Thermal Analysis and Optimization of Gearboxes by Simulation

Björn Bauer, Ralf Hambrecht, Andreas Kube and Simon Becka

Introduction

With the increasing mechanical power capacity of gearboxes, the thermal power limit tends to become the limiting factor. To achieve a balanced system, the gear unit needs extra cooling. Using a fan that is mounted to a fast rotating shaft is a common solution. For this solution an optimal design is investigated. Due to the complexity of a gearbox's heat balance, analytical calculation methods are too inaccurate for precise evaluations of changes to the cooling system. The goal of this work is to present an optimal cooling concept — with fan and air guiding cover — by using a numerical approach.

Thermal Balance as Dimensioning Criterion

Converting torque and revolution speed in spur and bevel gear units causes energy losses within the moving machine parts. Without an external cooling device, a specific operation temperature is required to achieve an energy balance, which is influenced by factors illustrated in Figure 1. Inside the gearbox the heat is transported by the oil, which is distributed by the rotating parts — like gears. Without external cooling, the major part of the heat is dissipated by convection and radiation.

The transmittable power of a gearbox grows to the power of three related to its dimension — as do its losses. In contrast, the surface grows only to the power of two. This misalignment limits the power (Fig. 3). In addition to the size effect, the ongoing development of gearboxes is affected by a continuous increase of power density. New and better materials, enhanced manufacturing technologies, and numerical design methods like shape optimizations lead to a higher utilization of available space. The energy balance can only be maintained if the temperature rises or the cooling capacity of the surface is used more efficiently. Increasing the oil temperature is limited due to lifetime reduction effects of the lubricant and restrictions on surface temperature limits. Therefore it gets more and more probable that, at the end, it is not the mechanical requirements that determine the selected size of a gearbox and therefore the price, but rather the thermal power limit.

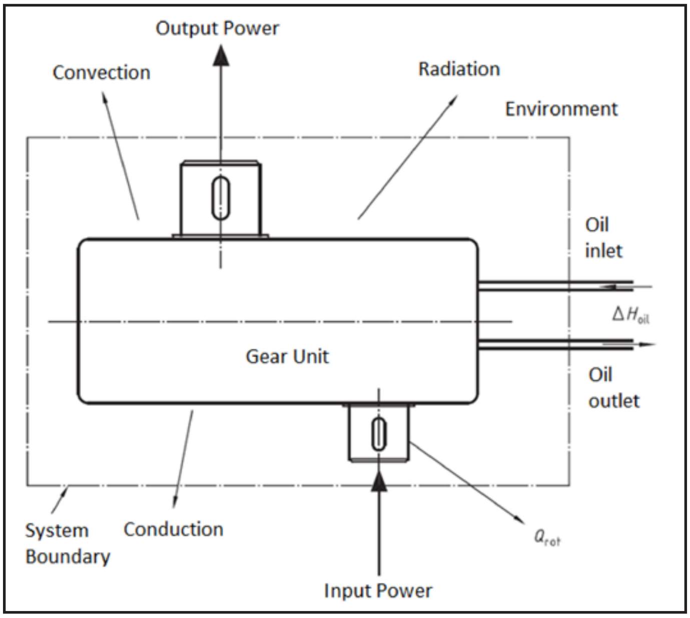

Figure 1 Influences on the thermal behavior of gearboxes (Ref 1).

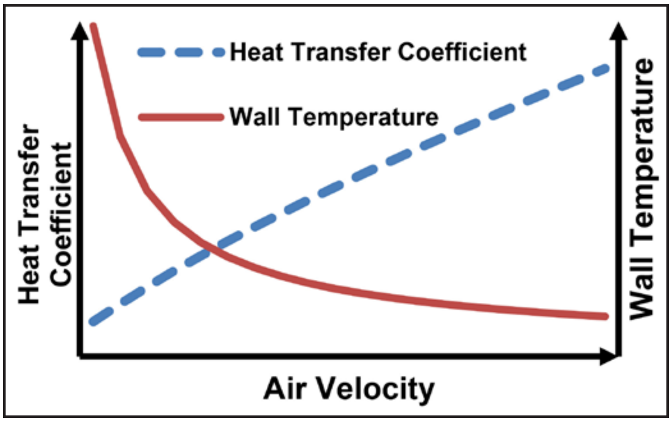

Figure 2 Comparison of mechanical and thermal power rating.

