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Rolling bearing solutions for mixed-media and media lubrication in compressors or pumps

CIF- research & development

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ABSTRACT

Many experts consider "climate change as the defining issue of our time" (A. Guterres). Therefore, solutions with low GWP (Global Warming Potential) are adopted to establish green processes with low energy consumption.

Research and development is accelerated to cope with new targets and regulations associated to this change, and rolling bearing development is strongly affected by the need to use lubricating oil diluted by new refrigerants or partly corrosive media like sour gas (H2S). In state-of the art applications, rolling bearings are only lubricated by liquified gases like LNG or hydrogen, or other ultra low-viscosity fluids like kerosine, without the presence of lubricating oils.

SKF has developed, tested and industrialized new materials, designs, simulation tools and application knowledge, to provide robust solutions for these challenges. It is now possible to combine the advantages of two - so far incompatible - worlds: rolling contact and oil-free operation. In addition, the new solutions can lead to considerable simplification, increase in power density and maintenance savings.

In this paper, new bearing materials, technologies, tribology background and testing experience will be presented, and successful application examples will be given.

1 INTRODUCTION

There is a broad consensus today that climate change is a “defining issue of our time” (António Guterres). As a consequence, products and solutions with high energy efficiency and low global warming potential (GWP) are rapidly adopted by global industries and markets.

For industrial equipment like pumps, compressors, and blowers, yearly runtimes of 5000 to 8500 hours are common, which implies that the power to drive the machine is usually the by far largest contributor to life cycle cost (LCC) and emissions. Often, an effective measure to improve energy efficiency is the use of variable speed drives (VSD). In addition, the careful choice of the working fluid and optimisation of pressure ratios and thermodynamic aspects are key [1].

Considerable efficiency improvements of typically 3 to 4% can also be achieved by using oil-lubricated rolling element bearings instead of journal or hydrodynamic bearings, for example in compressors in chillers. In some cases, this only becomes an option by the introduction of hybrid bearings, which comprise ceramic rolling elements made from bearing grade silicon nitride (Si_3N_4). Note that only recently a new Generalized Bearing Life Model (GBLM) for hybrid bearings was published [2]. In addition to above savings, some 2 to 3% of efficiency savings can be gained by developing oil-free chiller designs with pure refrigerant lubricated (PRL) rolling bearings [3] as presented further below.

The paper at hand, though, will not put the focus on energy efficiency optimisation, but more general on bearing and lubrication technologies that enable robust application performance under thin film conditions that, for instance, became important due to the introduction of new low GWP refrigerants, low speed condition in connection with VSD, the increased use of natural gases with acidic content, or vacuum and hot gas applications, and so bearing tribology R&D was challenged to cope with heavily diluted oils or (liquid) gases and corrosive media.

With state-of-the art technology, rolling bearings can now even be “media-lubricated”, which means that the rolling contacts are no longer separated by a viscous oil, but by liquified gases like liquid natural gas (LNG), liquid refrigerant [4], or other ultra-low viscosity fluids, with kinematic viscosities typically around 1cSt [5]. This breakthrough was enabled by a combination of advances in material and tribology research, computer-aided application design and improved manufacturing processes.

2 NEW BEARING TECHNOLOGIES & TRIBOLOGY CONSIDERATIONS

In the past decades, SKF developed, tested and industrialized new materials and designs that provide robust solutions for mixed-media and media-lubricated rolling bearing applications, combining the benefits of two - so far mostly incompatible – regimes (Figure 1): rolling contact motion and oil-free operation.

Figure 1. Media lubricated rolling bearings combine the advantages and challenges of rolling contact and oil-free operation.

Beside extended service life, the new solutions can also lead to simplified machine designs, higher efficiency, more safety, and considerable maintenance savings [6]. Of course, for robust bearing performance under the challenging oil-free conditions, all elements of the application design must be well understood by the application engineers and bearing supplier:

1 Variation of operating conditions and manufacturing tolerances of the machine;

2 Bearing design and manufacturing tolerances;

3 Material choice and surface specifications;

4 Lubricant flow and cleanliness control;

5 Manufacturing process and quality control.

2.1 Tribology theory

Traditional rolling bearing lubricants such as oils are specifically composed to optimise rolling contact behaviour. They physically protect the surfaces by creating a separating film, they provide cooling, and they avoid chemical attack or corrosion of the bearing components. The lubrication film also influences important performance parameters such as friction, heat generation, and damping. If other fluids are used to lubricate bearings, not all the usual requirements on a lubricant might be fulfilled, and the bearings needs to be designed to withstand these challenges. In the following some tribological aspects of media lubrication are explained.

