

STAR-CCM+ and *SPEED* for electric machine cooling analysis

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Abstract: This paper shows how two well established software programs can be used to determine the electrical machine performance and the temperature rise within the machine parts using a permanent magnet interior rotor synchronous machine as an example. Both software packages, STAR-CCM+ providing an engineering process code for solving problems involving fluid flow, conjugate heat transfer and solid stress and *SPEED* the specialized analysis tool for the design of electric machines such as motors, generators and alternators including the drive with inverters and their control, are developed by CD-adapco. In the latest versions of the 2 packages a link was established to exchange the data needed from *SPEED* to STAR-CCM+. The process is presented in more detail in this paper.

Introduction

Regulatory efficiency requirements for electric machines and tremendous price rise in material costs of permanent magnets are two important motivators for analyzing the thermal performance of electric machines in greater detail. *SPEED* offers thermal circuit simulations to look at component temperatures during drive cycle load conditions or steady state conditions. This is a first approximate but fast thermal simulation approach. For a detailed more accurate thermal simulation a complete 3D-CAD model needs to be built and multiphase flow calculations are performed. A process where CD-adapco can now offer a more streamlined simulation approach by combining *SPEED* and STAR-CCM+.

As one of the first steps to facilitate data transfer between the two codes, CD-adapco has built import capabilities for STAR-CCM+ to read the *SPEED* geometry descriptions as well as the loss density distributions to use as heat sources in the flow, thermal and stress simulation in STAR-CCM+. This presentation will display the process of joint simulation work in *SPEED* and STAR-CCM+ using an example machine to show the benefit of such simulations. An important next step is the generation of end windings to a given specification, a feature that is currently under development in *SPEED* and STAR-CCM+. This set of capabilities is extended further to facilitate also electromagnetic analysis within STAR-CCM+ and finally lead to highly and advantageous use of the GoFER (go to finite element and return the results) and GoTAR (go to thermal analysis and return the results) capabilities included already in the *SPEED* software.

Used Simulation Methodology

Predominant thermal impact typically stems from the current running through the copper winding causing the joule or I^2R -losses at lower speeds. At higher speed the iron losses may become the significant part of the losses. With choosing a single tooth wound stator armature for our example machine the copper losses in the end turns can be reduced compared to a classical lap or concentric winding. Obviously the CAD description of the windings can be obtained more easily as well. As explained above we have chosen for our example two different load points to show the influence of the different loss sources: The first one with dominating joule losses in the winding and the second one with increased iron losses in the lamination of the stator and rotor at higher speed.

The general steps of the electrical machine design procedure are the following (see Fig. 1):

- 1) Initial analytical design of the electrical machine using *SPEED* (in this particular case PC-BDC for a interior permanent magnet synchronous machines).
- 2) Refinement with PC-FEA using the i - Ψ -GoFER.
- 3) Calculating the performance data on estimated temperatures using PC-FEA to calculate the loss distribution (“*Element table*”) for STAR-CCM+.

