Reduction of hot oil carry-over in high speed running turbo application bearings

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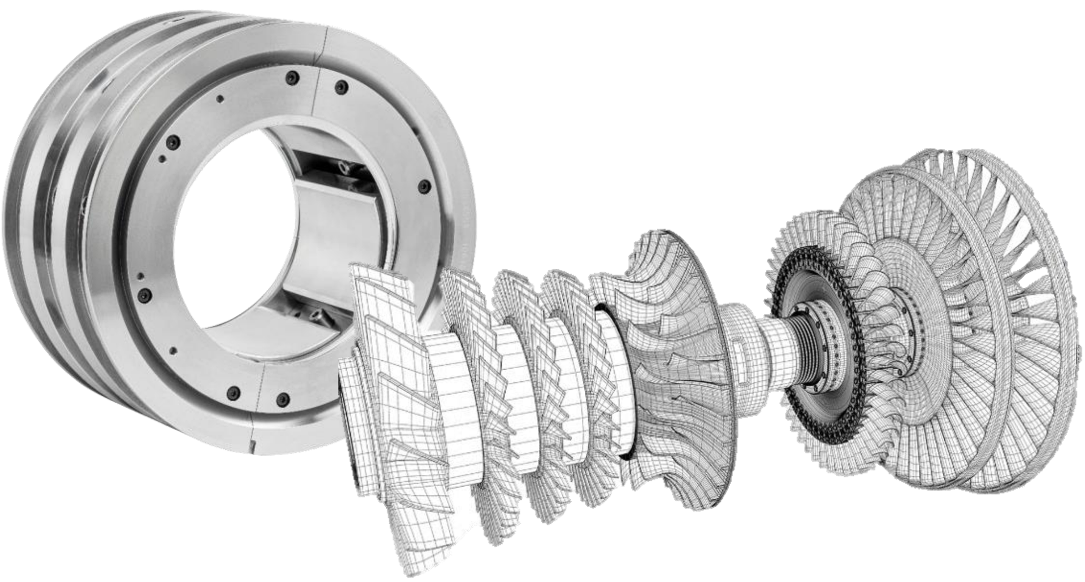
Tilting pad journal bearings are used in turbo machines like turbo compressors, turbo gears, gas turbines and steam turbines. By increasing the power density, the applied loads and velocities have been increased simultaneously over the last decades.

To overcome conservative operation limits it is helpful to reduce the oil film temperatures by certain design modifications. Especially the hot oil carry-over is reduced when certain design measures are taken to prevent large parts of the hot oil coming out of one pad to reach the next pad, so that the fresh and hot oil are mixed as little as possible.

The article is based on the paper “Reduction of hot oil carry-over in high speed running turbo application bearings” presented at the 12th EDF / Prime Workshop, Futuroscope [1].



1 Limits of operating conditions

Tilting pad bearings are usually used in high speed running rotors and perform with higher stability compared to multi-lobe bearings and better oil distribution in the loaded area than flooded bearings. The limitations in regard to load and speed are given by the minimum lubrication film thickness and the maximum temperature of oil film and tilting pad surface.

The maximum surface temperature rises over a non-allowable value (e.g. 130°C) when both specific load and speed are increased (far) above the mentioned values (see Fig 1).

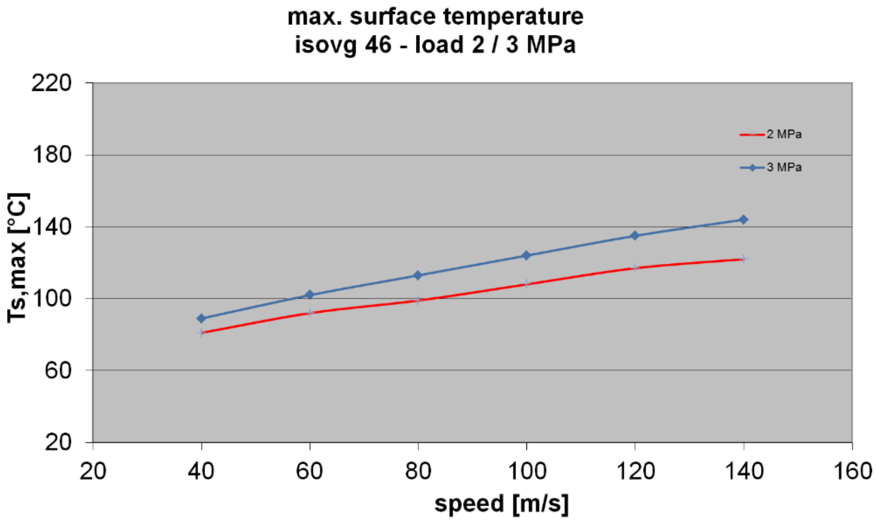


Fig 1 – Example for increase of max. surface temperature of sliding pad related to circumferential speed

