View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Purdue E-Pubs

Purdue University
Purdue e-Pubs

International Compressor Engineering Conference

School of Mechanical Engineering

2018

Rolling Bearings Lubricated With Refrigerant

Rudolf Hauleitner
SKF Oesterreich AG, Austria, rudolf.hauleitner@skf.com

Guillermo E. Morales-Espejel
SKF Research & Technology Development, The Netherlands;Université de Lyon, INSA-Lyon, France, guillermo.morales@skf.com

Ralph Meeuwenoord
SKF Research & Technology Development, The Netherlands, ralph.meeuwenoord@skf.com

Magnus Arvidsson
SKF Application Competence Centre, Sweden, magnus.arvidsson@skf.com

Follow this and additional works at: https://docs.lib.purdue.edu/icec

Hauleitner, Rudolf; Morales-Espejel, Guillermo E.; Meeuwenoord, Ralph; and Arvidsson, Magnus, "Rolling Bearings Lubricated With Refrigerant" (2018). *International Compressor Engineering Conference.* Paper 2556.
https://docs.lib.purdue.edu/icec/2556

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at https://engineering.purdue.edu/Herrick/Events/orderlit.html

Rolling Bearings Lubricated With Refrigerant

Rudolf HAULEITNER[1]*, Guillermo E. MORALES-ESPEJEL[2,3], Ralph MEEUWENOORD[2], Magnus ARVIDSSON[4]

[1]SKF Product Development, Steyr, Austria
rudolf.hauleitner@skf.com

[2]SKF Research & Technology Development, Nieuwegein, The Netherlands
guillermo.morales@skf.com
ralph.meeuwenoord@skf.com

[3]Université de Lyon, INSA-Lyon, CNRS, LaMCoS UMR5259, F69621, France

[4]SKF Application Competence Centre, Gothenburg, Sweden
magnus.arvidsson@skf.com

* Corresponding Author

ABSTRACT

Oil-free operation, high overall efficiency and low environmental impact are main drivers in the refrigeration compressor industry. The use of pure refrigerant for bearing lubrication supports these industry trends and is a reliable alternative to other oil-free solutions such as magnetic bearing systems. This paper describes the pure refrigerant lubrication technology for rolling element bearings. It is shown that refrigerants are capable of forming film thickness in the concentrated contact. Film thickness measurements on a ball on disk setup with one low (R-1233zd) and one medium vapor pressure (R-1234ze) refrigerant are presented. Further, functional bearing tests on a dedicated pure refrigerant lubrication test rig have been performed with the refrigerants R-134a and R-1233zd. The results in relation to friction and power consumption measurements in bearings are reported and underline the potential of this technology. At the same time, it is attempted to derive valid operating limits.

1. INTRODUCTION

Lubrication is a key component for a robust, long-lasting operation of rolling element bearings. Due to the important influence of lubrication conditions on bearing performance, the bearing cavity is often sealed or isolated from the rest of the application, so that clean and reliable lubrication conditions are obtained. The majority of these bearings are lubricated by oil or grease. In some applications, such as compressors, it is not feasible to separate the working fluid and the lubricant completely. The bearings are either directly or indirectly (dilution of the lubricant by the working medium) affected by the process medium.

One example of such systems are refrigeration compressors. Rolling element bearings in this application are traditionally lubricated by oil. But since the oil is exposed to the refrigerant, it will be diluted to a certain extent. This dilution of the oil with refrigerant has a significant impact on the lubricating capabilities of the mixture. As refrigerants are poor lubricants compared to oils, they negatively influence the lubrication regime. Important aspects of the rheological behavior are the viscosity and the piezo-viscosity, which are drastically reduced by the refrigerant content in the mixture. Also, the chemical properties of the refrigerant may affect the performance of the rolling element bearings. With new developments in the refrigerant market, the lubrication conditions of oil-refrigerant mixtures are subjected to permanent adjustments. Combinations of some oils and refrigerants that are being developed to reduce their environmental impact can lead to substantially increased dilution rates compared to mixtures used in the past. In such cases, it may be necessary to implement special bearing technologies, such as surface treatments, different bearing materials, the use of ceramic materials for the rolling elements or coatings (Morales-Espejel *et al.*, 2017).

An alternative approach is to remove the oil from the system completely. Oil-free technology is often related to reduced maintenance, higher system efficiency and smaller environmental footprint (Morales-Espejel *et al.*, 2017). By applying the pure refrigerant lubrication (PRL) bearing technology, the traditional oil lubrication system can be removed and the bearings are lubricated only with refrigerant (Morales-Espejel *et al.*, 2001). This removes the challenges related to mixtures of fluids - on the chiller side (by efficiency reduction due to oil contamination of the working fluid) as well as on the lubrication side (by the lubricant diluted with refrigerant). The challenge which pure refrigerant lubrication imposed on rolling bearings was overcome by a special bearing development.