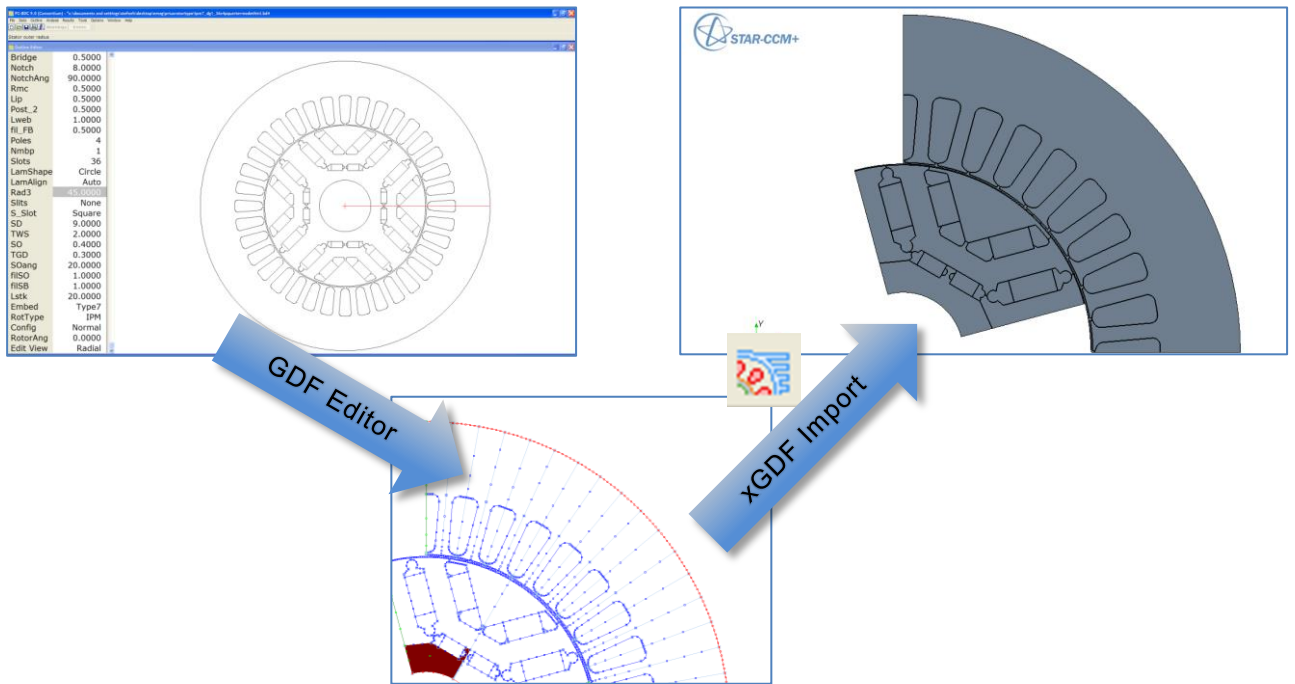


Fig. 1: Process flow: From *SPEED* to STAR-CCM+

- 4) Reading the *SPEED* geometry (xGDF, xDEF) and the loss distribution (*.sbd) file from STAR-CCM+, setting up the CFD 3D model and running the final advanced thermal calculation.

Analytical/numerical design of an IPM SM using *SPEED* PC-BDC and PC-FEA

The cross section of the electrical machine example is shown in the outline editor of PC-BDC, the *SPEED* program for the design of permanent magnet and electric excited synchronous machines, see figure 2a. It shows an IPM (interior permanent magnet) machine with 12 slots and 10 poles. The outer stator diameter is 200.0 mm and the stack length is 50.0 mm. The permanent magnet material is NdFeB with a remanence flux density of 1.26 T allowing higher temperatures for the rotor without the risk of demagnetizing the magnets. The magnet blocks are assumed to be subdivided (in axial and circumferential direction) such as to minimize the magnet losses due to eddy currents induces to a negligible value. The winding is a 3-phase single tooth (fractional slot) double layer winding, see figure 2b. We will focus on two operating points at 1000.0 rpm and 6000.0 rpm with a constant shaft power of 6.0 kW. The DC link voltage is 400.0 V. This machine runs with sinusoidal current supply through a PWM inverter. The machine is cooled by means of a water cooling jacket, see figure 5.