A significant reduction of the maximum pad temperature is one important option to reduce the bearing and subsequently the shaft size of the rotor, if other boundary conditions like rotor masses and natural frequencies will allow this measure.

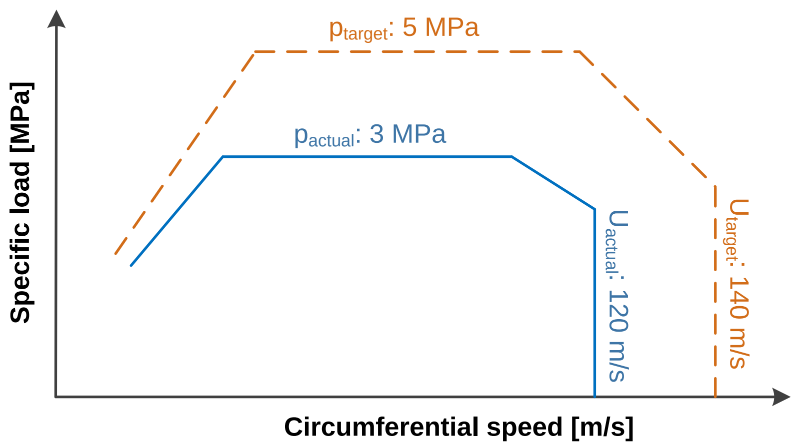


Fig 2 – Combination of specific load and circumferential speed of a tilting pad bearing application – usual limits may be shifted in future applications

2 Options for optimization

It is common practice to accommodate design features to the present application. There are geometric options like:

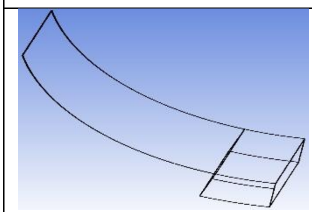
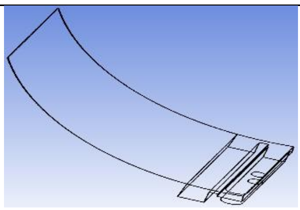
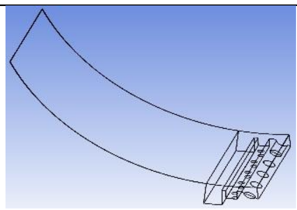
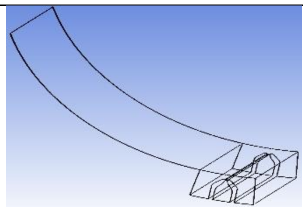
- Size of diameter and width
- Number of pads
- Geometry of pads
- Other geometric parameters

but also, oil supply measures, as the following:

- Design of lubrication nozzles
- Number of nozzles
- Distance of nozzle to the shaft
- Amount of oil
- Oil pressure

There are many possibilities to optimize the oil supply in a tilting pad bearing. For instance, an increase in efficiency is achieved by supplying more cool oil or when cool oil is led to the highest loaded area or the hottest spots of the plain bearing. , hot oil can be prevented from entering the gap between the subsequent tilting pad and the shaft.

Tab 1 serves as an example, representing different design options of an oil supply unit:

E0	*E1*	*E2*	*E3*
			

Tab1 – Different units for oil supply: E0: Simple oil supply (flooded lubrication); E1: Supply unit with dam and tank; E2: Supply unit consisting of oil drainage, dams, injections; E3: Supply unit consisting of dam and longitudinal slit.

3 Investigating common and future design options

To verify the efficiency of several design elements the usual technique is to run such plain bearings in radial test rigs before starting a field test or even run them in a real application. A rather modern approach is the investigation of the three-dimensional oil flow by using CFD technology (see also outputs of ANSYS CFX software in Fig 3 and Fig 4). This method is a useful tool to select the most promising design features before executing time-consuming test rig runs.