Extensive work has been done in the past to study the properties of oil-refrigerant mixtures in elastohydrodynamic lubrication (EHL) conditions (Akei *et al.*, 1996, Akei and Mizuhara, 1997, Masayoshi and Takashi, 2000, Yamamoto *et al.*, 2003, Jonsson and Lilje, 1998, Bair *et al.*, 2017, Bair, 2016). Also, the behavior of oil-refrigerant mixtures has been investigated in rolling bearing conditions (Jonsson, 2001, Davis *et al.*, 1992, Tuomas, 2006, Jonsson and Hansson, 1998). When it comes to PRL, important work has been done to assess the critical lubrication properties of some refrigerants, for instance, viscosity and pressure-viscosity and pressure-density in EHL conditions (Jacobson and Morales-Espejel, 2006, Laesecke and Bair, 2011, Vergne *et al.*, 2015, Tuomas and Isaksson, 2006), and on traction measurements (Morales-Espejel *et al.*, 2014). No traction results have been reported in complete bearings.

In the current paper, after making a short review of the rolling bearing technology in refrigeration compressors, film thickness measurement results of R-1234ze will be presented and compared with previous measurement results of R-1233zd. Friction torque measurements in bearings with R-1233zd and R-134a will be reported with the use of a newly in-house developed test rig for rolling bearings in PRL conditions. The observations from this test rig are further used to define operating limits for the performance of PRL bearings.

2. PURE REFRIGERANT LUBRICATION

In the 1990s bearing tests were carried out to investigate the dilution of lubricant oils with refrigerants and the consequences in bearing performance and life (Wardle *et al.*, 1992, Meyers, 1997). It was found that conventional all-steel bearings started to exhibit signs of inadequate lubrication at dilution levels of 20 % to 30 %. This led to the investigation of alternative bearing designs and materials to improve bearing operation and life under these poor-lubricant conditions. The studies showed that it was difficult to find a limiting dilution ratio for hybrid bearings that have steel rings and ceramic balls made of bearing grade silicon nitride. Finally, specialized hybrid bearings were run in pure refrigerant with no traces of oil, and it was found that following the feasibility test, the bearings were in as-new condition. This was a crucial test result – one that opened the possibility of using refrigerant as a lubricant for special rolling bearings (Morales-Espejel *et al.*, 2017). This technology is in use by some compressor manufacturers and is catching up importance with the rest of the refrigerant compressor industry, especially because it offers relative simplicity and good value compared with other alternative technologies like magnetic bearings. In the following sections of the present paper more technical aspects of the tribology of PRL conditions in hybrid bearings are given, such as film thickness conditions and friction results in rolling bearing conditions. Some aspects of this work could not be possible without the in-house development of a dedicated PRL test rig for rolling bearings.

3. FILM THICKNESS IN PRL CONDITIONS

One fundamental purpose of the lubricant in a bearing is the separation of the raceways and the rolling elements. Several studies (Habchi *et al.*, 2011, Morales-Espejel *et al.*, 2014, Vergne *et al.*, 2015) have shown that refrigerants could actually form an elastohydrodynamic lubricant film. The thickness of this film depends on the operating parameters, such as load, speed, the geometric parameters and the lubricant properties. Especially, the viscosity, the piezo-viscosity and the compressibility play a major role. When these properties are known, the film thickness can be calculated using an appropriate model (Habchi *et al.*, 2011, Morales-Espejel *et al.*, 2014).
Understanding to what extent a refrigerant can form a lubricating film in heavy loaded rolling contacts, as oil

does, has been a crucial development in PRL technology. Rolling bearings are lubricated by means of the elastohydrodynamic lubrication (EHL) mechanism (Akei *et al.*, 1996). In other words, since rolling bearings rely on heavily loaded contacts, under normal lubrication conditions the lubricant shows an increase of viscosity with rising pressure, at the same time the elastic deformation of the steel bodies takes place to accommodate the lubricant. These two mechanisms are responsible for the build-up of a thin lubricating film of less than one to a few microns thick in EHL conditions that is able to separate the contacting bodies in a normal oil-lubricated situation. However, until recently it was unknown whether some of the refrigerants used have this property of piezo-viscosity (increase of viscosity with pressure) and how much the roughness of the bodies and its elastic deformation will affect the separation. Now, having a film thickness of only a few decades of nanometers, in almost all application conditions a rolling bearing in PRL will work most of the time under mixed lubrication conditions. Therefore, the proper design and manufacture of the raceway roughness is crucial to the robust operation of the contacts by allowing elastic deformation and film build-up (Morales-Espejel *et al.*, 2013). This effect combined with the excellent tribological properties of hybrid bearings working in poor lubrications conditions (Brizmer *et al.*, 2015, Vieillard *et al.*, 2016) makes this technology work.

