Enhancements in the Electric Machine Cooling Analysis

New efficiency regulations for electrical machines are placing greater demands on electrical machine designers. Now, alongside an optimized electromagnetic design, the thermal analysis has also become increasingly important in the design process. In the same way that SPEED’s analytical approach supports the electric and electro-magnetic design, Motor-CAD’s speed and accuracy is invaluable to the thermal design. At the same time, the CFD capabilities of STAR CCM+ enable a detailed and thorough insight into the machine’s thermal loads.

The result is a streamlined simulation process from Motor-CAD to STAR-CCM+ which will also include the use of SPEED for the loss calculation.

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Over the last decade it is noticeable that there is a growing need for electric machines with

- high torque or
- high power density along with a
- high efficiency demand or/and
- reduction in size, weight, cost

A higher power density can be achieved by applying higher current densities to the electric machine windings or running the machine at higher speeds or a combination of the 2 methods. But both measures are resulting in higher losses: A higher current density in the stator winding increases the copper losses and a higher rotor speed leads to higher current and voltage frequencies that increase the iron losses in the stator and rotor steel laminations and in the presence of permanent magnets also in higher permanent magnet eddy current losses.
Today’s demands

Electrical machines are being driven by means of variable speed drive (inverters) supplying the machine with the fundamental current but also with higher harmonics causing additional losses.

Providing a higher power density will lead to an increase in the temperature rise in the machine as the heat density increases, which will greatly effect its performance and life expectancy: Leading to

– higher temperature gradients with a higher demand on the materials in general, but esp. on the insulation materials
– shorter lifetime expectation due to a higher risk of thermal damages (esp. in the insulation materials).
– a higher risk of demagnetization of the magnets
Today’s demands

To accomplish today’s demand the new machine designs have to eliminate the safety factors of the over-sizing designs of the past to finally ensure the requested high power densities. The need of having besides an optimized electro-magnetic design an optimized thermal design increases.
Losses in Electrical Machines

The heat generated inside the motor originates from two main sources:

Electrical losses include
  the copper losses - also $I^2 \cdot R$ losses - in the windings
  (heating effect due to copper resistance),
  core losses and
  (magnetic hysteresis ($\sim B^k \cdot f$) and eddy currents ($\sim B^2 \cdot f^2$) in iron cores)
  eddy current losses in other parts of the machine being electric conductive, e.g. permanent magnets, end shields, housing parts, ...

Mechanical losses, such as
  frictional losses generated by the bearings as well as
  windage losses
Cooling of Electrical Machines

Cooling types of electrical machines

- Cooling with aggregate phase change
- Liquid cooling
- Cooling with gas

- Oil
- Ethylene
- Water
- Glycol
- Liquid gases
- Air
- Helium
- Hydrogen
# Cooling of Electrical Machines

<table>
<thead>
<tr>
<th>TENV</th>
<th>OV</th>
<th>TEFC</th>
<th>TEHE</th>
<th>Hollow conductor cooling (direct cooling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totally enclosed non ventilated</td>
<td>Open ventilation</td>
<td>Totally enclosed forced cooling</td>
<td>Totally enclosed with heat exchanger</td>
<td>Coolant: hydrogen gas, oil or deionized water</td>
</tr>
<tr>
<td>Coolant: air</td>
<td>Coolant: air</td>
<td>Coolant: air or water jacket</td>
<td>Coolant: air</td>
<td>Heat exchanger: air-air or air-water</td>
</tr>
<tr>
<td>No fan: Cooling only due to natural convection and heat radiation</td>
<td>Shaft mounted fan: Speed dependent air flow for cooling</td>
<td>Externally driven fan: Air flow independent of motor speed</td>
<td>Shaft mounted or external fans: Coolant flow is directed through machine and heat exchange in closed loop</td>
<td>External pump presses coolant through hollow conductors</td>
</tr>
<tr>
<td>Increase of machine surface by fins</td>
<td>End shields are open for coolant flow</td>
<td>Increase of machine surface by fins or tubes for air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to several kW</td>
<td>Up to 500 kW</td>
<td>Up to 2,000 kW</td>
<td>Up to 400 MW</td>
<td>Up to biggest machine power (2,000 kW)</td>
</tr>
</tbody>
</table>

The design process for electric machines involves a series of electric, magnetic, mechanic and thermal analysis.

