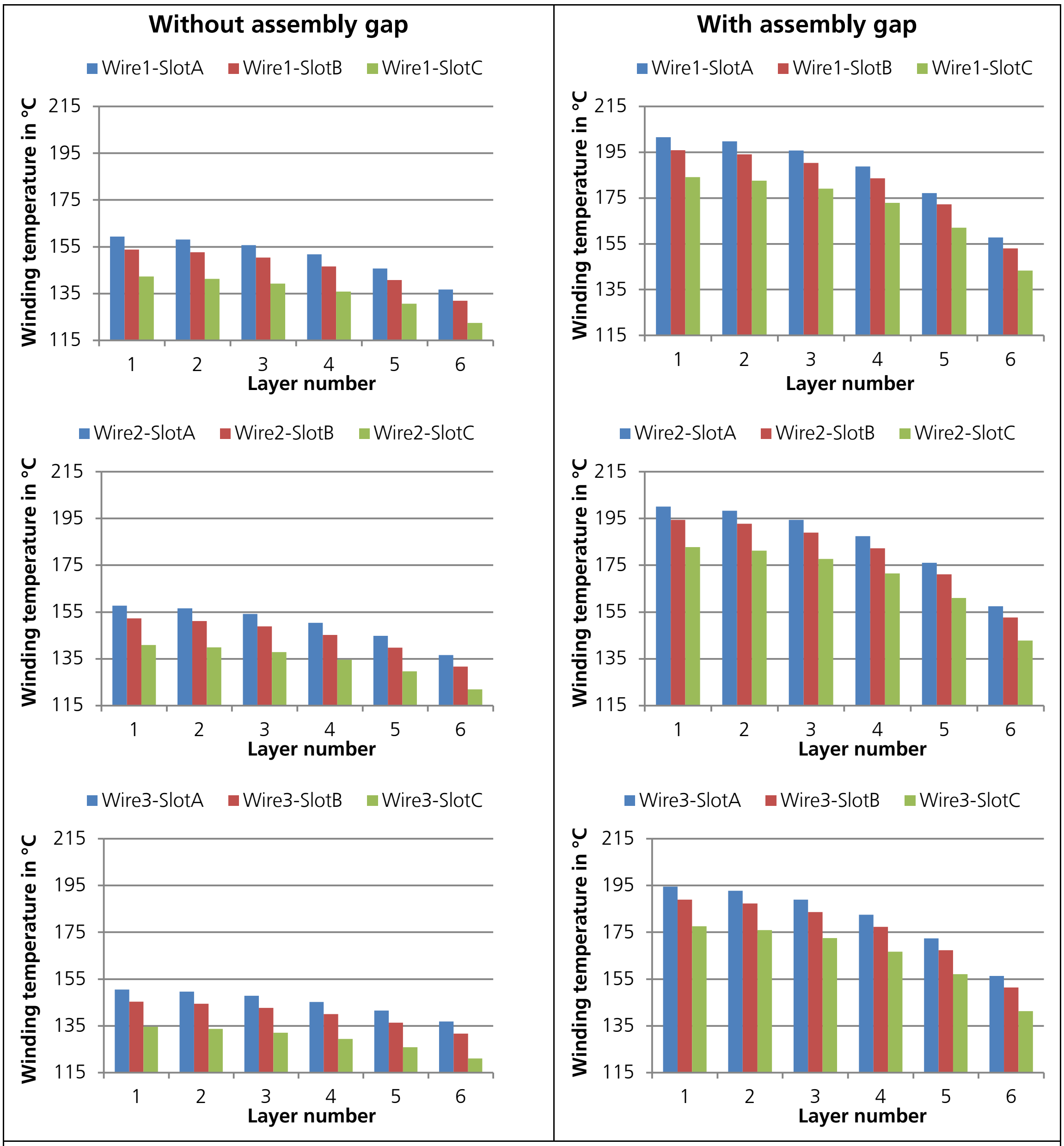

Figure 4: Winding temperatures at forced convection at 200 °C

For a better overview Figure 5 shows the average coil temperature for every combination of the wire-slot-insulation with and without assembly gap grouped by different end temperature conditions. It is obvious that the combinations with “SlotC” insulation material offer the best heat transfer resulting in the lowest end temperature even with realistic assembly gap. This behavior results from the very good thermal conductivity of the slot insulation.