3.1 Pressure-Viscosity Coefficient

Like with oils, the viscosity of refrigerants increases under the very high pressure developed in the contact areas between the rolling elements and the bearing raceways. The increase is not as significant as with lubricating oils ($\alpha_{ref} \approx 4 - 6\, GPa^{-1}$, $\alpha_{oil} \approx 15 - 20\, GPa^{-1}$), but it is sufficient to produce a very thin lubricant film. In conventional all-steel bearings, this thin film would be inadequate for lubrication, but the ceramic (Si_3N_4)/steel material combination and other features of the newly developed hybrid bearings enable reliable operation with this very thin film of refrigerant. Nowadays studies and measurements of lubricating properties of typical chiller refrigerants at bearing relevant pressure ranges are emerging (Akei and Mizuhara, 1997, Masayoshi and Takashi, 2000, Yamamoto *et al.*, 2003).

3.2 Film Thickness Measurements R-1233zd

Film-thickness measurements with various refrigerants have been carried out using a ball-on-disk tribometer equipped with film thickness measurement based on white light interferometry. Two very attractive refrigerants for the chiller industry are the low pressure refrigerant R-1233zd and the medium pressure refrigerant R-1234ze. With this set-up Morales-Espejel *et al.* (2014) have shown that indeed a lubricant film can be formed with the R-1233zd refrigerant.

3.3 Film Thickness Measurements R-1234ze

Details on the measurement procedure in general and the conditions of the measurement with R-1233zd are described by Morales-Espejel *et al.* (2014). The current paper focusses on the use of the same interferometry technique but now for the film thickness of R-1234ze. Cooling of the test chamber with liquid Nitrogen was necessary to keep the refrigerant liquid during the test. The operating conditions, material and geometry values of the test with R-1234ze are summarized in Table 1.

Table 1: Summary of approximated film thickness properties for refrigerants as found in literature

Parameter	Unit	Value
Ball diameter	mm	20.6
Contact load	N	10
Max. Hertz pressure	GPa	0.35
Disc temp. at start	°C	-5
Refrigerant temp. at start	°C	-28
Air temp. inside isolating box	°C	-25
Entrainment speed	m/s	0.1 – 0.8
Young’s modulus, steel ball	GPa	210
Poisson ratio, steel ball	-	0.3
Young’s modulus, glass disk	GPa	63
Poisson ratio, glass disk	-	0.2
Surface roughness, steel ball R_q	nm	10
Surface roughness, glass disk R_q	nm	< 1

The results of the central film thickness measurements with a steel ball and a glass disc were averaged for every speed value for R-1234ze and are shown in Figure 1. It must be acknowledged that although this figure shows film thickness values close to zero, the accuracy limit of the measurements for film thickness is around 5 nm; therefore, values close or lower than this limit should be interpreted with caution. Similar as for the measurement of R-1233zd, the figure shows that the film thickness increases with speed. For R-1234ze, the film thickness reaches values above 20 nm at speeds higher than 0.5 m/s. For the comparison between the two measured refrigerants, it is important to note that the measurements were performed at different temperatures. The film thickness of R-1233zd, which was measured at temperatures just above 0 °C, is close to 15 nm at a speed of 2 m/s.

3.4 Comparison of film thickness-model prediction versus measurements

Several fluid parameters such as the liquid density, the viscosity at atmospheric pressure and the temperature at the contact inlet are needed to calculate film thickness using the equations in literature. Therefore, a literature search was carried out to find data for this fluid. Some of this data is summarized in Table 2. Values for lower temperatures (closer to measurements) have not been found. The fluid properties of R-1234ze at -26 °C have been estimated using the Moes parameters. The last row of the table gives the values which were assumed for the calculation.

Table 2: Summary of used refrigerant properties

Refrigerant	Temp. in °C	η_0 in mPa•s	α in GPa^{-1}	ρ_0 in kg/m³	Reference
R-134a	40	0.2	5.0	Eq. from reference	Laesecke and Bair (2011) and Bair (2016)
R-1234ze	25	0.199	-	1163	Climalife Technical Data Sheet, Solstice™ ze, 2013,
R-1234ze	-26	0.366	7.8	(assumed same as at 25 °C)	Estimated with available data of other medium pressure refrigerants