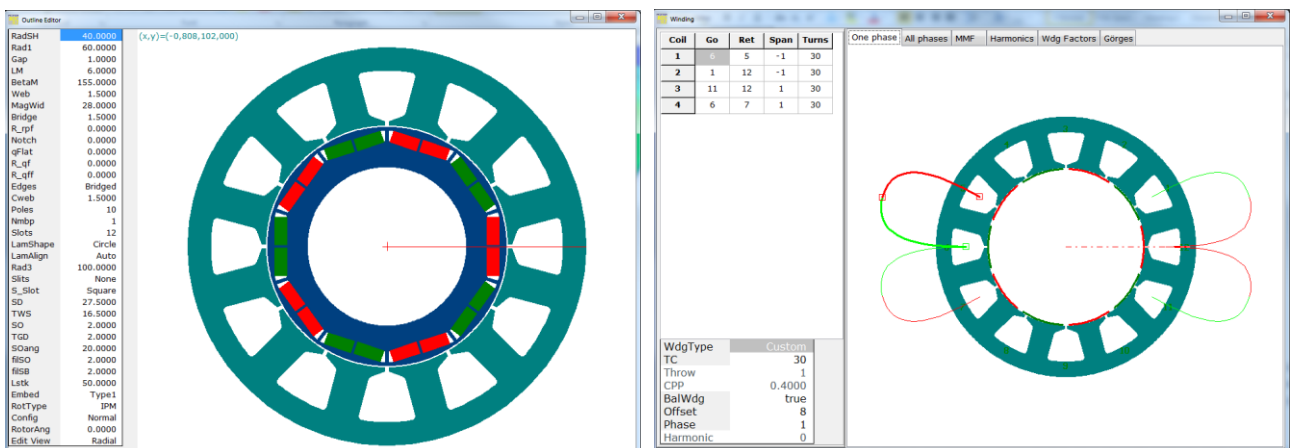


Fig. 2: a) Cross section editor and b) winding editor of the studied synchronous IPM motor in PC-BDC

Nevertheless our goal is *not* to show an optimized machine, but the process on how to go from a design of an electrical machine using the *SPEED* software for an initial electromagnetic machine design to an advanced CFD thermal analysis using STAR-CCM+.

Due to the IPM structure it is necessary to run FE calculation after first initial analytical calculations to take care about the high saturation levels in the bridges surrounding the interior magnets, which is the most difficult task for an analytical approach. PC-FEA which is available as the FE product of the *SPEED* electrical machine software suite is unique in that it is tightly integrated with all the motor programs, by means of:

- 1) The GoFER (**Go** to **F**inite **E**lement and **R**eturn the results):
Different dedicated procedures running PC-FEA as a separate program with pre- and post-processing options, but with predefined scripts and automated data transfer through files, written from PC-FEA, readable from the different *SPEED* motor programs. The FE results will be used to adjust the magnetic circuit X-factors from the analytical calculations.
- 2) The Embedded solver:
The finite element solver is directly activated in PC-BDC (or the other motor programs) and the main X-factors for the magnetic circuit are adjusted automatically (no pre- and post-processing options) – best to use for automation and optimization processes or algorithms.

PC-FEA is designed to be extremely fast in operation.

For the design of our example machine we have used the *i- Ψ -GoFER* [1]. Its name comes from the symbols *i* for current and Ψ for flux-linkage. The *i- Ψ -GoFER* is valuable for calculations with highly saturated PM motors, especially those with embedded magnets. The result is valid even when the windings are not sine-distributed. It also takes into account any variation in the level of saturation as the rotor rotates. In such cases the *i- Ψ -GoFER* is the only rigorous method for calculating the average electromagnetic torque from the energy-conversion loop (flux linkage vs. current). The driving current waveform can be either ideal sinusoidal or square-wave. The *i- Ψ -GoFER* obtains the variation of the phase flux-linkage Ψ as the rotor rotates through one electrical cycle, with the ampere-conductor distribution correctly phased according to the rotor position. As the rotor rotates, the current varies in synchronism according to its ideal sinusoidal or square waveform. In each phase the point (*i*, Ψ) traces out a closed loop once per electrical cycle. The area enclosed by the *i- Ψ -loop* is then equal to the average energy conversion per cycle in each phase, and if this is accumulated for all the phases and divided by 2π , the result is the average electromagnetic torque.

The *i- Ψ -GoFER* can also compute iron loss on an element-by-element basis as the rotor rotates. The *Element table* instructs PC-FEA to produce a table containing the magnetic flux-density and field strength and other parameters for every element in the solution, see figure 4. This “raw data” can be processed for computing the iron losses using a modified Steinmetz equation on an element-by-element basis. The flux-density in motor laminations may be far from sinusoidal. *SPEED* therefore uses a modified Steinmetz equation [2].

Table 1 shows finally the results for the initial design of the electrical machine performance after a few iterations using the *i- Ψ -GoFER* for the two different load cases

- 1) Base speed: 1000.0 rpm and
- 2) Highest speed: 6000.0 rpm,

both for an equal mechanical output power of 6.0 kW. At the higher speed the iron losses have become the dominating ones – the copper losses are significantly reduced due to the constant power regime resulting in a 6 times less torque demand as the speed has increased by a factor of 6.