The lubricant is an essential component of rolling element bearing systems. Any film thickness, life, or friction calculation under elasto-hydrodynamic lubrication (EHL) conditions requires reliable lubricant property data: viscosity, pressure-viscosity index and compressibility (or density function) with pressure. Other important parameters are boundary friction coefficient and lubricant rheology. The dilution of common lubricants with low viscosity fluids substantially influences their film build-up capability. [7] describes a procedure how to estimate the lubrication properties of mixtures of various fluids at different mixture ratios. [8] contains guidelines for the calculation of oil-refrigerant mixtures present in oil lubricated refrigerant compressors.

Certain applications require oil-free operation or provide substantial advantages if oil can be eliminated from the system. For such machines, the working fluid itself can be considered as lubricant. This requires the characterisation of the fluid to evaluate the potential use for rolling bearing lubrication and define the application limits. For refrigerant compressors, the liquid refrigerant properties have been analysed [9]. Additionally, the film build-up capabilities have been validated on single contact (ball on disk) test rigs. Such measurements have confirmed the film formation capability of low vapour pressure refrigerants, such as R-123 [10] and R-1233zd [11], as well as medium vapour pressure refrigerants as R-1234ze [12] under typical EHL conditions in rolling bearings. An example of such a film thickness measurement is shown in Figure 2, which clearly demonstrates the formation of a higher film thickness with increasing rolling contact speed.

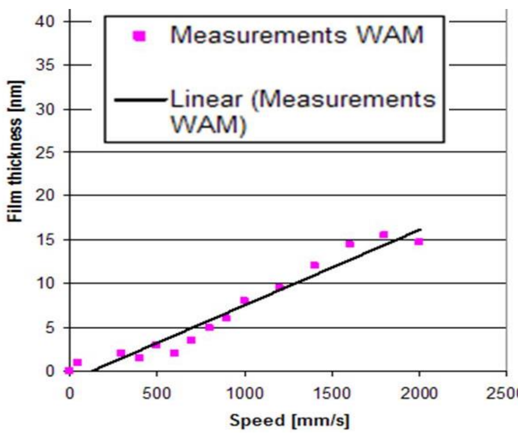

Figure 2. Central Film thickness measurements for R-1233zd when increasing speed (averaged values) [11].

Most media and diluted oil lubricated bearings must sustain much thinner lubrication films in the rolling contacts compared to traditional oil and grease lubricated applications. This is mainly caused by the lower viscosity and pressure-viscosities of these media. The marginal lubrication combined with generally low maximum Hertzian contact pressures – for example typically below 2 GPa in refrigerant compressor bearings - leads to a higher loading of the raceway surface region compared to sub-surface fatigue of well lubricated bearing applications. Typical failure modes of bearings which suffer under surface related problems are wear, surface distress (also known as micro-pitting) or smearing (adhesive wear), see also ISO 15243 [13]. In addition, corrosion and embrittlement phenomena can be performance critical for the functional bearing surfaces.

2.2 Bearing design

As said, (mixed-)media lubricated applications create demanding conditions for the bearing components and require high-tech materials and refined specifications. A bearing solution which has proven its reliability in the here discussed extreme environments comprises the following elements:

1. Inner and outer rings made of a through-hardened martensitic stainless steel with high nitrogen content according to SKF specification VC444 or VC4444, heat-treated and super finished with processes developed by SKF. Not only does this steel show very high corrosion-protection, but it also has a very fine microstructure, making it an excellent bearing material for tough rolling contact conditions.
2. Rolling elements made of the highest-quality bearing-grade silicon nitride (Si_3N_4) and most stringent SKF inspection procedures [14].
3. A cage made of fibre-reinforced PEEK material, in some cases with special geometrical design.
4. If needed: special geometry of the raceways.

All this is assisted by expert application engineering to define bearing arrangements, lubrication methods, filtration degree, preload and tolerances.

These special features can be incorporated in various bearing types depending on the demands of the application. Common executions include ball bearings such as deep groove ball bearings (DGBB) or angular contact ball bearings (ACBB), as well as roller bearings such as cylindrical roller bearings (CRB), see Figure 3. This allows the use in a wide field of operations from primarily radial to pure thrust loads, as well as combined loads such as in screw compressors.