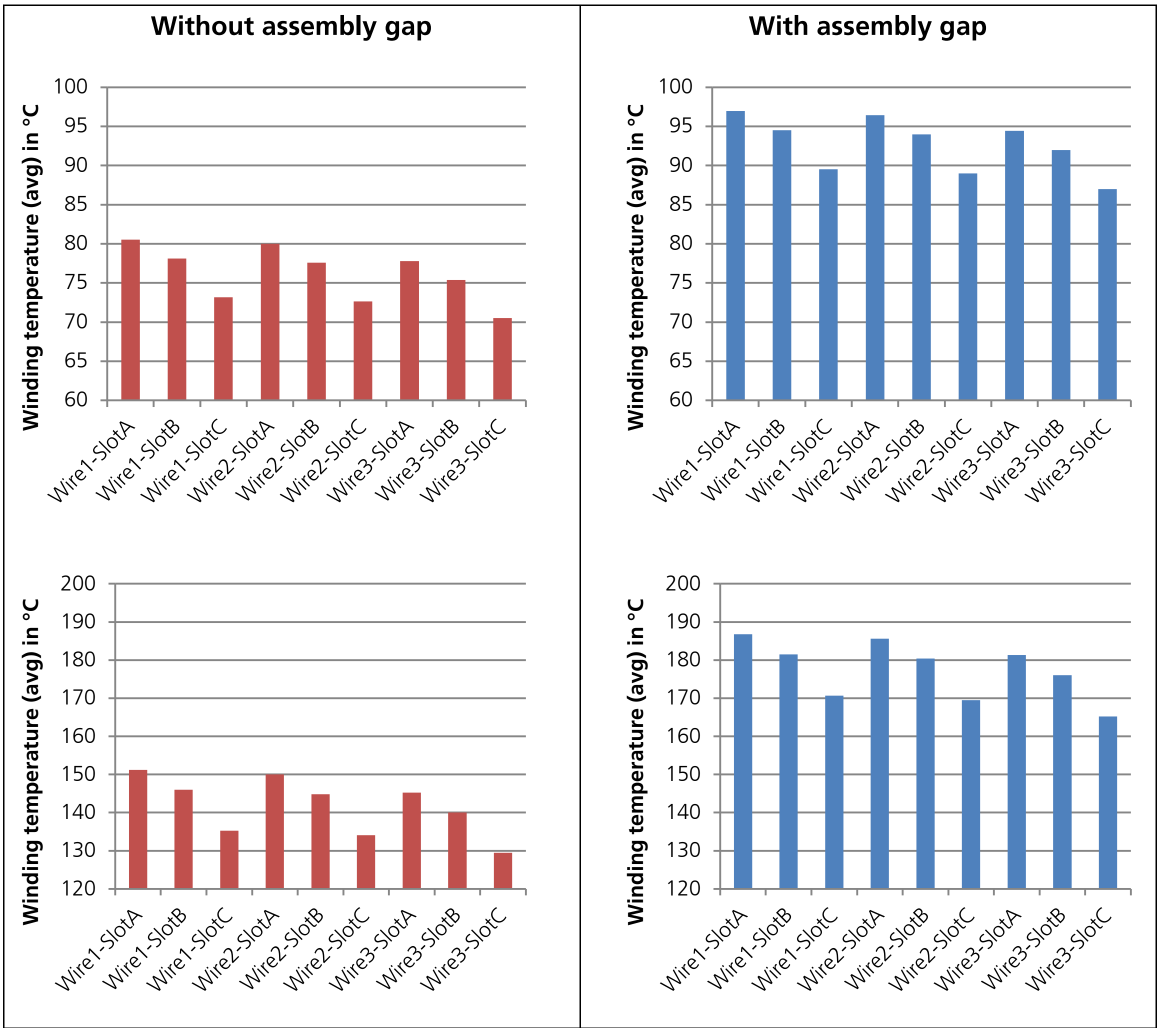

Figure 5: Coil temperatures (avg) at forced convection at different end temperature conditions

To describe the influence of an assembly gap Figure 6 shows the temperature difference inside the coil with and without assembly gap for every combination of the wire-slot-insulation at different end temperature conditions. As might be expected, the assembly gap decreases the heat transfer due to the very low thermal conductivity of the air that is about 10 times smaller than the slot insulation material. The resulting temperature differences are higher than without assembly gap. If there is no assembly gap, a more effective heat transfer is monitored especially due to the very high thermal conductivity of the insulation paper "SlotC".

