



PROCESS CHAIN FOR QUICK, EFFICIENT THERMAL ASSESSMENT OF MOTOR DESIGNS IN FAN DEVELOPMENT

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SUMMARY

When it comes to designing electric motors, it has to be taken into account that the residual flux density of the permanent magnets and the winding resistance depend on temperature. Therefore, this temperature must be known for the electromagnetic simulation. For establishing temperature, however, the losses occurring need to be established first, as they are assigned to the relevant components by the CFD tool. In order to precisely calculate temperatures and speed-torque behaviour, both software tools have thus to be coupled/linked/interconnected. This paper shows how the process chain operates over time and gives the calculation results compared to a temperature rise measurement, as well as a study on the ratio of diameter to length.

NOMENCLATURE

Latin Symbols

a	temperature coefficient of copper	A	area
A	Ampere	C	Celsius
d	Thickness of	I_{PC}	phase current
K	Kelvin	n	number of strands
n	revolutions per minute	P_{CU}	copper losses
P_{el}	electronic power	P_{fl}	friction losses
P_H	hysteresis losses	P_I	iron losses
P_{shaft}	shaft power	P_W	eddy current

R_{20}	winding resistance at 20°C	$R(T)$	Winding resistance at temperature T
\dot{Q}	heat flow	W	Watt

Greek Symbols

a	heat-transfer coefficient	λ	Thermal conductivity
η	Efficiency		

Abbreviations

2D	two dimensional	3D	Three dimensional
CAD	Computer Aided Design	CFD	Computational Fluid Dynamics
D/L	ratio diameter/length		

INTRODUCTION

Basics: Electric motors

As with all electro-mechanical devices, losses occur with an electric motor. These losses are essentially made up of the copper, iron and friction losses. The higher the losses, the lower the ratio between output and input power (P_{out} und P_{in}) and thus efficiency η of the motor. To calculate efficiency, the following formula is used:

$$\eta = \frac{P_{shaft}}{P_{el}} \tag{1}$$

$$\eta = \frac{P_a}{P_{at}}$$

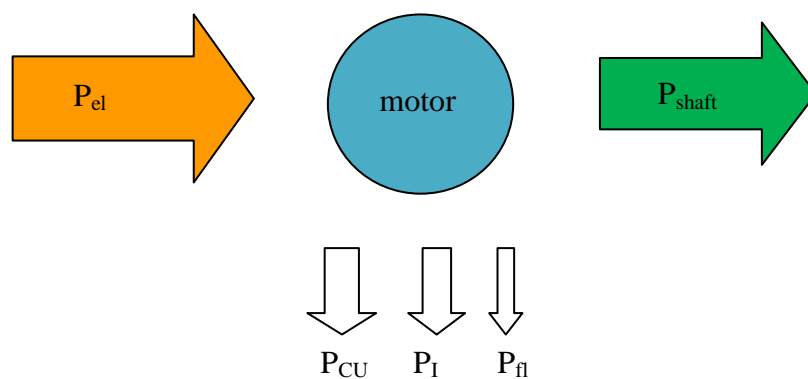


Figure 1: Power-output distribution with motor [1]

Copper losses, also known as electric heat losses, are generated in all conductive parts, thus also in windings, and can be calculated as follows:

$$P_{Cu} = n \cdot R(T)_{pc} \cdot I_{pc}^2 \tag{2}$$

Temperature-related resistance can be calculated using equation 3:

$$R(T) = R_{20} \cdot [1 + a \cdot (T - 20^\circ)] \tag{3}$$

Iron losses occur in all active iron parts permeated by magnetic fields varying over time. A differentiation is made between hysteresis losses and eddy current losses here.

$$P_I = P_H + P_W \quad P_I = P_H + P_W \quad (4)$$

Friction losses mainly occur in the bearings, but air friction caused by shear forces in the gap or cooling impellers may not be completely ignored. The following interrelation to speed may thus be assumed:

$$\text{Bearing losses: } \sim n^2; \text{ air friction losses: } \sim n^3$$

Magnetic design

To get a rough dimensioning of the drive motor, 2D calculation programmes are used in developing the magnetic design as an individual design can be calculated very quickly, so a great number of variants may be analysed in very short time. Target parameters are the torque-speed performance and the permitted installation space. To meet these targets, the following parameters have to be provided: motor topology (external-/internal-rotor motor), winding system, magnet and sheet metal materials, mains voltage, and mains frequency. At first, permissible current load and temperatures to be expected in the windings as well as the temperatures in the permanent magnets need to be estimated.