The contact angle of ACBBs is optimised based on the load and speed conditions which are expected during operation. Calculation tools allow the detailed analysis of the dynamic behaviour including structural flexibility, bearing stiffness, and critical frequencies. If multiple bearings are needed in the application, the matching of sets and proper selection of clearance or preload are key aspects in the design process.

Figure 3. Different examples of SKF hybrid bearings using high-nitrogen stainless steel SKF Nitromax™ according to SKF specification VC444.

2.3 Manufacturing process optimisation

For ultra-thin film bearing applications, the quality of material microstructure and raceway surfaces is of critical importance. As said, special silicon nitride ceramics are used for balls or rollers, with a finer and cleaner microstructure compared to less demanding applications. With special honing and lapping, surface roughness values (Ra) of less than 0.01 µm are achieved. For rollers, careful specification and manufacturing of the roller profile is another crucial aspect. For larger ball or roller sizes, an even more stringent quality inspection of the sintered material is applied.

Production of the martensitic nitrogen steel for the rings is using a pressurized electroslag-remelting process to achieve low carbon and oxygen levels, and high nitrogen content (~0.4%). Nitrogen partly replaces carbon in the martensite lattice, thereby reducing the need for carbon content in the steel. With less carbon in the steel there are fewer chromium carbides resulting in fine microstructure. As a result, corrosion resistance and toughness are strongly increased. Hardening of the nitrogen steel is done in vacuum furnaces according to refined SKF specifications, and with a tempering procedure that can be adapted to dimensional stability needs. In particular, SKF specifications ensure low remaining austenite levels and avoidance of larger chromium rich phases that can reduce rolling contact performance.

Economical grinding of the hardened nitrogen steel required optimisation of the entire grinding process, due the steel's high toughness and abrasion resistance. Different grinding wheel and tool specifications were tested and grinding parameters were adapted. Similarly, this was done for the raceway honing operations, where more stringent specifications related to surface roughness, imperfections and cleanliness are applied for media lubricated applications.

2.4 Experimental verification

2.4.1 Life testing under thin film conditions

In an early testing program, a very low viscosity oil (kinematic viscosities in the order of 2 to 4 cSt) was used to study thin film lubrication. The bearings comprised ceramic rolling elements and rings made of standard bearing steel and alternatively the martensitic high nitrogen steel. The tests demonstrated the superior performance of the high-nitrogen steel hybrid bearings, which did not show any damages or relevant failures. This promising result lead to further development of, for instance, "Pure Refrigerant Lubricated" (PRL) bearings, which are presented later in this document.

Figure 4 shows the results of some additional life testing, with a comparison of standard hybrid bearings versus hybrid bearings using high-nitrogen steel rings according SKF VC444 specification.

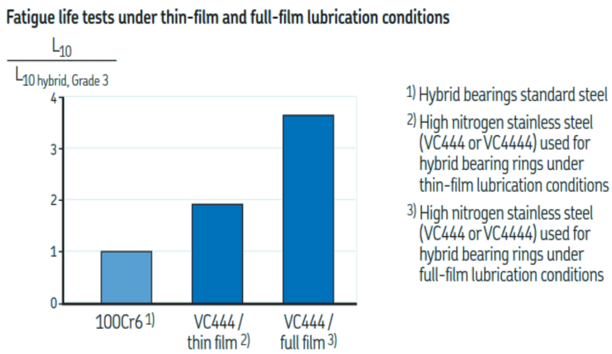

Figure 4. Life testing results with different hybrid bearing executions under full film and thin film conditions [15].

2.4.2 Friction measurements for refrigerant lubricated contacts

Friction is an important parameter for PRL bearings, not only for the overall performance of the machine but also since it is linked to the thermodynamics of the refrigerant. The heat generation can influence refrigerant evaporation and starvation of the contacts. Various traction measurements were performed on the WAM 5 (Wedeven Associates Inc.) machine using the same hybrid contact regime as in the industrial application of PRL bearings. During these measurements the friction coefficient under different lubrication regimes was analysed and it turned out that for some tested material-refrigerant combinations the traction coefficients (traction loss factors) were less than half compared to typical oil lubricated contacts. A similar result was reported in [11] based on refrigerant R-1233zd.

2.4.3 Functional PRL bearing test rig

The development of a special bearing test rig for refrigerant lubricated bearings was described in detail in [12]. The test rig as shown in Figure 5 can be operated with various low and medium pressure refrigerants and is used to confirm the robust performance of PRL bearings under various operating conditions. A special feature of the test rig is the unique high-safety observation window which allows to observe the test bearings and the lubrication conditions.