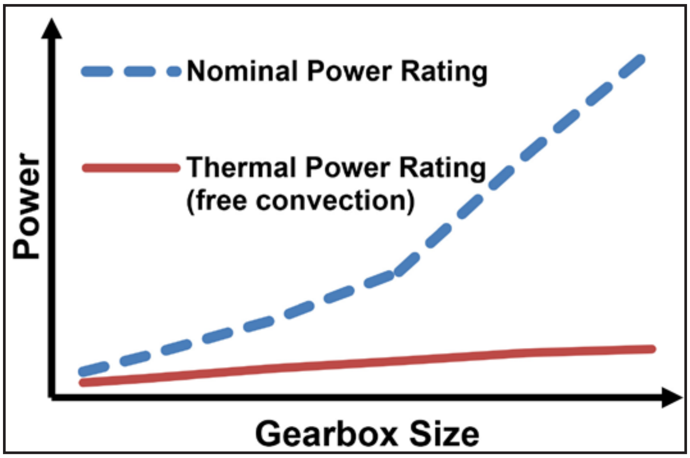

Figure 3 Influence of air velocity on heat transfer coefficient.

This paper was first presented at the International VDI Conference on Gears 2017, Garching/Munich [VDI-Berichte 2294, 2017, VDI Verlag GmbH] and is reprinted here with VDI approval.

Optimization of Surface Cooling

The air velocity near the surface has a high influence on the heat transfer coefficient (Ref. 3). This relationship and its effect on the temperature of the passed wall are shown (Fig. 2). To raise the air velocity of surface-cooled gearboxes, using fans is a common solution. Mounted to the fast rotating input shaft, a high-volume flow rate is generated to pass the surface; sometimes, cooling fins are added to enlarge the surface area.

Figure 4 shows a Flender B3SH gearbox with fan and air-guiding cover. The cover aligns the airflow to the gearbox housing, which improves the thermal power limit significantly. Figure 5 shows a comparison of power limits for different cooling options.

Forced convection helps minimize the gap between mechanical and thermal power limits. But especially for larger gearboxes, this cooling effect is not sufficient—even when using housings with fins. A more effective solution is required.

Figure 4 Gearbox with radial fan and short air guiding cover.

Analytical Approach to Calculate Gearbox Temperatures

Today's common method for calculating gearbox temperatures is described (Ref. 1). To begin, the losses of the machine elements are calculated. Then the heat outflow is regarded, separated in two steps: 1) the heat transfer from the oil to the housing material, subdivided in areas with and without direct oil contact; and 2) calculate the heat flow from the housing to the environment, considering areas with and without fins, losses by radiation, and also heat conduction to the basement and other parts that are connected to the shafts.

This analytic approach is exact—as long as the boundary conditions are ideal. But in reality the surface temperature is not homogenously distributed, and the air flow is neither laminar nor steady. One reason for the inhomogeneity is the way the thermal energy passes to reach each surface point. The transport of the energy starts at a heat source; contains a distribution through the oil; goes via wetting of the inside surface of the housing over to the housing material; and then passes an individual distance to reach an outside surface location. For any surface point, an individual heat flow develops (Fig. 7).

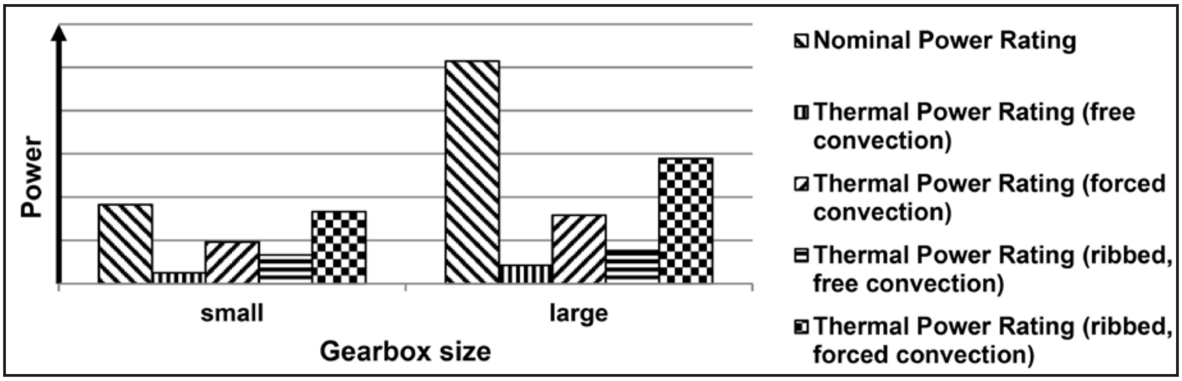

Figure 5 Influence of forced convection on thermal capacity.