Thermal analysis is either
- based on empirical data (current density, loss density, ...) or
- performed by using
  - the resistance network method,
  - the finite element method or
  - CFD techniques.

<table>
<thead>
<tr>
<th>Condition</th>
<th>A/mm²</th>
<th>A/in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totally enclosed</td>
<td>1.5—5</td>
<td>1000—3000</td>
</tr>
<tr>
<td>Air-over, fan-cooled</td>
<td>5—10</td>
<td>3000—6000</td>
</tr>
<tr>
<td>Liquid cooled</td>
<td>10—30</td>
<td>6000—2000</td>
</tr>
</tbody>
</table>
Thermal Modeling

*Steady state thermal analysis* predicts temperatures if the individual motor components will remain under rated operating load.

If a *transient thermal analysis* is performed (such as overloading the motor for a specific period of time), it can also predict the temperature transients.
What **SPEED** is

**SPEED** is the leading *design software* for *electric machines*

Detailed analytical analysis with finite-element links or finite-embedded solver for

- motors, generators and alternators
- including inverters and other electronic controls
- The following machine types are available:
  - Brushless permanent magnet and wound-field AC synchronous
    - **PC-BDC**
  - Induction
    - **PC-IMD**
    - Direct current (PM)
    - **PC-DCM**
  - Switched reluctance
    - **PC-SRD**
    - Wound field and PM commutator
    - **PC-WFC**
What *Motor-CAD* is

- Analytical network analysis package dedicated to thermal analysis of electric motors and generators
- input geometry using dedicated editors
- select cooling type, materials, etc. and calculate steady state or transient temperatures
- all difficult heat transfer data calculated automatically
- easy to use by non heat transfer specialists
- provides detailed understanding of cooling & facilitates optimisation
Motor-CAD Motor Types

- BPM
- Outer Rotor BPM
- PMDC
- Induction
- Synchronous
- Switched Reluctance
- Claw Pole
Many Cooling Options

*Motor-CAD* includes proven models for an extensive range of cooling types:

- **TENV**: Totally enclosed non-ventilated
  - natural convection from housing
- **TEFC**: Totally enclosed fan cooled
  - forced convection from housing
- **Through Ventilation**
- **TE with Internal Circulating Air**
  - Internal air circulating path
  - water jacket as heat exchanger
- **Open end-shield cooling**
- **Water Jackets**
  - axial or circumferential
- **Submersible cooling**
- **Wet Rotor & Wet Stator cooling**
- **Spray Cooling**, e.g. oil spray cooling of end windings
- **Direct conductor cooling**, e.g. slot ducts with oil
Many Geometry Options

Many geometry options such as housings, rotors, slot types etc.
Fast Analytical Solver + Integrated FEA

- Fast analytical thermal solution based on lumped circuit analysis allows long/complex duty cycle thermal transients to be solved in seconds
- Fully integrated FEA thermal solver allows fast calibration of analytical model giving best compromise of accuracy & calculation speed
What *STAR-CCM+* is

- *STAR-CCM+* is a powerful, all-in-one tool which combines:
  - Ease of use
  - 3D-CAD Modeller
  - Automatic meshing
  - Extensive modeling capabilities
  - Powerful post-processing
  - All in one software, all in one interface
  - Integrated, multipurpose, multidisciplinary

- Developed since 2004
  - Uses the latest numerics and software technologies
  - Designed from the onset to handle very large models (100M+ cells)
  - Full process integration: CAD to CAE in one package
What **STAR-CCM+** is

**Integrated** engineering solution for solving multidisciplinary problems
What *STAR-CCM*+ is

Integrated engineering solution for solving *multidisciplinary* problems
Thermal Modeling

In *STAR-CCM*:

- Simulation of fluids moving in and around objects
  - Liquids and/or gases

- Heat transfer
  - Conduction
  - Convection (natural and forced)
  - Radiation

- Including
  - Spray cooling
  - Oil drip cooling
  - ...
Motor-CAD and SPEED?

- Motor-CAD fits ideally alongside SPEED to give instantaneous answers to design questions
  - electromagnetic and thermal
- Both have a similar user interface and work with parameters such as $Tw$ (tooth width), $SD$ (slot depth), etc.
- ActiveX links automate data transfer
Motor-CAD and SPEED!