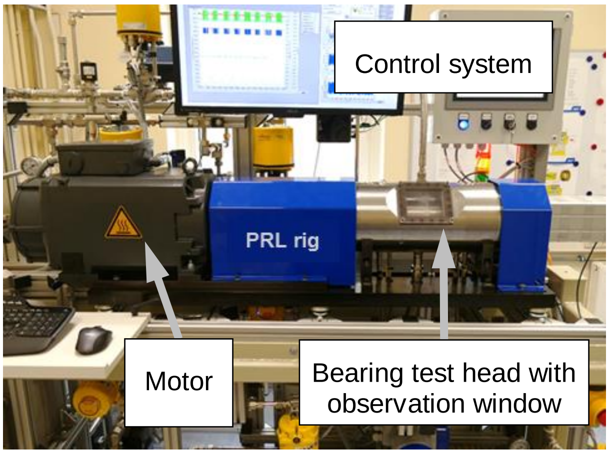

Figure 5. Photograph of the SKF PRL test rig with its unique design for the qualification of refrigerant lubricated bearings.

The PRL test rig allows the investigation of various combinations of refrigerant, load, speed, lubricant injection parameters, as well as transient conditions. In such a way the performance of the bearings can be characterized without the need of a complete chiller prototype.

Another unique feature of the test rig is the possibility to accurately measure bearing friction [16]. The mapping of the friction behaviour under various PRL operating conditions allows the optimization of the injection properties. It could be demonstrated that under the given conditions the friction losses of the bearings lubricated by low-pressure refrigerant is only around 10% of that in classical oil-lubricated journal bearings, or only about 25% compared to the losses in oil-lubricated ball bearings.

PRL bearings enable machine designs with higher overall system efficiency which go beyond the contribution of the bearing itself and include the elimination of heat transfer losses due to oil contamination and better aerodynamic performance of the machine. As a rough indication, overall power loss values for chiller applications using PRL bearings are in the range or even lower compared to systems using magnetic bearings.

Another important capability of the test rig is that by accurately measuring the friction and temperature behaviour, tribological limits for the contact loading can be determined, see [12].

In summary, the findings from the tests performed on the rig shown in Figure 5 are as follows:

- The very low friction torque already indicated by the WAM tests (see section 2.4.2) were also confirmed on the bearing test rig.
- The supply of liquid refrigerant to the bearings could be optimized and provides very effective cooling to the bearings.
- Actually very little lubricant is needed, and even lubrication shut-off tests were performed successfully.
- Speed levels of n*dm up to 1,500,000 mm/min were so far explored with the rig (where n*dm is the scalar product of shaft speed and bearing pitch diameter).
- The measurements allowed the development of application specific operating guidelines (load-speed limitations).
- No wear, and smooth running (no vibration) were observed.

2.5 PRL bearing lubrication system

A key factor for successful operation of an oil-free chiller with PRL bearings is that liquid refrigerant is supplied in a controlled way to the bearing raceways, for example using the pressure differential at steady state and a variable speed positive displacement pump at start up.

Beside theoretical lubricant flow analysis, much experience was gained from lab tests and many years of field operation, related to the refrigerant flow rate, and how to lubricate the bearings during startup or shutdown. In addition, design rules and specifications for the jet lubrication spacers (rings) adjacent to the bearings where developed and are further optimised by computational fluid dynamics (CFD) analyses, see Figure 6.

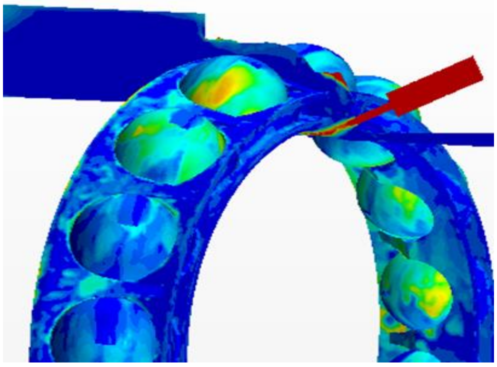

Figure 6. CFD analyses are used to support the experimental measurements in media lubricated conditions.