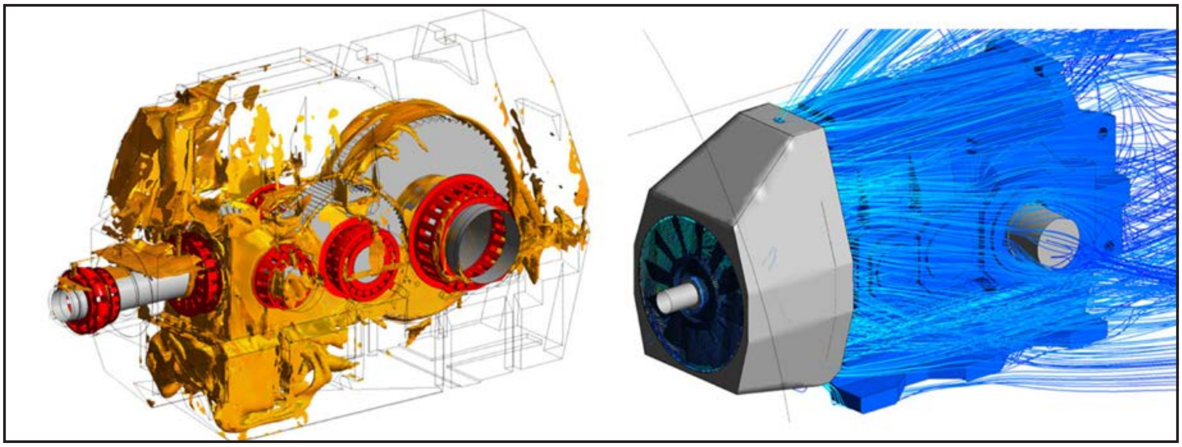

Figure 6 Simulation of oil distribution (left) and airflow (right) around a Siemens Flender gearbox with standard air guide hood.

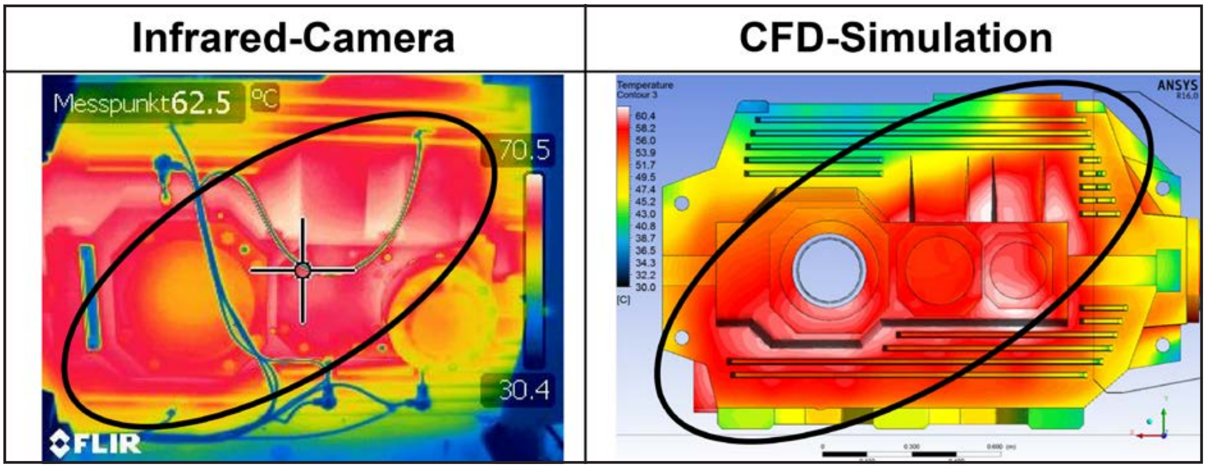

Figure 7 Comparison between infrared camera and a CFD simulation.

Furthermore, the terms to calculate the losses of the machine elements are only good as estimations. An example is the calculation of gear mesh losses according to Mauz (Ref. 2); that approach is valid up to modulus 5, but for an industrial gearbox this is not sufficient. Often, bigger gears are used and thus the calculation is rendered inaccurate.

Bottom line, this approach is insufficient to predict the thermal behavior of a changed gearbox design.

Numerical Approach to Calculate Gearbox Temperatures

The state-of-the-art numerical approach is computational fluid dynamics (CFD). This method is capable of closing the gap between calculated and measured gearbox temperatures. With CFD it is possible to simulate the oil flow inside the gearbox (Fig. 6, left) and the airflow around it (Fig. 6, right). This makes it possible to consider all influences that are important for the heat distribution; e.g. — the local wetting of the inside surface, the rotational speed and direction of moved parts, and the immersion depth of the gears' wheels.