As the following example (Fig 3 and 4) shows the effect on bearing temperature and oil pressure can be simulated:

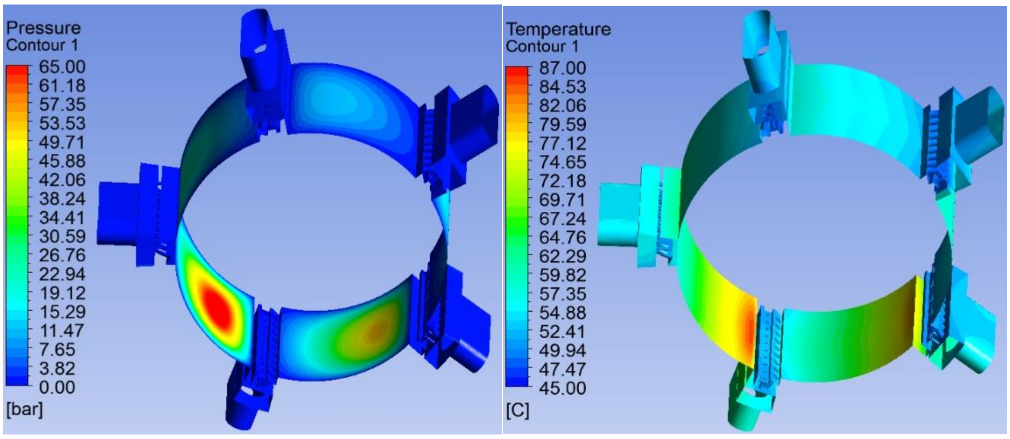


Fig 3 - Distribution of temperature and oil pressure in an oil supply pocket presented by CFX simulation

A simple, flooded lubrication unit (see version Tab 1 E0) would lead to a whirl flow within the pocket due to the Couette flow effect of the shaft rotation.

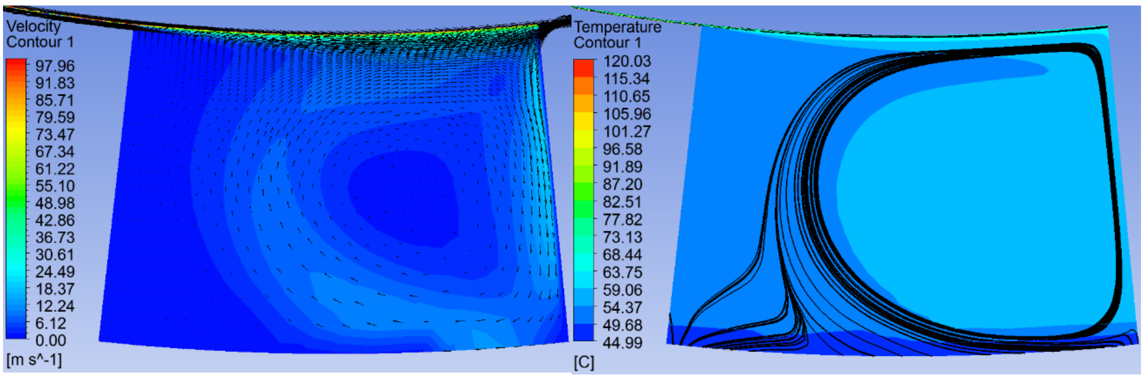


Fig 4 – Distribution of velocity and temperature in an oil supply pocket according to design E0 presented by CFX simulation

The hot oil layer which is transported away from the previous pad enters the lubrication gap of the following pad. A major portion of the fresh cool oil is leaving the bearing on both sides without reaching the lubrication gap. A better tilting pad oil feed can for instance be achieved by optimizing the oil flow through the oil supply unit. By using the latest design features a hot oil carry-over, so carrying the hot oil from lubrication gap to lubrication gap, can be reduced or even completely prevented.

For example, each pad has at least one hot oil drainage disposed in the space between two tilting pads. This represents a first oil discharge. Furthermore, a first dam and an oil injection, which is directly located behind the first dam, could be included in the design, which splashes oil onto the shaft to spray-wash the thin layer of hot oil off the shaft.