| | | | | |
|------------------------------------|---------------|------------|---------------|------------|
| Speed | 1000.0 | rpm | 6000.0 | rpm |
| Shaft Power | 6.0 | kW | 6.0 | kW |
| Torque | 57.4 | Nm | 9.6 | Nm |
| Phase current, rms | 54.4 | A | 12.9 | A |
| Phase advance angle | 22.0 | el. Deg | 57.0 | el. Deg |
| Copper losses | 577.5 | W | 26.1 | W |
| Iron losses, stator teeth | 34.0 | W | 115.0 | W |
| Iron losses, stator yoke | 17.0 | W | 55.0 | W |
| Iron losses, rotor | 5.0 | W | 28.5 | W |
| Machine efficiency | 90.5 | % | 93.5 | % |
| DC link voltage | 400.0 | V | 400.0 | V |
| Predicted mean winding temperature | 150.0 | °C | 75.0 | °C |
| Predicted mean magnet temperature | 75.0 | °C | 65.0 | °C |

Table 1: Performance data of the example machine using PC-FEA and the i - Ψ -GoFER

Figure 3 shows the different flux density distributions for the two load cases with the highly saturated parts in red ($B > 2.1$ T, mainly in figure 3a). As the current is decreased for the high speed operating point, the flux density in the stator yoke is reduced as well, but the rotor bridges still remain highly saturated.

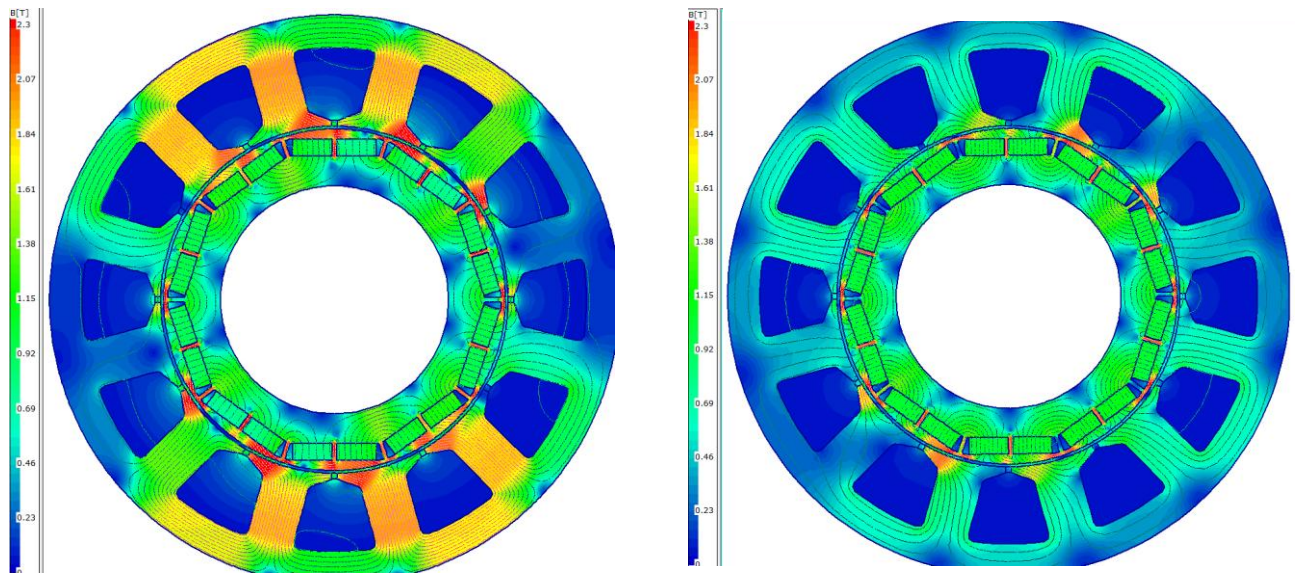


Fig. 3: Flux density distribution, PC-FEA running the i - Ψ -GoFER for a certain rotor position:
a) load point 1000.0 rpm
b) load point 6000.0 rpm

Figure 4 is showing the element table with all the detailed information on each element (Triangle row). Under the Summary tab all the single element results have been added to a region as “rotor steel” or “stator steel”. This information has been taken to get the iron losses for the stator and the rotor in table 1.