The operational behaviour of the motor is calculated using the 2D design programme SPEED which is based on Maxwell's equations. Once all target parameters are met, SPEED allows the geometries of the magnetically active components to be exported. Apart from the geometry, the electromagnetic design also provides information on the distribution of iron losses and copper losses.

State-of-the-art:

For thermal consideration of electric machines, calculation programmes are frequently used which calculate the temperatures in the individual components based on resistor networks[2]. The advantage of this method is that the analytical calculation approach only requires very short computation time. The most commercially used programme in the industry is MotorCAD[3]. However, the disadvantage of programmes based on such a method is that you need to know quite a number of the parameters in order to be able to describe a network comprehensively, and more often than not you can only choose from a limited number of motor geometries, or some of the details of the geometry are not even implemented in the commercial programmes.

Thermal simulation

The heat dissipation of the motor depends to a great extent on the flow conditions in and around it. Winding temperatures depend on how well heat can be dissipated into the surroundings. Such processes can be calculated via CFD tools. In our case, the commercial programme CCM+ V9.04.009 by CD-adapco [7] is used, solving the energy equation, the equation of continuity and the Navier-Stokes equations.

The calculations take into account the heat transfer mechanisms of the thermal conduction (eq. 5) and convection (eq.6)[4].

$$\dot{Q} = \lambda \cdot \frac{A}{d} \cdot \Delta T \quad \dot{Q} = \lambda \cdot \frac{A}{d} \cdot \Delta T \quad (5)$$

$$\dot{Q} = \alpha \cdot A \cdot \Delta T \quad \dot{Q} = \alpha \cdot A \cdot \Delta T \quad (6)$$

To calculate the temperatures of a motor, the geometries of all components and the boundings of the air surrounding them must be known for the simulation, and the losses in the individual components need to be known as well.

Coupling of magnetic design and thermal simulation

Both disciplines are interdependent, so interchanging information on temperatures and losses with the respective other calculation programme becomes a necessity. An iterative method is the solution to this problem. With this iterative coupling, the first electromagnetic design in SPEED starts with an initial temperature of 20°C. The calculated losses are exported to STAR-CCM+. This results in the temperatures in the individual motor components matching the losses at 20°C. This first loop done, the established temperatures from STAR-CCM+ now form the basis for the calculation of losses in SPEED once more. This process is repeated until the differences from one loop to the next are so small as to be almost negligible, rendering the system almost convergent.

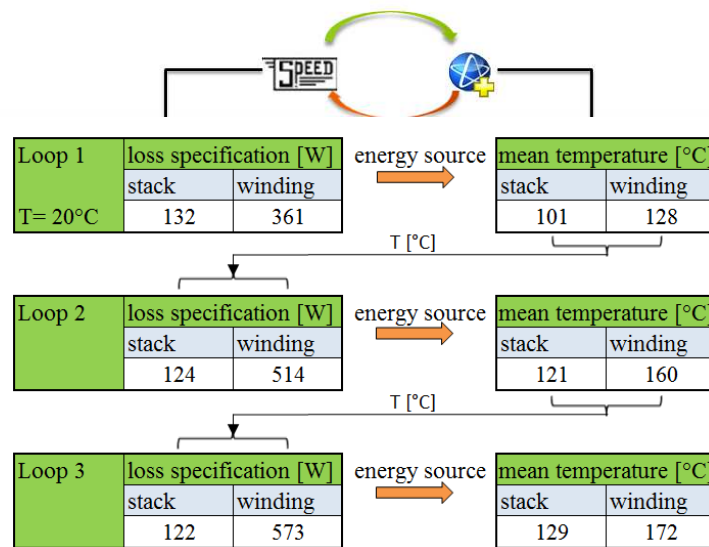


Figure 2: Principle of the coupling process [5]

The decision to use the SPEED programme was based on the fact that it not only yields the calculated losses, but also the data on the geometries of the magnetically active components.