A mixture of the removed oil and the oil injected is being discharged by a second oil discharge unit.

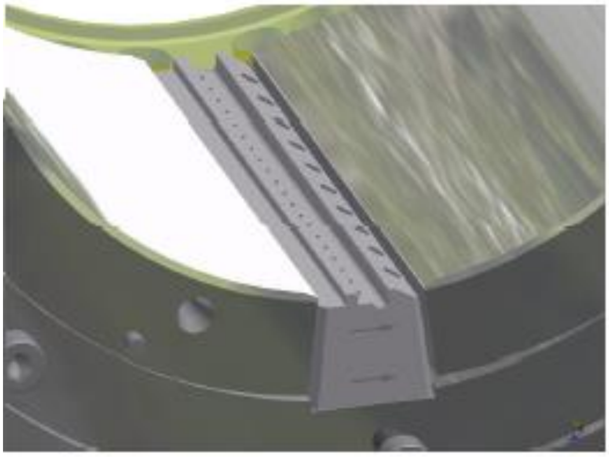


Fig 5 – Three-dimensional presentation of a tilting-pad bearing; space between pads filled by means of oil drainage, dams and oil injection unit according to design E2.

The first hot oil drainage replaces known oil injections, which can be placed in spaces between the tilting pads. Moreover, by using hot oil drainage the space between the two adjacent tilting pads is filled so that the occurrence of a large oil supply in that area is hindered. Consequently, the unnecessary heating of the oil is prevented and thus performance of the bearing is improved.

A hot oil drainage can be installed in a housing ring on which the tilting pads are fixed and does not restrict the tilting motion of the individual tilting pads. Care must be taken, of course, that the first dam does not come into contact with the shaft. For this, the first dam has to have a clearance that is at least equal to the maximum misalignment to the shaft. Injection temperatures of the oil are e.g. around 40 to 50 C° In individual cases, injection temperatures of 55 to 60 C° may occur. A lower temperature of the injected oil and a cooling of the shaft often leads to a higher efficiency of the tilting pad bearing.

By means of the oil injection, the last residual oil on the shaft, which is dragged over from the previous lubrication gap, is broken and detached from the shaft. It then forms a mixture with the freshly supplied oil. Since a portion of the warm oil was already intercepted by the first dam, the detached hot oil from the shaft contributes to the mixture. The temperature of this mixture is therefore substantially determined by the temperature of the injected fresh oil. However, the hot oil drainage also has a second oil discharge, through which a portion of the mixture from the hot oil detached from the shaft and the injected cool oil can be discharged again.

This has several advantages. First, the portion of hot oil that comes from the previous tilting pad, is effectively prevented from entering the next lubrication gap. In addition, the oil discharge could allow more fresh oil injection. The ratio between the injected cool oil and hot oil released from the shaft is further shifted in favor of the fresh oil. Hence, the average temperature of the mixture continues to decrease, so that a more effective cooling of the tilting pad bearing is achieved by the oil discharge.

This design of the oil discharge/drainage unit should ensure that only a very small part of the warm oil of the previous lubrication gap can enter the next lubrication gap. This might be achieved by the combination of the various hot oil drainage components.

The space between two adjacent tilting pads can almost completely be filled by the drainage unit and fluid losses can be minimized.

Using a second dam offers the option that the mixture of the injected fresh oil and the heated oil can be, at least partially discharged and is not used for lubrication within the next lubrication gap. Thus, a hot oil carry-over to the subsequent lubrication gap is almost completely prevented.

Fig 6 – Examples of oil supply units consisting of oil drainage, dams and oil injections. E1: Supply unit with dam and tank; E2: Supply unit consisting of oil drainage, dams and injections.

The necessary lubrication oil of the following lubricating gap is provided by the additional fresh oil supply. Subsequently, this one can work with a lower pressure. A more laminar flow of the lubricating oil into the gap can be achieved, thereby it also prevents losses caused by friction and turbulence.

The oil injector in the axial direction might contains several nozzles. By this, the oil is injected perpendicular to the shaft and the residual hot oil film on the shaft can be reliably broken and splashed off. Another phenomenon which can be stated by looking at the following figure 7, is that the hot oil from the previous pad is being prevented in streaming through the gap between dam and shaft due to the back flow of the fresh oil (see Fig 7).