| Elements table (a) | | | | | | | | Elements table (b) | | | | | | | | | | |
|--|-----|----------------|----------|---|---------|----------|-------|--|----------|-----|----------------|---|----------|---------|----------|-------|---|--|
| I 1 G 1 R 1 I 77 A G 22 ° | | | | Wtotal 32.240 W Weight 7.260 kg WHys 24.283 W WEddy 7.957 W | | | | I 18.4 A G 57 ° | | | | Wtotal 115.282 W Weight 7.260 kg WHys 43.139 W WEddy 72.143 W | | | | | | |
| Method Modified Steinmetz MaxHx 21 Recalculate | | | | | | | | Method Modified Steinmetz MaxHx 21 Recalculate | | | | | | | | | | |
| Element Data B Graph Plot Summary | | | | | | | | Element Data B Graph Plot Summary | | | | | | | | | | |
| Triangle | Sub | Reg | LossDens | EddyDens | HysDens | CondDens | Bpeak | f | Triangle | Sub | Reg | LossDens | EddyDens | HysDens | CondDens | Bpeak | f | |
| 1 | 1 | Rotor_Stt5,391 | 2,095 | 3,296 | 0 | 0,9245 | 200 | | 1 | 1 | Rotor_Stt52,24 | 42,41 | 9,826 | 0 | 0,5788 | 1200 | | |
| 2 | 1 | Rotor_Stt5,355 | 2,081 | 3,274 | 0 | 0,9206 | 200 | | 2 | 1 | Rotor_Stt51,52 | 41,78 | 9,74 | 0 | 0,5752 | 1200 | | |
| 3 | 1 | Rotor_Stt6,268 | 2,576 | 3,691 | 0 | 0,9909 | 200 | | 3 | 1 | Rotor_Stt57,26 | 48,12 | 9,142 | 0 | 0,5496 | 1200 | | |
| 4 | 1 | Rotor_Stt5,305 | 2,062 | 3,242 | 0 | 0,9152 | 200 | | 4 | 1 | Rotor_Stt50,57 | 40,88 | 9,695 | 0 | 0,5733 | 1200 | | |

Fig. 4: Flux density distribution, PC-FEA running the i - Ψ -GoFER for a certain rotor position:
a) load point 1000.0 rpm
b) load point 6000.0 rpm

Having a first machine design with a proper magnetic and motor performance design, we proceed with the next step: the calculation of the machine temperature in STAR-CCM+.

Numerical treatment in STAR-CCM+

The geometric description of the model will focus on the cooling mechanism and the elements in the material description that largely affect the performance of the machine. The water cooling that runs through the casing is depicted in figure 5. To simplify the geometry we model very thin parts through so called thermal contact resistances between volumetric domains. In this way we avoid thin geometric details like the slot liner and contact imperfections between the housing and the stator. The coolant path affects the local temperatures. We therefore simulate the complete motor and housing.

The material properties of the solids in this conjugate heat transfer problems are taken from *SPEED* during the initial model import. The air and water flow is solved using RANS approximation that solves for mass, momentum and energy and models unresolved velocity fluctuations with a so-called *Eddy viscosity* model. Here we follow the recommended settings in STAR-CCM+ by using the realizable $k-\varepsilon$ turbulence model with the two-layer wall treatment.