Morales-Espejel *et al.* (2014) showed that the best prediction of the measured film thickness of R-1233zd with simple analytical equations was obtained with the Hamrock-Dowson equation. Therefore, this equation is also used for the comparison with the R-1234ze measurements. In Figure 1, the measured film thickness is compared with the central film-thickness equation by Hamrock–Dowson adapted for circular contact

$$H_c = 2.69U^{0.67}G^{0.53}W^{-0.067} \tag{1}$$

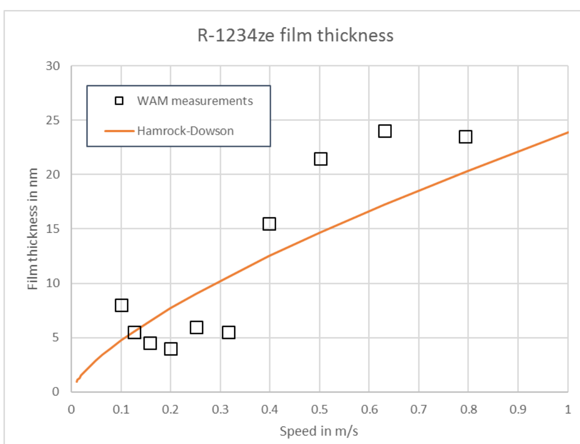

Figure 1: R-1234ze film thickness measurement using an interferometry technique in a WAM (Wedeven Associates Inc.) Tribometer compared with the calculation result

The Hamrock-Dowson equation underestimates slightly the measured film thickness once the film thickness increases above 10 nm within the measured speed range for both – R-1233zd and R-1234ze - refrigerants.

4. PURE REFRIGERANT LUBRICATION BEARING TEST RIG

A special bearing test rig has been developed, which allows the investigation of the bearing performance under pure refrigerant lubrication conditions. Figure 2 shows a picture together with a schematic of the test rig. Its main components are the hermetic bearing test head and the refrigerant supply system. The test rig was designed to withstand the conditions present in refrigerant environments and enables the investigation of typical bearing operating conditions in chiller applications. A pump drives the refrigerant through the fluid circuit and controls the pressure rise required to obtain a given refrigerant flow at a certain injection speed to pass the filter and injection nozzles. The filter before the test head limits the size of possible contamination which is feasible to obtain in industrial chiller applications. In the current setup, the stainless steel housing of the test head encloses a shaft, which is supported by two angular contact ball bearings. Each bearing has its own refrigerant injection mechanism. The refrigerant is injected into the bearing to provide cooling and lubrication. The injection conditions can be adjusted to study the influence on the bearing performance. The bearings can be subjected to various load and rotational speed combinations. A heat exchanger removes the heat emitted by the bearings and controls the refrigerant conditions. The refrigerant reservoir stores a certain quantity of refrigerant to ensure stable operating conditions and sufficient supply of liquid refrigerant to the bearings.

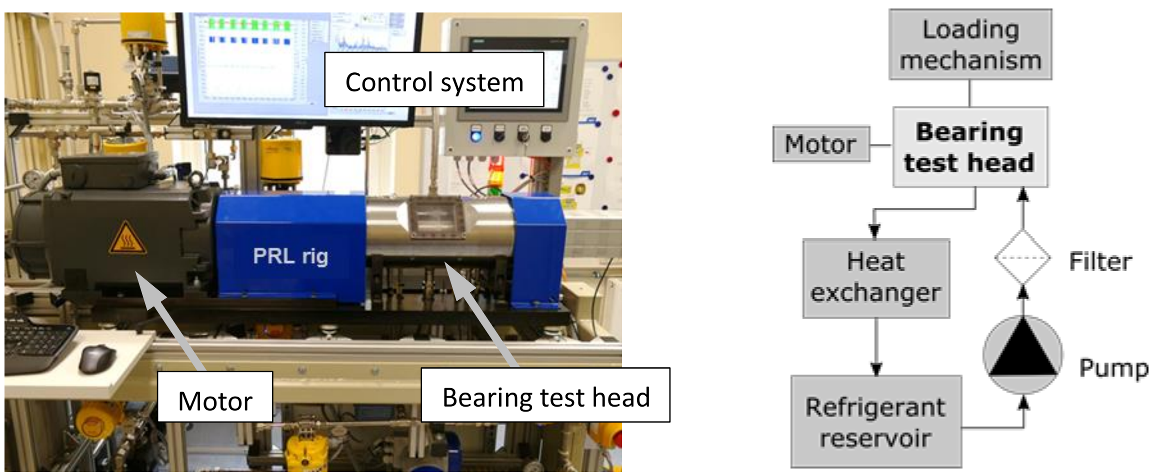

Figure 2: In-House pure refrigerant lubrication bearing test rig

4.1 Surface Appearance Of Pure Refrigerant Lubricated Bearings

Various operating conditions have been investigated on the PRL bearing test rig to verify the reliable development of a lubrication film in a complete shaft/bearing system. Figure 3a to c show optical microscopy images of the ring raceway surface in the area of the running track of the ball. The operating conditions represent typical compressor conditions. In this functional test, the surfaces were analyzed every few hundred hours to investigate the progression of the surface appearance. An indentation of a soft particle which was formed during an early stage of operation on the test rig was used to identify the same location for all the images. The refrigerant used in this test was R-1233zd.