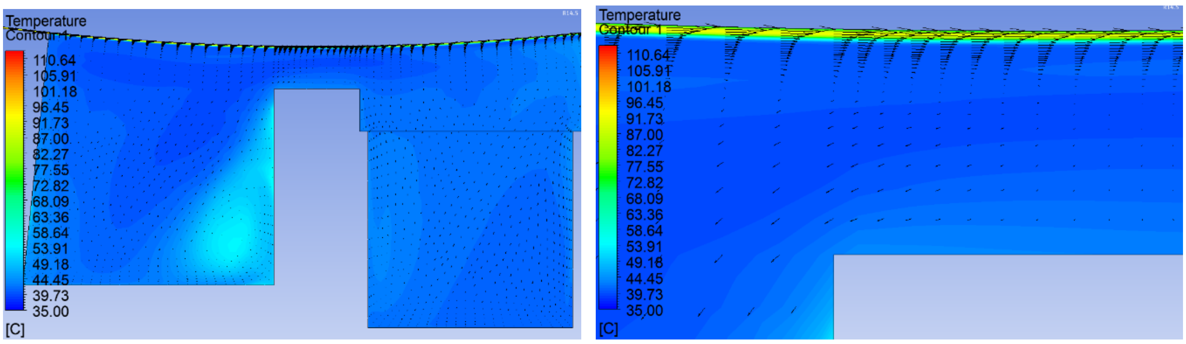


Fig 7 – Distribution of temperature and oil flux vectors in an oil supply unit according to design E1. Flow back of fresh oil between dam and shaft towards previous pad.

The advantages of design E1 can be combined with separated oil injections e.g. by means of two separated oil injections consisting of a row of nozzles. The first oil injection represents the warm oil reduction (splashing off the hot oil) and the second represents the fresh oil supply (see Fig. 8).

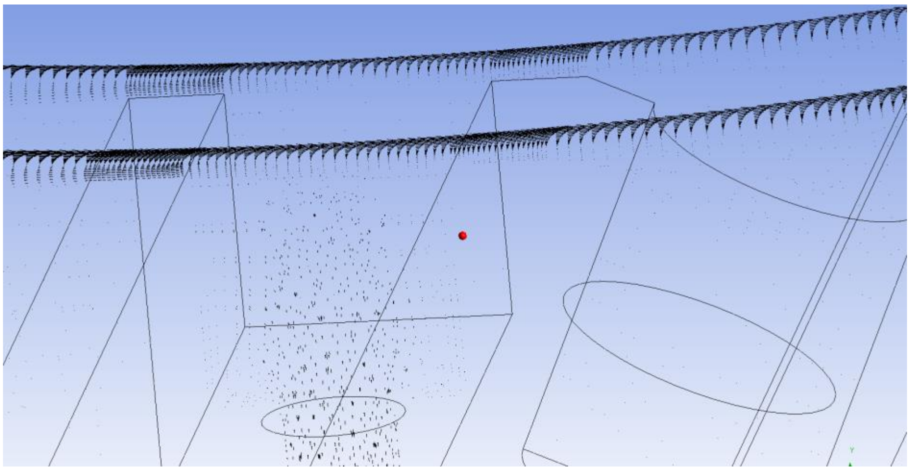


Fig 8 – Distribution of oil flow in an oil supply unit according to design E2. Separation of flow back of fresh oil by means of the first oil injection.

Attention has to be taken in regard to the distance of the nozzles. This distance should not be greater than e.g. one or two millimeters depending on the size of the bearing. Otherwise the single oil sprays are focused on a very limited area which cannot essentially increase the ratio of fresh and hot oil before the leading edge area (see Fig 9).