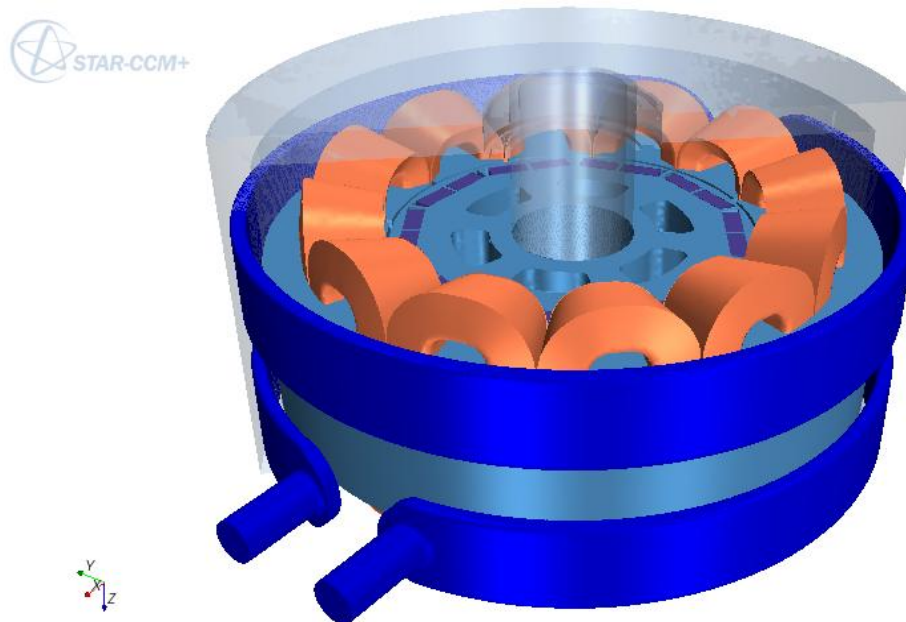


Fig. 5: Geometric additions for 3D thermal conjugate heat transfer simulation

The elements with particular treatment of their anisotropic thermal properties are the shape of the end windings, with a higher thermal conductivity in the direction of the copper wires and the cross-sectional thermal conductivity representing the fill factor and the insulating material with a reduced thermal conductivity coefficient and similarly the steel laminations.

The thermal loads for the volumetric parts of the respective type will be applied in the way that the total load in Watt matches the values obtained in *SPEED*. Particularly the iron losses are extrapolated in the normal direction from their 2D distribution.

The rotation rate is represented in STAR-CCM+ using a so-called moving reference frame approach, which applies a fixed grid flux distribution in a designated region around the rotating parts to the momentum equation. In this case the cylindrical domain is set to go through the center of the air gap. Parts of the shaft region stick out of this domain, here we apply a tangential velocity according to the rotation rate of the load point. This approach is particularly useful for steady state simulations as the costly mesh motion calculations are avoided.

Numerical Example

Preliminary studies have shown that the deviation between max. and mean temperatures in the winding filled regions are very sensitive to the choice of cross sectional thermal conductivities. The maximum temperature strongly depends on the resistance representing the slot liner. For the simulation of the two above mentioned operating points the following settings have been applied (see table 2).

| | Value [cross-directional] | |
|-------------------------------|---------------------------|--------------------|
| Copper thermal conductivity | 386.0 [3.0] | W/(m·K) |
| Steel lamination conductivity | 25.0 [20.0] | W/(m·K) |
| Housing/Stator resistance | 0.0012 | m ² K/W |
| Winding/Stator resistance | 0.0073 | m ² K/W |
| Magnets/Rotor resistance | 0.0002 | m ² K/W |
| Water inlet temperature | 50.0 | °C |

Table 2: Thermal properties

As the cross directional conductivity depends on the slot fill factor and insulation materials being used the choice taken here should be regarded with care and should be validated with appropriate measurements. As a first result we list the maximum temperatures for the various components. For the windings we include the mean temperature as it can be set in the electromagnetic calculations in *SPEED*. Temperature distributions are depicted in figure 6. Table 3 points out some temperatures. The hottest point is for the load point 1 in the winding. At 6000.0 rpm with the higher iron losses but the reduced copper losses the temperature distribution is more or less on an equal level of 50°C.

| | 1000.0 rpm | | 6000.0 rpm | |
|---------|------------------|--|----------------|--|
| Housing | 62.3 °C | | 50.3 °C | |
| Water | 62.2 °C | | 50.2 °C | |
| Stator | 106.3 °C | | 52.9 °C | |
| Rotor | 80.9 °C | | 49.3 °C | |
| Winding | 170.3 [163.2] °C | | 57.0 [56.6] °C | |
| Magnets | 80.4 °C | | 49.2 °C | |

Table 3: Max. [mean] Temperatures

Figure 6 shows also the outline of the cylindrical region around the rotating parts where the moving reference frame approach has been applied. The coolant flow clearly has an effect on the winding maximum temperature.