At the outside surface the exact streaming conditions are simulated and allow considering models of different fan types, covers, and flow-disturbing details of the surface topology.

The heat flow via conduction to connected machine parts, or to the basement, play a minor role within global balance. More important when seeking the correct absolute temperature level is the precision of the efficiency factor of the gearbox. The analytic terms provide a good estimation of the relation of the different losses to each other, but the absolute level has poor precision. To calibrate the CFD simulation, it is possible to simply scale these losses so that the simulated absolute temperature level fits a measurement. This is advantageous if one wants to precisely predict the absolute temperature (or thermal power limit) of a gear unit with a changed cooling design. But simply finding the optimal design is not sufficient. Mainly, three things are required: 1) the mechanical losses in good proportion to each other at the correct locations; 2) the correct oil flow and resulting distribution; and 3) the correct airflow around the gearbox. Figure 7 illustrates the resulting, simulated heat distribution over the gearbox surface and compares it to an infrared camera picture. The comparison shows that the position of the hotspots, the distribution, and absolute temperature values are nearly exact — with an acceptable maximum error of 3 kelvin.

Computation Time

The required computation power to perform CFD is enormous compared to analytical calculations. For example, the transient simulation of 5 seconds real time of a medium-sized gearbox in appropriate accuracy concerning grid resolution and time step size, takes about seven days of computation on a well-equipped desktop form computer with two 3 GHz multi-core CPUs, 128 GB memory and solid state hard disks. Bigger gearboxes are hardly computable at all on desktop computers because the number of nodes in the 3-D model grows proportionally with the volumetric size of the gearbox.

For such problems Siemens offers a service to use a worldwide-distributed computer cluster infrastructure. This solution makes it possible to simulate even the biggest gearboxes in best resolution and accuracy. The computation period reduces to a fraction, so that complete work on one test case, including pre- and post-processing, can be done in hours and days, instead of days and weeks.

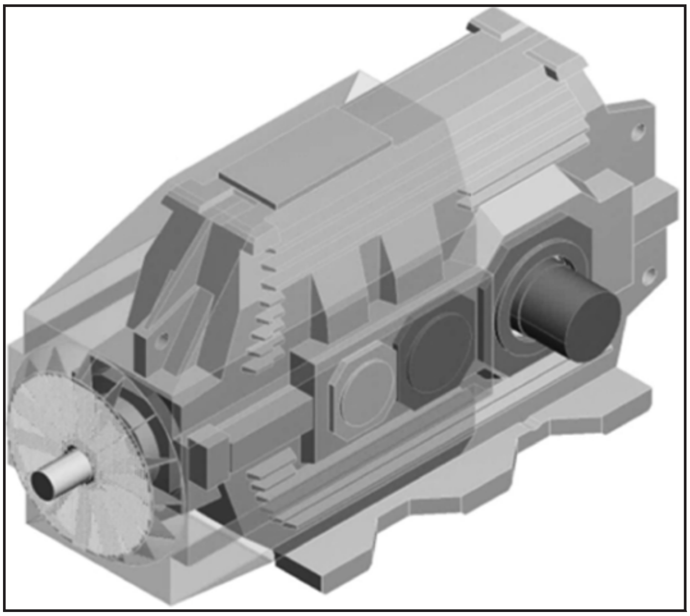

Figure 8 3-D model of optimized radial fan with long cover.