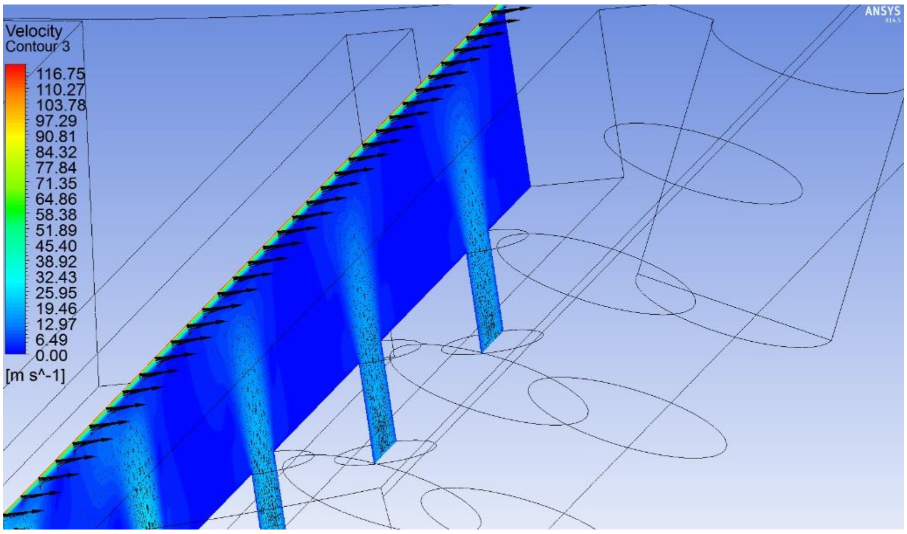


Fig 9 – Local effectiveness of oil nozzles over the width of the pad.

A similar behaviour of the back flow of the fresh oil can be seen for an oil supply unit with longitudinal slit according to design E3 (see Fig 10).

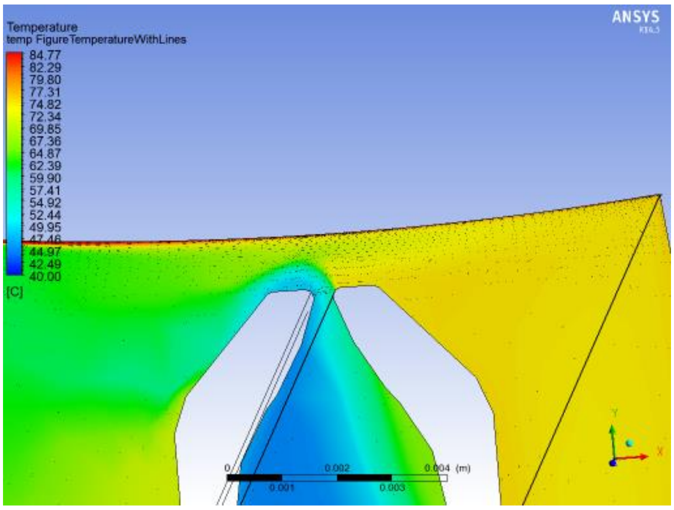


Fig 10 – Hydraulic back flow of fresh oil in an oil supply unit with longitudinal slit according to design E3.

4 Combining simulation and calculation tools

One of the main questions now is: How much can the mentioned design measures decrease the maximum temperature, or increase the minimum film thickness?

For calculating the relevant data in tilting pad bearings, such as minimum film thickness or temperature of lubrication film, Miba Industrial Bearings uses a state-of-the-art software program. It has been developed by using the latest hydrodynamic theory knowledge. The mathematical model is based on the Reynold's and the energy balance equation, serving as a simplification of the Navier-Stoke's equations.

$$\frac{\partial}{\partial \varphi}\left(\frac{H^3}{12\ \eta_P^*\ K_x}\frac{\partial \Pi}{\partial \varphi}\right)+\frac{\partial}{\partial z}\left(\frac{H^3}{12\ \eta_P^*\ K_z}\frac{\partial \Pi}{\partial z}\right)=\frac{1}{2}\frac{\partial}{\partial \varphi}(\rho^*\ f_c\ H)+\frac{\partial}{\partial \tau}(\rho^*\ H) \qquad (1)\ \ .)$$

$$\underbrace{c\ \rho\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)}_{\text{Specific change of internal energy}}\ldots \qquad (2)$$

$$=\underbrace{\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)}_{\text{Specific exchange by heat conduction}}+\underbrace{\Phi}_{\text{Dissipation}}$$

The model uses a finite volume method and calculates three-dimensional arrays of pressure, temperature and oil flow. It offers furthermore a user-friendly input mask and an individual post-processing

One approach in further developing the performance of any oil flow within a tilting pad bearing is to include physical results from the simulation software (e.g. CFD from ANSYS) and transfer it to the software program. Following, the model for the mixture of lubrication oil between adjacent pads can be optimized. The so-called warm-oil-reduction factor may be used for describing the efficiency of the oil supply. This usually depends on the operating conditions like oil viscosity, load, speed, oil supply design, oil supply pressure and others. In common industrial applications e.g. bearings for gas and steam turbines the factor varies somewhere between app. 30% and 60%.