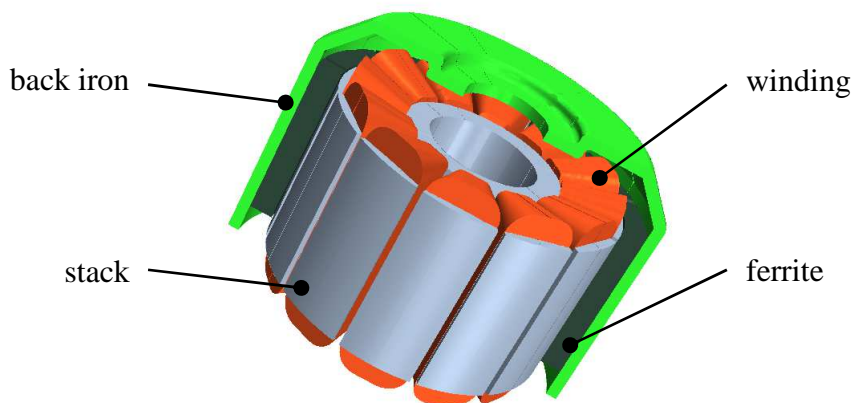


Figure 3: Components of 2D design

Standard procedure until then had been to pass the geometries on to the engineering design department which then constructed the remaining motor components together with the magnetically active components. As this was found to be quite time-consuming, a parametric CAD model was developed which generates a complete subassembly for CAD calculation/simulation based on the magnetically active parameters coming from SPEED plus the parameters having an impact on the cooling geometries.

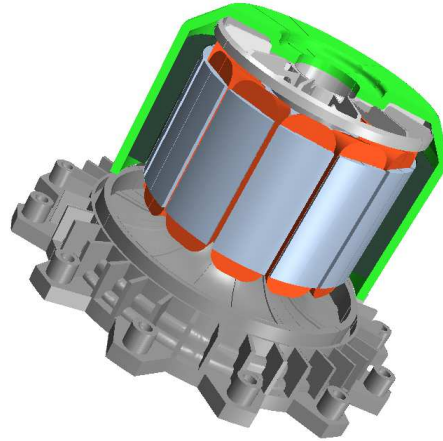


Figure 4: Geometry of a motor

Figure 4 illustrates the typical motor geometry of an external-rotor motor which can be generated by the parametric CAD model. This model has 46 geometry parameters, of which 16 are determined by SPEED. The parametric model does not only contain the components, but also the air volumes surrounding them needed for the thermal simulation.

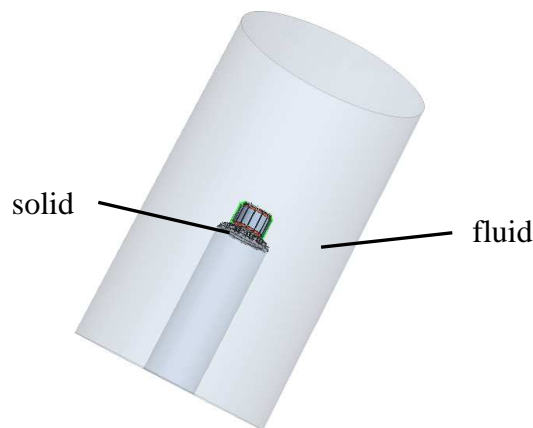


Figure 5: Simulation geometry

For the calculation, the geometry has to be meshed in the CFD programme. This is done with unstructured polyhedral mesh and, for the wall treatment, with prism layers.

For the thermal simulation, the individual components are assigned their physical properties. For stationary thermal analysis, the thermal conductivity of the components is configured. Apart from thermal conductivity, the contact resistances between the components play an important role and must thus be configured based on experience respectively measuring data.

The losses occurring in winding, lamination stack and the bearings are defined as energy sources. Information on bearing losses is taken directly from manufacturer's data.