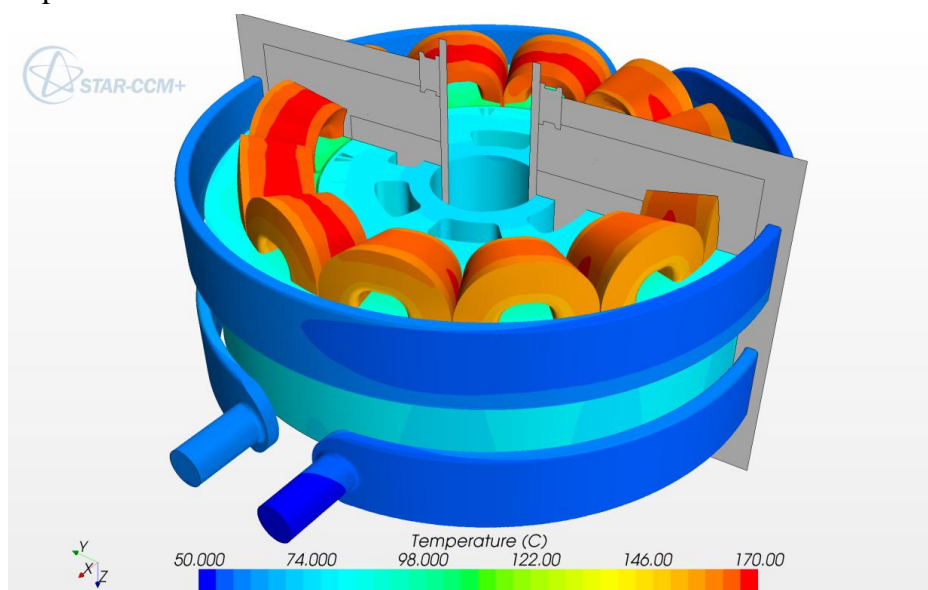


Fig. 6: Temperature distribution, 3D view for 1000.0 rpm (including the grey cross section view for Fig. 7)

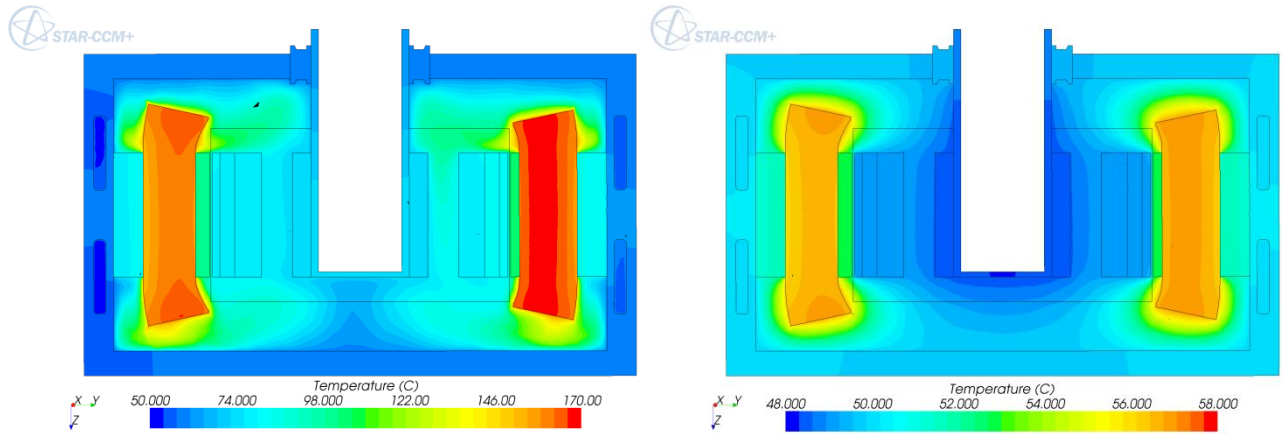


Fig. 7: Section normal view for a) 1000.0 rpm and b) 6000.0 rpm

On the right hand side (Fig 7a) the winding is hotter than on the left hand side as the water is already pre heated from the right half. For the 6000.0 rpm load case the cooling with the minimum temperature drops below the 50°C of the coolant inflow temperature. Here the external air has an effect.

Conclusion

A new coupled approach of thermal modelling of electric machines has been presented using the combination of an electromagnetic analysis tool (to obtain the correct electromechanical operation and loss data) and a CFD 3D package (to obtain the detailed thermal temperature distribution). With this combination a deeper insight of the cooling for electrical machines is more easily possible.

But the current status of the project still requires a considerable amount of initial user input. Once the *SPEED* and STAR-CCM+ model have been set-up the process of data transfer is well defined. Together with the scripting capabilities of both tools, ActiveX for *SPEED* and Java for STAR-CCM+ a natural further development step will be to automate the mapping and monitoring the convergence of the coupled simulation.

References

- [1] *SPEED* BDCGoFER, T.J.E.Miller 2011, CD-adapco
- [2] *SPEED*'s Electric Machines, T.J.E.Miller 2002-2011, CD-adapco