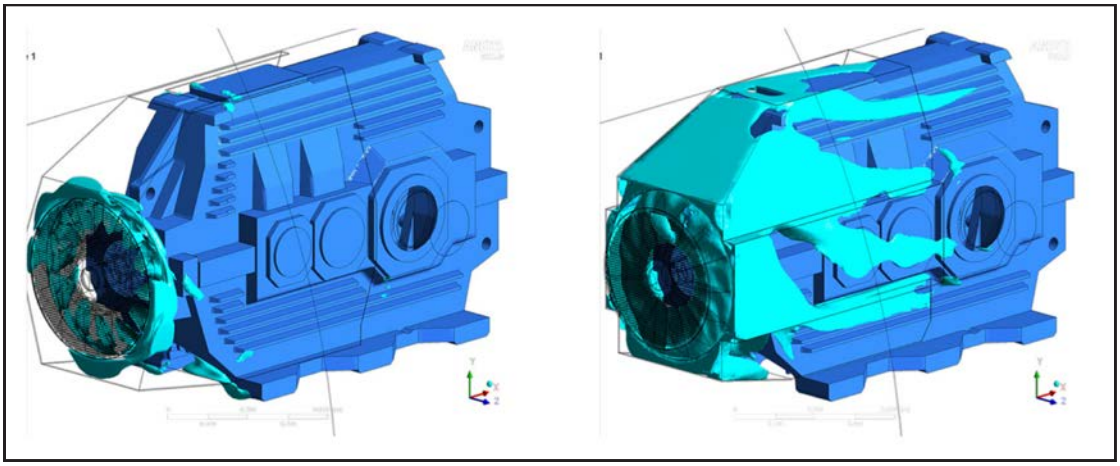

Figure 9 Concept 1 flow conditions for axial fan (left) and radial fan (right); the illustrated ISO surfaces show areas with air velocities higher than 15 m/s.

Optimization of the Thermal Power Limit

To optimize the heat balance of a gearbox, there are basically two possibilities. First, reduce the power losses inside the gearbox. Second, enhance the heat dissipation rate. The target of our CFD simulation is to show the consequences of changes to the airflow for the gearbox temperature; from this the optimal cooling solution shall be derived. Three things are possible to be modified, i.e. — the gearbox surface, the fan, and the cover. To modify the surface, which means to modify the gearbox housing, requires great effort and therefore only the second choice. Modifying fan and cover is much easier and faster to accomplish. To determine whether this approach is sufficient, two cover variants are investigated.

Concept 1: Long cover + radial fan. The first approach is to extend the cover (Fig. 8). The intention is to achieve higher air velocities directly at the gearbox surface — over a maximized area. The length of the cover and the flow cross-section has been modified in several iterations to find an optimum and to keep it simple. The longer cover leads to a higher resistance against the flow, and using the common axial fan failed to provide a better cooling effect; in order to compensate, an optimized radial fan has been utilized. Though radial fans produce higher pressure, axial fans normally have advantages because of their higher volume flow rate — but not in this case. Figure 9 shows air velocities for both fan types. A welcome secondary effect is that the radial fan is independent of its rotational direction, which makes use of the gear unit more flexible. The simulation shows an expected reduction of the gearbox temperature of 5 kelvin over the complete torque range (Fig. 12).

Concept 2: reversed flow direction. The produced airflow of a fan always has a rotational speed component. This air rotation results in regions with an accumulation of air due to barriers around the gearbox in circular direction. An optimal airflow, straight along the gearbox side, cannot be achieved this way. To avoid disadvantage, the direction of the airflow

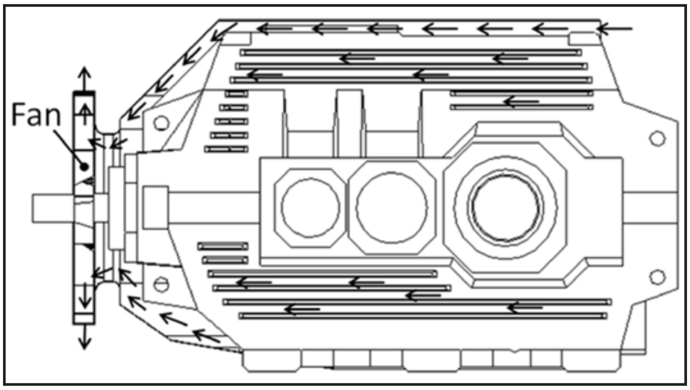

Figure 10 Schematic of concept 2.

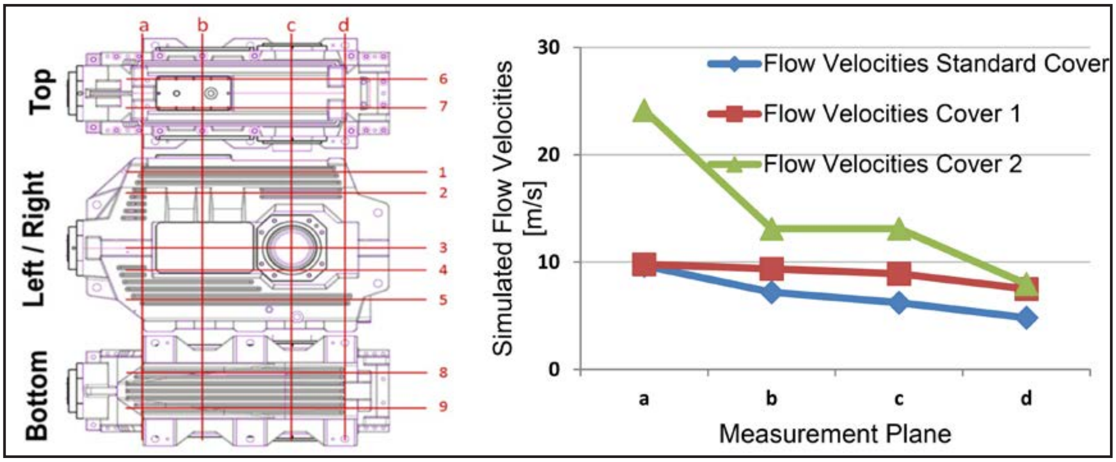

Figure 11 Increased flow velocities of different covers.