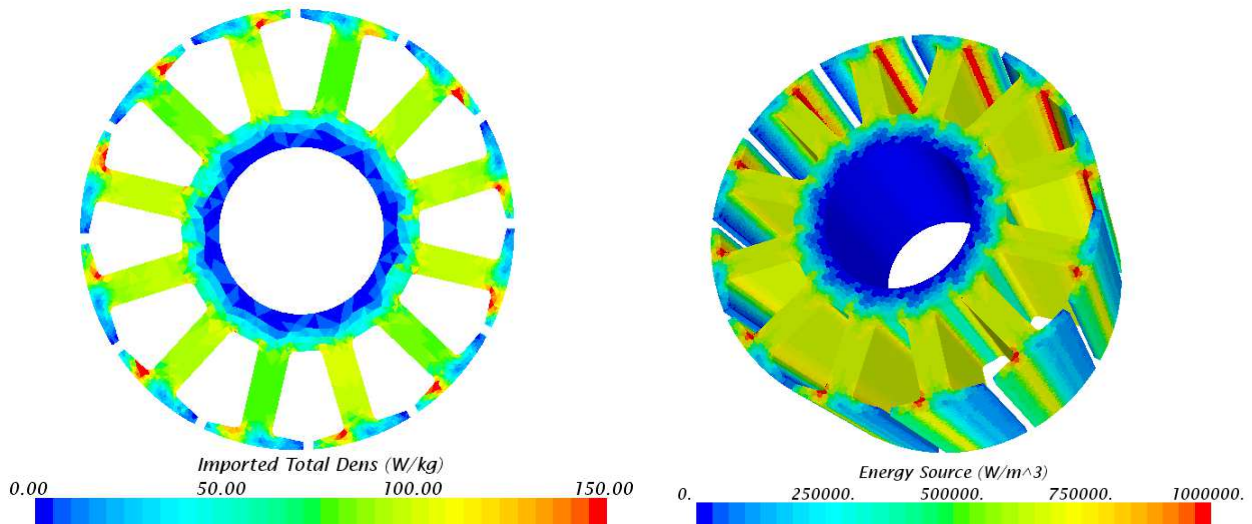


Figure 6: The figure left shows the distribution of losses in the stator stack on a plane section, on the right we see their definition as energy source in 3D

In order to calculate the flow in and around the motor, the speed inside the rotating fluid volume of the motor must be configured in the simulation. Calculation here is stationary, without rotating mesh. Turbulence is calculated via 2-equation model. Real gas effects and gravitational effects are neglected.

Validation of process chain

To validate the process chain, an existing motor was used. On the basis of this motor, the required parameters for the definition of the SPEED design are defined, and the parameters for the parametric 3D CAD model are derived from the already designed motor. Parallel to this, temperature rise measurements of this very same motor were carried out. To allow comparison with the process chain, the motor under examination was fitted with thermal elements in different positions.