- SPEED is predominantly used for electromagnetic performance prediction
  - includes calculation methods for the full electromagnetic performance including resistance, inductance, magnetic circuit, drive, current/emf/torque, etc
  - calculate the overall performance rather than just the magnetic circuit
  - very simple thermal network models built into software but require calibration
- Motor-CAD has sophisticated thermal models that require the user to have NO knowledge of heat transfer
- To predict the performance accurately both packages can be used together
  - losses are critically dependent on temperature
  - temperatures are critically dependent on loss
- Automated links ease the transfer of geometry, loss and temperature data between packages
  - written using ActiveX Technology
  - standard Windows® method for transfer of data between programs
Both SPEED and Motor-CAD are analytical analysis packages providing instantaneous calculation speeds.

Most Importantly - the user just needs to input the geometry and selects a few winding/drive/material options and then all the difficult magnetic and heat transfer parameters are calculated automatically.

User need not be a magnetic or thermal expert.

Also ideal for training.

Both SPEED and Motor-CAD are excellent for carrying out “What If” calculations.

direct access to physical input parameters such as “Tooth Width”, “Airgap”, “Liner Thickness”, “Turns Per Coil”, “Liner Thermal Conductivity”, etc.

direct access to physical output parameters such as “Shaft Torque”, “Copper Loss”, “Winding Average Temperature”, “Winding Hotspot Temperature”, “Magnet Temperature”, etc.
**SPEED links to Motor-CAD**

- a design can be exported from *SPEED* to *Motor-CAD*
  - geometry, winding and losses
    - intelligent geometry scaling means that dimensional details not available in *SPEED* are given reasonable values
  - housing, endcaps, bearings, etc.
SPEED / Motor-CAD Data Links

Typical Procedure:

- Import geometry, winding and losses from SPEED with temperatures of winding and magnets at expected values.
- Set geometric data for non electromagnetic components such as the housing and bearings.
- Set the cooling type and choose materials.
  - Default materials can often be used initially with fine selection later.
- Calculate the temperatures and compare with expectations.
- [Iterate to Converged Solution] to make both models use the same loss and temperature data.
- Can change both electromagnetic (SPEED) and thermal (Motor-CAD) designs and try to optimise total solution.
• Create a new design in SPEED PC-BDC
SPEED / Motor-CAD Link Example

- Export the data to Motor-CAD
Motor-CAD Calibration using CFD

• CFD (STAR-CCM+) can be used to help calibrate some of the more difficult flow and convection cooling problems
  – flow through synchronous machine
  – end winding cooling
  – blow over leakage
  – etc.
Thermal Modeling

1. Creation of the Motor-CAD model based on geometry parameters and winding scheme or import from SPEED

2. FE-analysis and fitting of the analytical model

3. Run thermal calculations in Motor-CAD to check the model

4. Preparation of the geometry in STAR-CCM+ by running a Java script

5. Transfer of the heat loss distribution from the FE-analysis to STAR-CCM+ via the sbd-file

6. Mapping process for rotor and stator heat losses is carried out separately and automatically with transfer of the values from neighbor grid node in SPEED to STAR-CCM+

7. Solving and post processing in STAR-CCM+
**Thermal Modeling**

*SPEED* provides initial design
- Data export for further electromagnetic and thermal analysis

**FE calculation**
- For detailed EMAG and loss calculation and export of loss data

**STAR-CCM+ cooling analysis**
- Conjugate heat transfer using liquid and/or gaseous coolants
- Import of thermal loading from EMAG tool
  - 2D or 3D Loss distribution data is mapped onto *STAR-CCM+* grid
Calibration of Channel Leakage using CFD

- We are currently developing automated links from Motor-CAD to Star-CCM+ to allow automated calibration of the blown over semi-open channel leakage.
Calibration of Channel Leakage using CFD

- Fan editor being incorporated into Motor-CAD so we can export to STAR-CCM+
Examples

Induction machine, overblown/through ventilation with fan on the shaft: Temp. distribution
Examples

Induction machines, overblown/through ventilation with fan on the shaft: Heat flow

Stator:
- Copper Loss: 197 W
- Aux + Main Winding: 103 W
- Iron Loss: 113 W
- Air: 94 W
- Stator Lams: 46 W
- Housing: 70 W

Rotor:
- Copper Loss: 132 W
- Rotor Cage: 89 W
- Iron Loss: 17 W
- Air: 43 W
- Rotor Lams: 69 W
- Shaft: 37 W
Questions?