The factor of warm oil reduction might be increased for instance by the above-mentioned design options. When looking at the results from the calculations, it can be stated that a remarkable decrease of peak temperature occurred when the warm oil reduction factor is increased from e.g. 30% to 90% (see Fig 11).

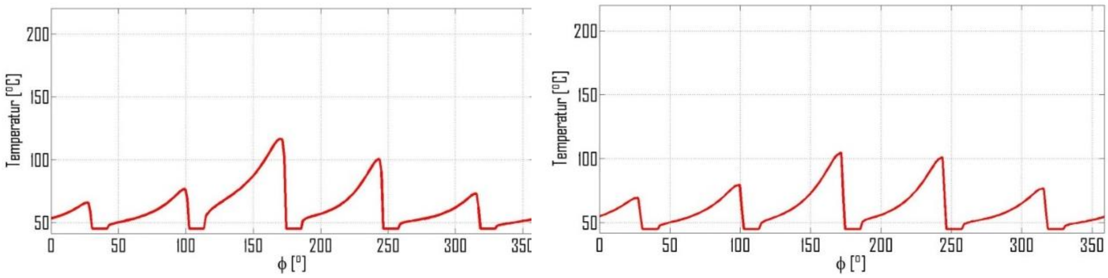


Fig 11 - Temperature of lubrication film pressure calculated by Miba with warm oil reduction of 30% and with 90%. Operating conditions: n = 19,098 1/min. F = 17,280 N. So = 0.142.

5 Conclusion

Reducing warm oil and minimizing the hot oil carry over effect within tilting pad bearings is a powerful method to increase efficiency in high speed running power train units. To investigate different oil supply unit designs, given practice is to use test rig trials. Before losing time by testing unsuccessful design versions one could use simulation technology. By combining this method with calculating tools for bearing characteristic conditions like minimum lubrication film or maximum oil film (or pad surface) temperatures, it is possible to receive results and decrease the number of test trials needed.

One of the outcomes of the bearing calculations in combination with the design simulations is that the design characteristic of the oil feed unit plays a decisive role in regard to the fresh and hot oil distribution, especially the number of oil nozzles and distribution thereof. The distance of the nozzles should not be greater than a few millimeters. Otherwise the single oil beams are focused on a very limited area which cannot sufficiently increase the ratio of fresh and hot oil before the leading edge area. Instead of using several nozzles (according to design E2) it might be advantageous under some conditions to use a kind of oil tank (according to design E1).

As a conclusion it can be stated that the concept of simulation and calculation will be able to evaluate the oil supply efficiency and enables the designer to optimize both, the oil drainage and injection.

For more information please contact Miba Industrial Bearings. Mibg_sales@miba.com

Miba Industrial Bearings produces hydrodynamic bearings and labyrinth seals for use in critical centrifugal equipment, such as turbines, compressors, gear boxes and industrial pumps. Established over 100 years ago; Miba Industrial Bearings provides a center of excellence in bearing design, repair, troubleshooting and analysis as well as reversed engineering solutions.

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Thilo Koch studied mechanical engineering at the university in Clausthal, Germany. He specialized in dynamic mechanical systems, vibration theory (rotor dynamics) and tribology (plain bearings). He gained 35 years of experience in the traditional slide bearing market as manager for the R&D, design and technical sales department. He is an expert in exploring new market opportunities and developing new products for examples for wind energy, steel work or automotive applications.

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After graduating as an engineer at the Technical University of Clausthal, Germany he started at the Institute of Tribology and Conversion Machinery as a scientific assistant, teaching and researching on hydraulics for oil and gas and turbomachinery as well as tribology and plain bearings' hydrodynamics. In 2010 having graduated with doctoral degree, he started working in the R&D, application simulation and calculation department for Zollern Plain Bearing Technology and then joined Miba Industrial Bearing in 2019.

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