It can be seen that the surface appearance does not change dramatically within the first few hundred hours of operation. As the honing marks are still visible after this time period, a lubricating film enabling at least mixed lubrication or even full film lubrication must develop in the contacts. A slight smoothening inside the running track can be seen and is normal during the running-in period of a bearing. The functional tests were suspended after a few hundred hours of successful operation.

It was noticed that the lightning situation during the bearing inspection has a strong impact. Figure 3d shows the same raceway section as Figure 3c and was also taken after 690 hours of running, but with a different light angle. In this case the light seems to be reflected by a layer on top of the steel surface. The development of a tribolayer was already reported by Morales-Espejel *et al.* (2014) with this refrigerant during a ball-on-disk test.

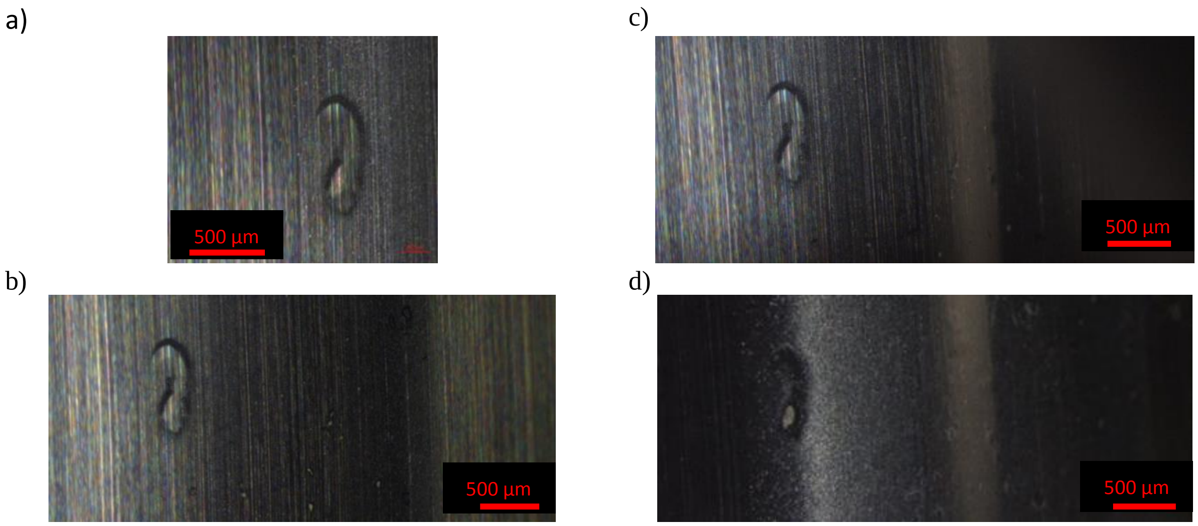

Figure 3: Running track after a) 240 hours, b) 400 hours, c) and d) 690 hours under PRL conditions

4.2 Power Losses

Accurate predictions of bearing power losses became a fundamental component of the bearing performance rating. For bearings operating in refrigerant environment, friction is even more important, since the heat generation affects the thermodynamics of the refrigerant, and can lead to evaporation and starvation. One focus area of this test rig is the assessment of the friction characteristics in a PRL bearing arrangement. The test rig has a hermetic test head containing the bearings and a shaft, which is driven through a magnetic coupling. Between the motor and the magnetic coupling a torque sensor measures the torque required to drive the coupling and the shaft inside the test head. The measurement includes losses from the magnetic coupling, the two test bearings and the rotating shaft inside the test head which can be in contact with refrigerant partly. Figure 4 shows an example of a bearing friction measurement for two different refrigerants under same operating conditions. The measurement was taken at a typical load in a compressor application. The friction values are plotted over the rotational speed of the bearing which is represented as speed value, also called "ndm"-value. The speed value is the product of the rotational speed in rpm and the bearing pitch diameter in mm and its unit is mm/min. It is considered that the measured torque is dominated by the friction of the two test bearings. This approach leads to a conservative prediction of the PRL bearing losses.

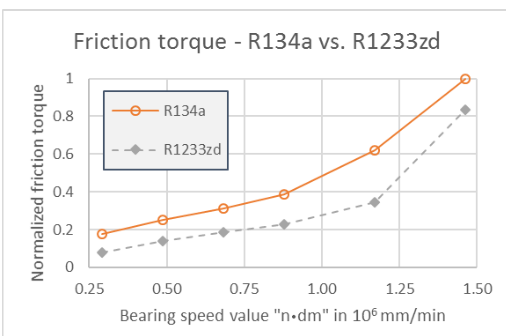

Figure 4: Comparison of friction measurements for R-134a and R-1233zd.
Lines are drawn to guide the eye of the viewer.