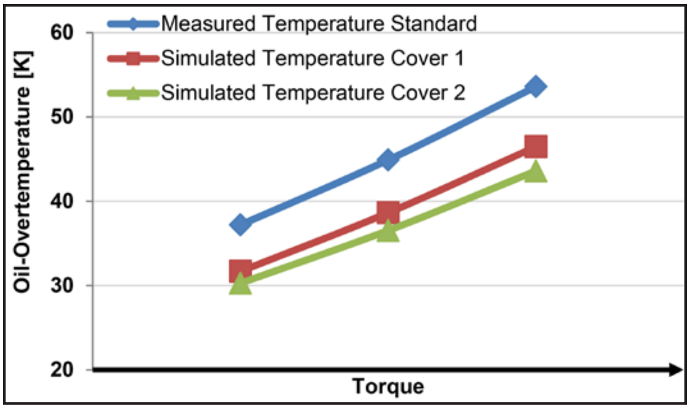

Figure 12 Simulated temperature for concept 1 and concept 2.

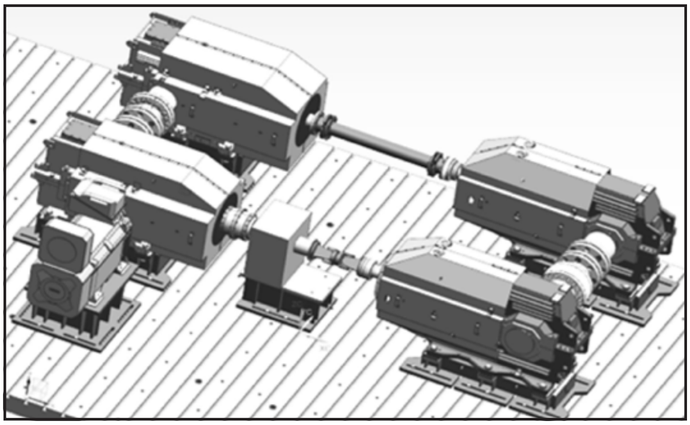

Figure 13 Test bench.

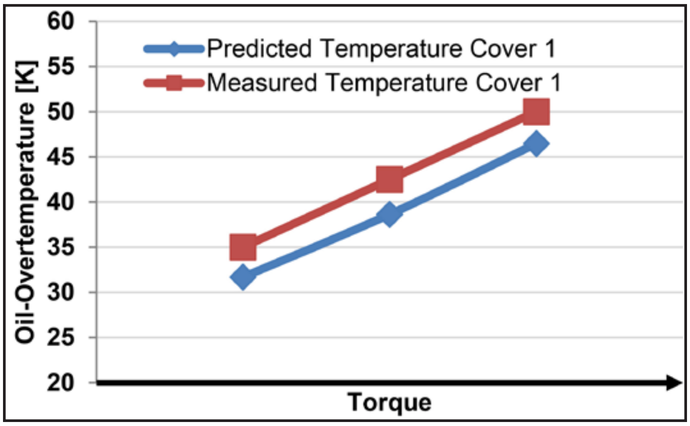

Figure 14 Comparison between prediction and measurement—concept 1.

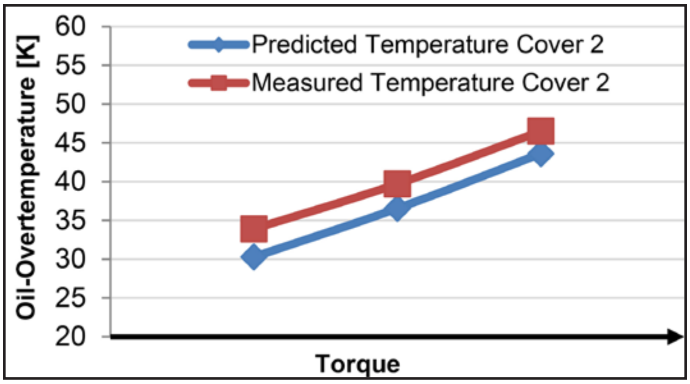

Figure 15 Comparison between prediction and measurement—concept 2.

can be reversed (Fig. 10).