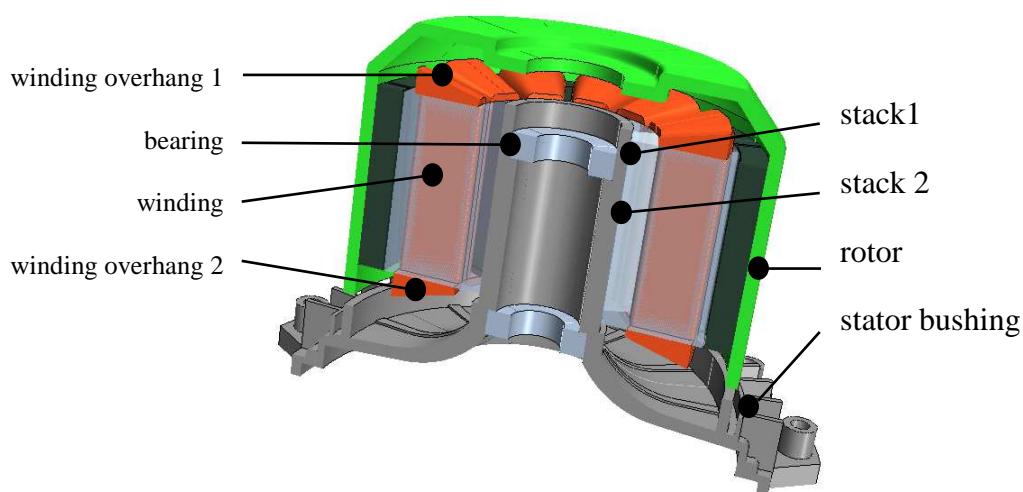


Figure 7: Motor with positions of thermocoupling elements

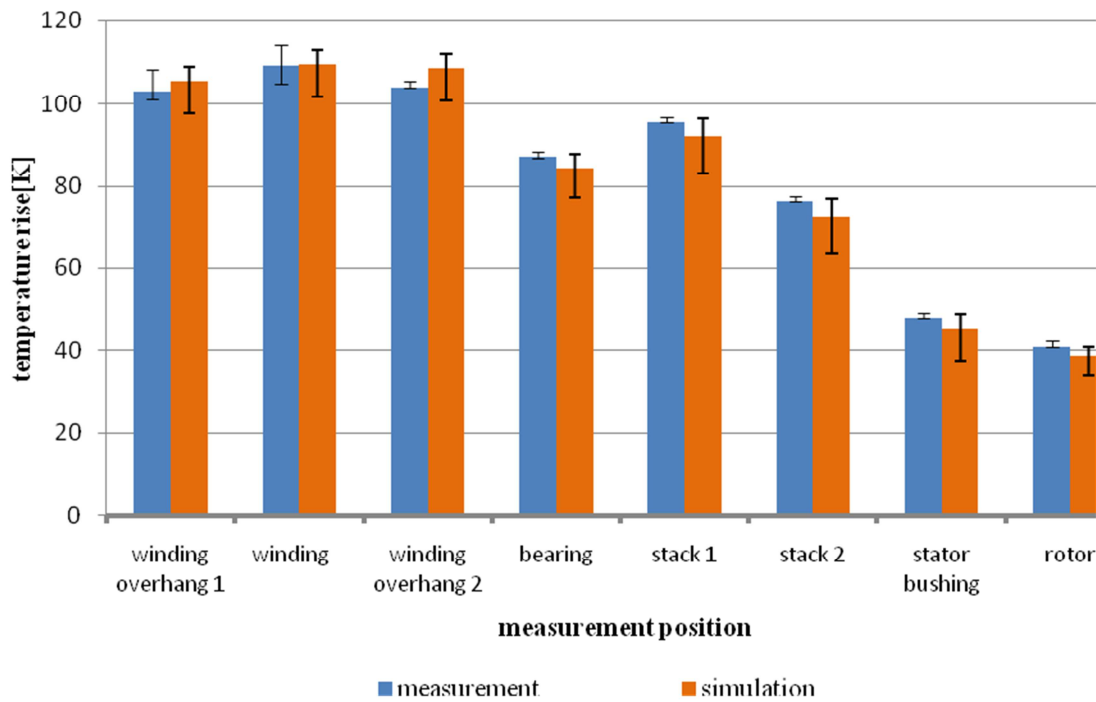


Figure 8: Comparison between measurement and simulation

Figure 6 shows both the measured and simulated temperatures. Taking measuring tolerance into account, it is clearly obvious that the deviations are minimal. As explained earlier on, there are always deviations caused by inaccurate assumptions of contact resistances and deviations in measuring positions, which is reflected in the error bars of the values.

Diameter/length optimisation[6]

To establish the optimal diameter/length ratio for constant output power, different electromagnetic designs are created. For the individual electromagnetic designs, the following boundary conditions apply:

- Torque: 65 Nm
- Current density: 8 A/mm²
- Air gap: 1 mm
- Slot/pole ratio: 12/10
- Speed (rpm): 1500 1/min

Table 1: Design points

Model	Stator $\varnothing(D)$ [mm]	Axial length (L)[mm]	Ratio D/L
1	151	380	0.25
2	172	240	0.44
3	187	180	0.64
4	214	120	1.10
5	230	90	1.58
6	262	60	2.69