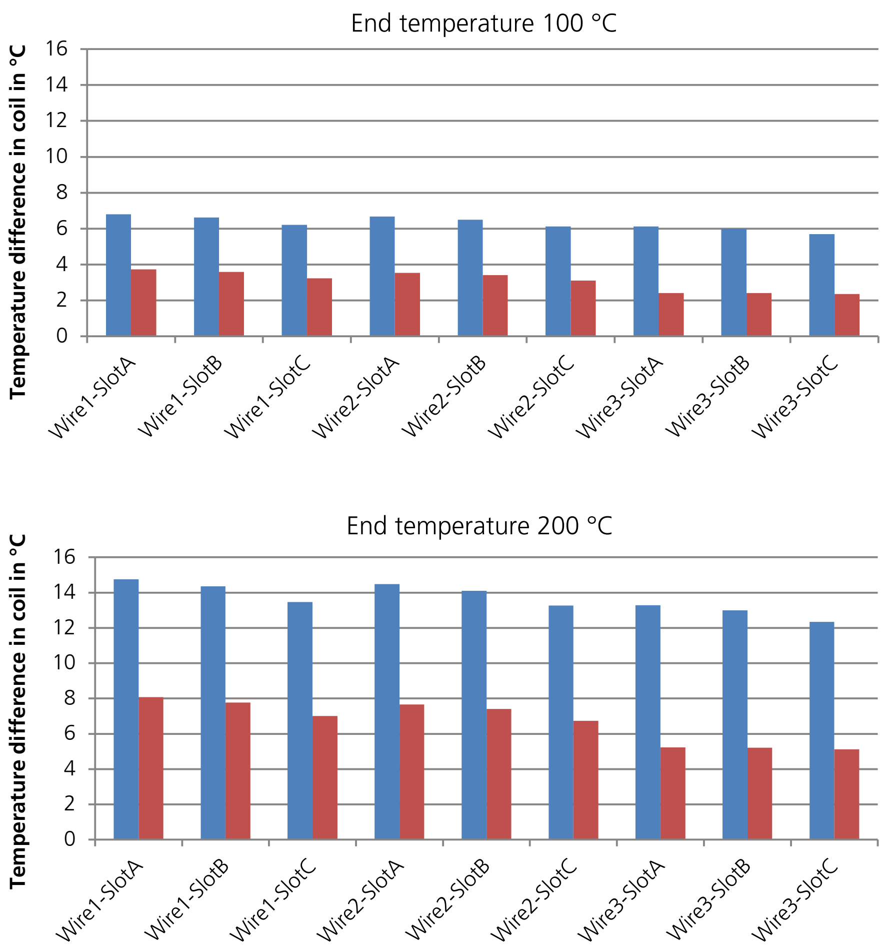

Figure 6: Temperature delta inside of the coil at forced convection at different end temperature conditions with assembly gap (blue) and without assembly gap (red)

Conclusion

In principle, a forced convection in electrical machines – like a water jacket cooling – leads to higher heat transfer even with conventional wire and slot insulation. Nevertheless the new wire insulation method (Wire2 and Wire3) in combination with the slot insulation (SlotB and SlotC) allows further significant improvements. Calculations indicate that by using slot insulation material SlotC, the temperature in the slots could be reduced by up to 15 K at 200 °C. This difference could be further increased to about 20 K when also optimizing the wire insulation as well as encapsulating the coils. New opportunities can be discovered to get superior utilization of an electrical machine because of the increased heat transfer. As a next step, the potential should be investigated by test specimen of realistic coil-Laminate stack models under realistic conditions.