This air-suctioning concept implicates higher demands on the guidance of the air. The cover has to overlap the housing over the complete length. Only directly beneath the cover is the airflow effective, as it relates to the desired cooling effect. A narrow gap between cover and housing surface results in a high pressure drop, but also leads to a good and homogenous flow.

The resulting air velocities are shown (Fig. 11). In (Fig. 11, left) the measurement points are marked. In the length direction, the gearbox is divided into four sections—a, b, c, and d.

In each section 14 measurement points have been defined (1-5 left and right; 6-7 on top; 8-9 under bottom). Not every point was reachable for the anemometer, but most of the simulated velocities have been successfully validated for the standard cover and long cover.

Figure 11 shows the simulated, averaged air velocities along the gearbox. The highest velocities are, in all cases, near to the fan directly in front of the gearbox. At this location there is also the highest heat production, due to the fast-rotating input shaft. Concept 2 shows an air velocity in this region that is more than two times higher compared to standard solution and concept 1. The over-all averaged velocity for the standard solution is 7 m/s; for the concept 1 it is 9 m/s; and for concept 2 it is 14.5 m/s.

The resulting, simulated oil-overtemperatures (compared to the environment) are shown (Fig. 12). Concept 2 reduces the oil temperature by 7 kelvin. The expected reduction is relatively small compared to concept 1; the explanation for it can be found in Figure 2. The major cooling effect is already reached with velocities from concept 1.

To validate the predicted enhancements of the simulations, prototypes of the designed solutions have been built and tested on a test bench.

Validation of Simulation Results

The test bench. A test bench has been set up in a square, containing two pairs of back-to-back connected gearboxes loaded with a controlled, hydraulic torque motor (Fig. 13). Torque sensors were placed at the input and output shaft of the test gearbox in order to facilitate detecting the input torque as well as the power losses. An intermediate shaft of a non-test-gearbox was used to drive the system. Several sensors had been placed to determine the temperature of the environment, oil, and bearings. Additionally, air velocities have been measured and infrared pictures taken.

Test Results

Figures 14 and 15 show the expected oil over-temperature (related to environment) from the simulation and the measured values from the test bench.

The simulated values were derived from a calibrated CFD simulation. The remaining error of constant 3 kelvin is acceptable and can be explained by inaccuracy of the simulation model and uncertainty of the measurement.

Comparison of Improvements

A comparison of the predicted and the measured oil temperatures shows two things. The simulation results are reliable and the elaborated cooling concepts are very effective. Gearboxes with the new cooling concepts maintain significantly lower temperatures under the same operating conditions. Figure 16 shows the measured temperatures of the new cooling concepts in comparison to the conventional, standard solution. The standard solution, with its shorter cover and axial fan, reaches the highest temperatures. Cooling concept 1, with longer cover and optimized radial fan, lowers the temperature by 3.5 K. Concept 2, with long, tight-fitting cover and air-suctioning radial fan, lowers the temperature by 7 K compared to standard solution.

The corresponding effect on the thermal power limit is shown (Fig. 17); the thermal capacity is shown for three typical operation speeds, with the standard thermal power limit as 100% reference. The new cooling options result in considerably higher thermal capacities. Concept 1 is up to 20% better than the standard solution; even better, concept 2 up to 33%.

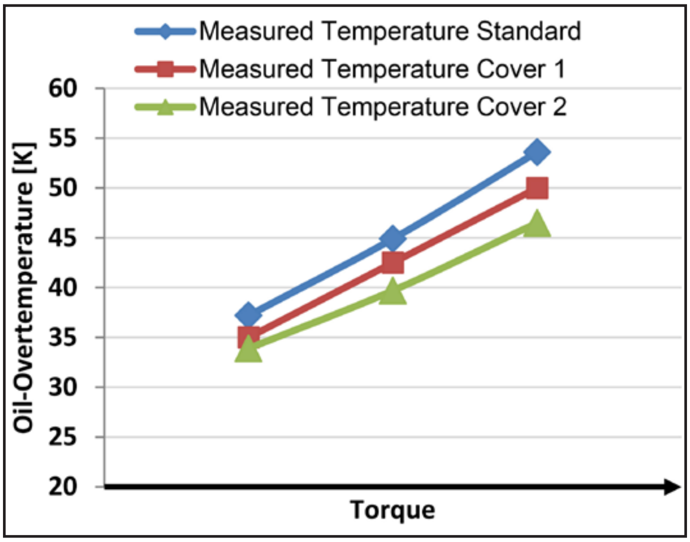

Figure 16 Comparison between temperatures with different covers.