For this case R-1233zd generates less friction in the bearings compared to R-134a under same conditions. The refrigerant properties such as film building ability, density and the boundary friction coefficient as well as possible evaporation influence the bearing friction characteristics. Morales-Espejel *et al.* (2014) have observed a very low boundary friction coefficient for R-1233zd in comparison with typical oils and steel-steel contacts. The mapping of the friction behavior under various operating conditions allows the optimization of the injection properties. PRL bearings enable machine designs which offer excellent overall system efficiency.

4.3 Load-Speed Combinations

Functional testing can be performed with different refrigerants to validate the permissible operating map. In these tests various parameters were investigated such as speed, load, injection properties, and start-stop operation. When screening the operating map, certain areas can be identified where performance parameters undergo dramatic changes. Such an example is shown in Figure 5, where a strong increase of friction is observed at a certain axial bearing load for two different speed cases.

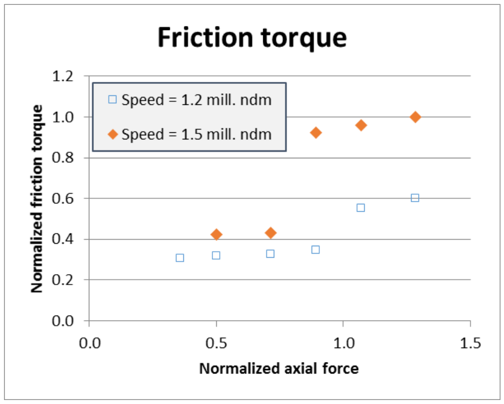

Figure 5: Experimental PRL test data with evidence of changes in the operating regime

At a speed of 1.2 million ndm, the friction trend shows a sudden increase close to an axial load which was used to normalize the scale. For the very high speed of 1.5 million ndm, the sudden increase of the friction torque occurs already at lower loads, around 80 % of the axial load at the lower speed. With this method, it is possible to define the limits of the operating window, if it is assumed that the limit of robust and reliable operation is indicated by these extreme changes of performance parameters. The aim of the authors was to link this behavior to a tribological model. It was found that the concept of flash temperature in the contact (Hauleitner *et al.*, 2017) gives a good agreement with the experimental data. The schematic of the used procedure is shown in Figure 6. Based on the heaviest loaded rolling element in the bearing and considering kinematic starvation, the solid-solid contact fraction and a suitable friction calculation, the flash temperature in the contact can be calculated.

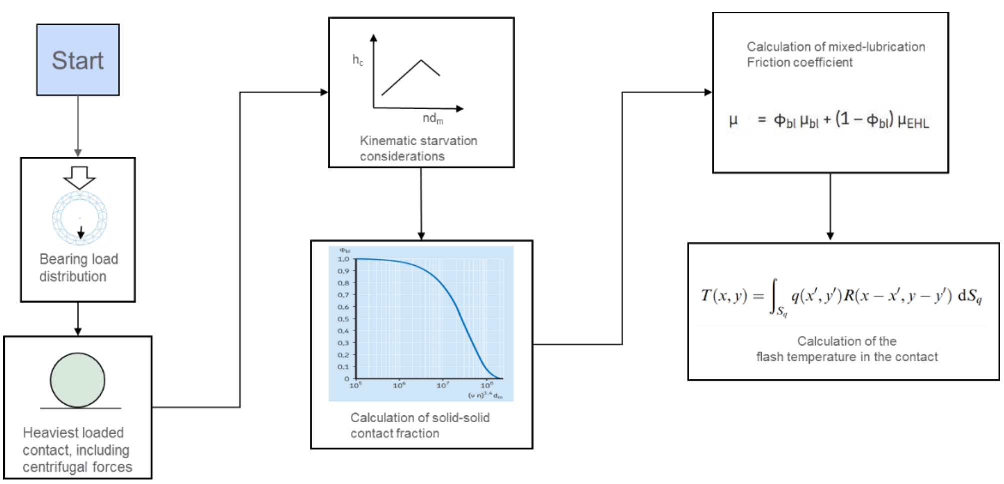

Figure 6: Calculation procedure of raceway-ball flash contact temperature

Figure 7 shows the result of such a calculation with 6 measurement points. Three of these points correspond to a refrigerant flow "A" and the other three points to a reduced flow of half the volume of "Flow A". For the "Flow A" an isothermal of the flash temperature model was added in the diagram. This phenomenon seems to describe the behavior observed on the test rig and allows – once calibrated with measurements - the computational prediction of the operating window.