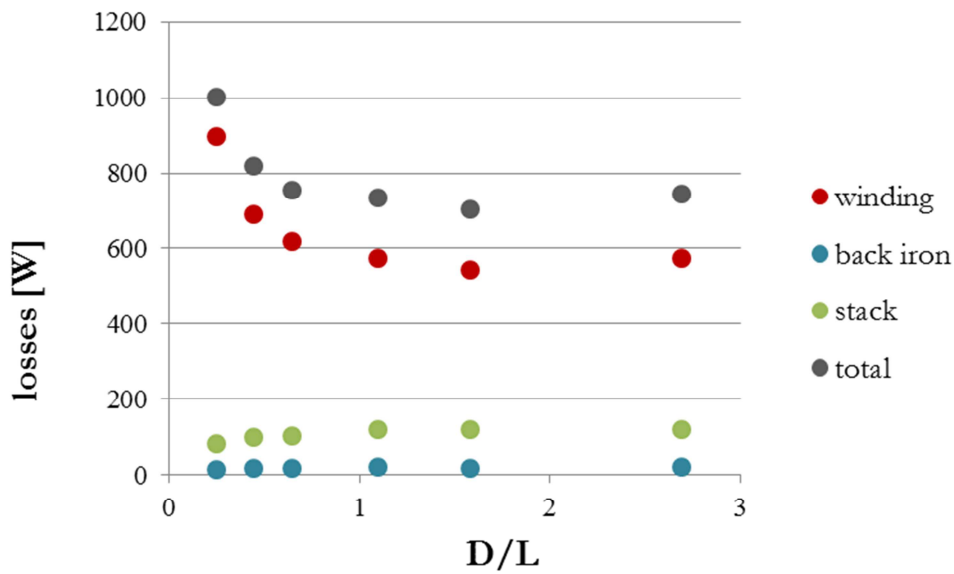


Figure 9: Losses at diameter/length ratio

In addition to the constant output power, the stator volume is constant. In figure 9, the losses across the diameter/length ratio can be seen to clearly vary. However, based on the known parameters, the optimal diameter/length ratio can be established as being 1.5 in this case.

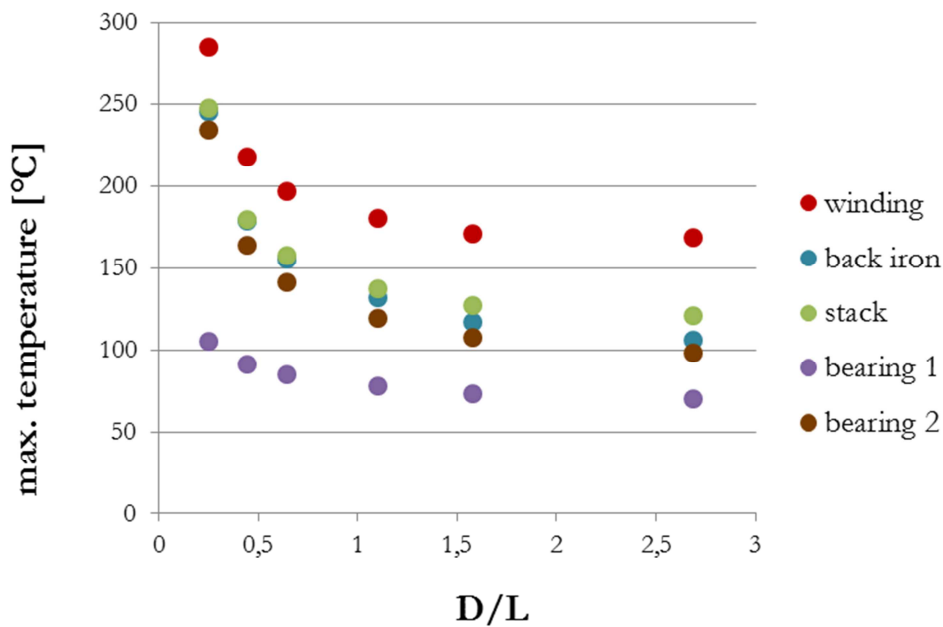


Figure 10: Temperatures at diameter/length ratio

As temperature rise is determined by the losses, the optimal diameter/length ratio is also found to be 1.5 for the temperatures. It has to be taken into account with this analysis, however, that the housing of the motor was scaled with the stator diameter and that the number of fins was the same each time.

CONCLUSION

The process chain owes its existence to the mutual dependence of both disciplines and offers the possibility to examine various motor designs in order to develop the optimal motor geometry for any given application.

As opposed to calculation approaches based on resistor networks, no assumptions have to be made for the convection, as this is part of the calculation, which contributes to the higher computation times here. As the rise in temperature of a fan motor depends decisively on the flow conditions around it, these have to be precisely established and known.

The results of an optimisation calculation can only be compared to a certain extent, as the contact resistances are often not accurately known even though they have a big impact on the temperature level of the motor. However, this is the case not only with this standardised, parametric process chain, but also with the manual simulation setup of prototypes.

The process chain is based on data transfer between SPEED and CCM+. Taking into account the parametric geometry model, a large number of variants can be examined very efficiently. This makes it possible to analyse a lot of motor designs without the need to physically create motors or run temperature rise measurements, making the development process a lot faster and reducing development costs. As demonstrated, the process chain is applicable and can be used for various problems presenting themselves during the development process.

Using the process chain, parameter studies can be carried out, making for deeper understanding. A standardised process chain always provides the same simulation structure, so simulations can be easily compared, with input errors made impossible. By defining meaningful parameters for the parametric 3D-CAD model, a high-quality geometry is generated which causes no problems when meshed, thus dispensing with the need for cleaning.

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