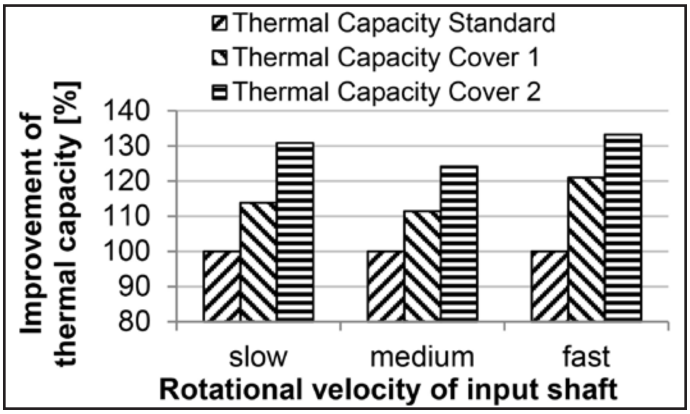

Figure 17 Improvements in thermal capacity.

For more information.

Questions or comments regarding this paper?
Contact Dr. Bjorn Bauer at *bjoern.bauer@flender.com*

Conclusion

The studies on hand have shown that it is possible to simulate the complex, thermal behavior of a gear unit with good accuracy and enables improvement of heat dissipation. Basically two different approaches have been investigated. Longer covers and more effective fans are the focus here. These simple but purposeful changes to the designs of the fans and the air guiding covers lead to significantly higher thermal power limits — up to 33% in the investigated example. These power limits have been validated on a test bench where the reliability of the computational fluid dynamics simulation technique has been reliably demonstrated. CFD is a powerful tool enabling prediction of a gearbox's temperature under consideration of the oil distribution inside and the airflow around the gearbox. Improvements demonstrated here for one type of gearbox can be transferred to several products. At Siemens Mechanical Drives, new and revised products are already profiting from the use of CFD. **PTE**

References

1. N.N., Gears — Thermal Capacity; Part 2: Thermal Load-Carrying Capacity; ISO Copyright Office Case Postale 56; CH-1211 Geneva 20.
2. Mauz, W. "Hydraulische Verluste von Stirnradgetrieben bei Umfangsgeschwindigkeiten bis 60 m/s," Diss. Universität Stuttgart, 1987.
3. Verein Deutscher Ingenieure: VDI-Wärmeatlas; 10. Auflage; Springer-Verlag, Berlin, 2010.

Björn Bauer, Dr.-Ing., is a gearbox specialist with focus on development of wind turbine and industrial gearboxes at Flender GmbH. His background is focused on drive technology, having received his Ph.D. in 2010 for research on smart actuators in drivetrain elements like gearboxes and couplings. Beginning in 2010 he was heading different groups in the area of gearbox development for wind turbines at Bosch Rexroth (2010–2014). Bauer later headed the department of product development for industrial gearboxes at Flender GmbH (2014–2018) — a Siemens Company with focus on the development of standard and application-specific gearboxes.

Ralf Hambrecht, Dr.-Ing., is head of drive systems at Winergy. After studying mechanical engineering at the Friedrich-Alexander University in Erlangen-Nürnberg, he worked at the Chair of Engineering Design and received a PhD for his research activities on wear prediction in roller bearings. Further on, Hambrecht worked for Schaeffler as head of bearing and vehicle applications testing, for Senvion as head of engineering for mechanical design, and for ZF Windpower as CTO.

Andreas A. Kube, Dipl.-Ing., received his diploma (2005) in mechanical engineering with a focus on IT at the RWTH Aachen University. From 2005 to 2011 he developed simulation software for machine dynamics at the RWTH Aachen Institute for Machine Elements and Machine Design (IME), where he led the group machine dynamics and software development. In 2011 he joined Siemens Mechanical Drives as a simulation engineer. Until 2018, he was responsible for setting up and managing the system engineering department. Today Kube works as a PLM solution architect at Flender GmbH.

Simon Becka, M.Eng., received his bachelor of engineering (2009) and master's degree (2012) in mechanical engineering at the University of Applied Sciences Aachen. From 2009 to 2012 he was a design engineer at Assmann Ingenieurdienste Aachen. He was project manager for DTC- and PLM-projects at Flender GmbH (2015 to 2017) and lecturer at the FOM University (2015 to 2018). Since 2012 he has worked a calculation engineer (FEM and CFD) at Flender GmbH and specializes in simulating the thermal behavior of gear units. By simulating flows inside and outside the gearboxes, Becka is permanently focused on trying to increase their thermal power density.