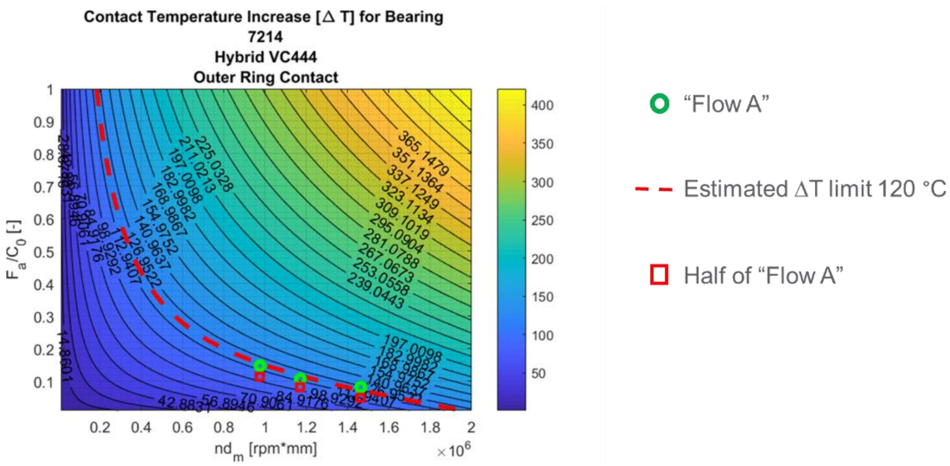

Figure 7: Calculation result of raceway-ball flash contact temperature

6. CONCLUSION

Different tribological aspects in rolling bearings used in refrigerant compressors have been described. It was shown that low as well as medium vapor pressure refrigerants can have the ability to form lubrication films. Finally, friction measurements in PRL conditions can be used to better understand lubrication aspects of bearings in these conditions. For the current work, the following conclusions can be drawn:

1. A solution for PRL rolling bearings was developed that is available for use in refrigerant-lubricated environments such as oil-free compressors.
2. The solution has been achieved via a careful selection of materials, design and quality, together with laboratory experimentation and testing. In addition, the correct bearing selection and application evaluation are of outmost importance.
3. Knowing viscosity and piezo-viscosity of the refrigerants is a first step in the calculation of film thickness and the correct design of an application.
4. Friction is an important parameter in PRL conditions, since it is linked to the thermodynamics of the refrigerant. The heat generation can influence refrigerant evaporation and starvation. On the other hand, refrigerant supply has a strong effect on bearing friction.

But also limits of this technology were identified experimentally and the observed phenomena were described by advanced modelling. This provided useful information for the implementation in an industrial application. As new refrigerants and blends of refrigerants are introduced on the market, their characteristics are investigated to estimate the impact on bearing tribology. Experimental validation on the PRL bearing test rig is continued. Based on this knowledge the PRL bearing technology can be adopted for an efficient implementation in compressor applications.

NOMENCLATURE

α	pressure-viscosity coefficient	(Pa^{-1})
η_0	liquid dynamic viscosity at atmospheric pressure	($Pa \cdot s$)
ρ_0	liquid density at atmospheric pressure	(kg/m^3)
H_c	dimensionless central film thickness	(-)
U	Dowson-Higginson dimensionless number	(-)
G	Dowson-Higginson dimensionless number	(-)
W	Dowson-Higginson dimensionless number	(-)
n	Rotational speed	(rpm)
d_m	Bearing pitch diameter	(mm)

Subscript

oil	properties for oil
ref	properties for refrigerant

REFERENCES

Akei, M., Mizuhara, K., Taki, T., *et al.* (1996). Evaluation of Film-Forming Capability of Refrigeration Lubricants in Pressurized Refrigerant Atmosphere. *Wear 1996*; 196: 180–187.

Akei, M., Mizuhara, K. (1997). The Elastohydrodynamic Properties of Lubricants in Refrigerant Environments. *Tribol Trans 1997,* 40: 1–10.

Bair, S. (2016). A new high-pressure viscometer for oil/refrigerant solutions and preliminary results. *Tribol Trans 2017*. DOI: 10.1080/10402004.2016.1168902.

Bair, S., Habchi, W., Baker, M., *et al*. (2017). Quantitative Elasto-Hydrodynamic Film-Forming for an Oil/Refrigerant System. *Tribol Trans 2017.* DOI: 10.1115/1.4036171.

Brizmer, V., Gabelli, A., Vieillard, C., *et al*. (2015). An experimental and Theoretical Study of Hybrid Bearing Micropitting Performance under Reduced Lubrication. *Tribol Trans 2015*, 58: 829–835.

Davis, B., Sheiretov, T., & Cusano, C. (1992). The Tribological Evaluation of Compressor Contacts Lubricated by Oil-Refrigerant Mixtures. *In: International compressor engineering conference, Purdue, West Lafayette, IN, USA, Paper 838.*

Habchi, W., Vergne, P., Eyheramendy, D., Morales-Espejel, G.E. (2011). Numerical Investigation of the Use of Machinery Low-Viscosity Working Fluids as Lubricants in Elastohydrodynamic Lubricated Point Contacts. *Proc. IMechE, Part J, Journal of Engineering Tribology, 225,* pp. 465-477, 2011.

Hauleitner, R., Morales-Espejel, G.E., Arvidsson, M. (2017). Tribological Aspects of Rolling Bearings Lubricated with Refrigerant. *In: World Tribology Conference 2017, Beijing, China*

Jacobson, B., Morales-Espejel, G.E. (2006). High Pressure Investigation of Refrigerants HFC245fa, R134a and R123. *In: Proceedings of the international compressor engineering conference, Purdue University, West Lafayette, IN*, paper 1789, pp.1–8.

Jonsson, U.J., Lilje, K.C. (1998). Elastohydrodynamic Lubrication Properties of Polyol Ester Lubricants-R134a Mixtures. *In: International compressor engineering conference, Purdue University, West Lafayette, IN, USA, 1998, paper 1227,* pp.123–128.

Jonsson, U.J., Hansson, N. (1998). Lubrication Limits of Rolling Element Bearings in Refrigeration Compressors. *In: Proceedings of international compressor engineering conference at Purdue, West Lafayette, IN, USA,* pp.129–134.

Jonsson, U.J. (2001). A Study of the Lubrication of Cylindrical Roller Bearings with Oil-Refrigerant Mixtures Using Capacitive Oil-Film Measurements. *In: 7th international conference on compressors and their systems, City University, London, 9–12 September 2001,* Paper C591/065/2001, pp.449–462.

Laesecke, A., Bair, S. (2011). High-Pressure Viscosity Measurements of 1,1,1,2-tetrafluoroethane. *Int J Thermophys 2011,* 32: 925–941.

Masayoshi, M., Takashi, S. (2000). Determination of Film Thickness and Traction of Polyol Ester under an EHD Contact in Some Refrigerant Environments. *Tribol Trans 2000,* 43: 15–20.

Meyers, K. (1997). Creating the Right Environment for Compressors Bearings. *SKF Evolution Magazine, November 1997, No. 4.*

Morales-Espejel, G.E., Gabelli, A., & Vieillard, C. (1996). Hybrid Bearings Lubricated with Pure Refrigerants. In: SRM, technical screw compressor conference, Stockholm, Sweden, 4–7 September 2001.

Morales-Espejel, G.E. (2013). Surface roughness effects in elastohydrodynamic lubrication: A review with contributions. *Proc. IMechE, Part J, Journal of Engineering Tribology, 228(11),* pp. 1217-1242, 2013.

Morales-Espejel, G.E., Meeuwenoord, R., Félix Quiñonez, A., Hauleitner, R. (2014). Film Thickness and Traction Measurements of Refrigerant R1233zd used as Lubricant in Elastohydrodynamic Conditions. *Proc IMechE, Part C: J Mechanical Engineering Science 2014*, 229: 244–253.

Morales-Espejel, G.E., Wallin, H.H., Hauleitner R., Arvidsson, M. (2017). Progress in Rolling Bearing Technology for Refrigerant Compressors, *IMechE, Part C, Journal of Mechanical Engineering Science, DOI: 10.1177/0954406217725772.*

Tuomas, R., Isaksson, O. (2006). Compressibility of Oil/Refrigerant Lubricants in Elasto-Hydrodynamic Contacts. *Trans. ASME, J. of Trib., vol. 128,* pp. 218-220, 2006.

Tuomas, R. (2006). Properties of Oil Refrigerant Mixtures - Lubrication of Ball Bearings in Refrigerant Compressors. *PhD Thesis, Lulea University of Technology, Sweden*.

Vergne, P., Fillot, N., Bouscharain, N., *et al.* (2015). An Experimental and Modelling Assessment of the HCFC-R123 Refrigerant Capabilities for Lubricating Rolling EHD Circular Contacts. *Proc IMechE, Part J: J Engineering Tribology 2015,* 229: 950–961.

Vieillard, C., Kadin, Y., Morales-Espejel, G.E., *et al.* (2016). An Experimental and Theoretical Study of Surface Rolling Contact Fatigue Damage Progression in Hybrid Bearings with Artificial Dents. *Wear 2016*, 364–365: 211–223.

Wardle, F.P., Jacobson, B., Dolfsma, H., *et al.* (1992). The effect of Refrigerants on the Lubrication of Rolling Element Bearings used in Screw Compressors. *In: Proceedings of international compressor engineering conference at Purdue, West Lafayette, IN, USA,* pp.523–534.

Yamamoto, Y., Gondo, S. & Kim, J. (2003). Solubility of HFC134a in Lubricants and its Influence on Tribological Performance. *Tribol Trans 2001,* 44: 209–214.

ACKNOWLEDGEMENT

The authors wish to thank Dr Stefan Lammens, Director SKF Research and Technology Development, for his permission to publish this article. The contribution of Mr. Hans Wallin on bearing and industry specific information is greatly acknowledged.