3 APPLICATION CASES AND DESIGN CONSIDERATIONS

3.1 Mixed media lubrication and diluted oils

3.1.1 Sour gas (H2S) and "acid gas" applications

Oil & gas and hydrocarbon processing industry is frequently confronted with acidic gases, for example natural gas or any other gas mixture containing higher quantities of hydrogen sulphide (H_2S), carbon dioxide (CO_2), and/or water. Oil-flooded screw compressors in this area suffer from the issue that the lubricating oil is mixed with those gases. Hydrogen and sulphur from H_2S can act as electrochemical cells under presence of water, and corrosive substances such as sulphuric acid are formed. In addition, diffusion of hydrogen atoms into the steel matrix is causing hydrogen embrittlement and sensibility to cracking. According to [8] and [17], the dominant failure modes can be categorized as Hydrogen Stress Cracking (HSC), Sulphide Stress Cracking (SSC), and Stress Corrosion Cracking (HSC).

Therefore, when using standard rolling bearings in gas screw compressors, acidic gas concentrations and water content must be held in very narrow limits, which can be difficult to achieve under field conditions. By using hybrid bearings with high-nitrogen steel rings, mean-time-between-failure (MTBF) values in sour gas screw compressors could be increased from one or two months to several years in practical cases, see example in Figure 7. H_2S or $C0_2$ concentrations of up to 40 mol% respectively 80 mol% can be handled today according to [17].

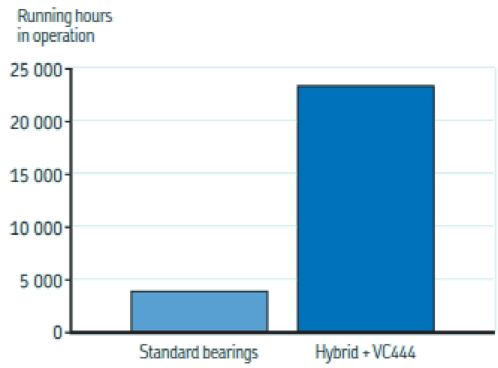

Figure 7. Service life comparison for an oil-flooded screw compressor used in a vapor recovery unit in a refinery, handling 30 to 40% H_2S content and 35% acid gas.

3.1.2 Oil-dilution by refrigerants

In oil lubricated refrigerant compressors it is difficult to avoid the mixing of oil and refrigerant. Thus, it is important to understand how this dilution of the oil affects rolling bearing performance. Refrigerants are not considered good lubricants, and the dilution reduces the viscosity of the mixture, increases the compressibility and reduces the increase of viscosity with pressure (piezo-viscosity). In order to understand the consequences of dilution on bearing performance, considerable experimental work has been carried out. It was found that conventional all steel bearings started to exhibit signs of inadequate lubrication at dilution levels of 20 to 30% [18]. With the industry transition to new low GWP refrigerants, dilution rates of even 30% or higher have been reported.

This led to the investigation of alternative bearing designs and materials. The studies showed that for hybrid bearings comprising bearing steel rings and ceramic balls made of bearing grade silicon nitride (Si_3N_4), it was hardly possible to find a limiting dilution ratio, and so this was also an indication that even pure refrigerant lubrication may have a chance to work, see chapter 3.2.1.

The classical theory of bearing life calculation has some limitations to analyse such tough tribological conditions. As mentioned in the introduction, SKF recently introduced the Generalized Bearing Life Model (GBLM) for hybrid bearings, and since then, work has continued focusing on specialized bearings and experimental validation of the model. SKF has now also implemented the GBLM formulas for hybrid bearings in its computer tools and so customers can take full advantage of the application of hybrid bearings.

3.2 Media lubrication

3.2.1 Pure Refrigerant Lubrication (PRL)

Large commercial chillers typically engage centrifugal compressors which compress a refrigerant gas to enable heat transfer from a lower temperature source to a higher temperature sink. Traditional designs require oil for lubrication of gears and bearings, as well as cooling and sealing of compressor elements. Nevertheless, the usage of two different fluids – oil and refrigerant - in one machine provides a couple of challenges: It is practically impossible to keep the two fluids completely separated, the compatibility of used materials and fluids needs to be analysed, environmental rules need to be fulfilled, and the fluids require regular checks, maintenance and proper disposal.

Pure refrigerant lubricated bearings [4] provide a much more “elegant” solution (Figure 8): they directly use the refrigerant as lubricant, a breakthrough that reduces chiller energy consumption while simplifying system design and maintenance requirements. A simplified schematic diagram of the thermodynamic cycle process and its components is shown in Figure 9. The performance of this bearing solution has been experimentally validated at different levels, starting from measurement of refrigerant properties (see chapter 2.1), film measurements of single contacts and ultimately the operation of complete bearing systems (see chapter 2.4.3).

Furthermore, this oil-free operating solution has been running in the field for more than a decade. The first field trial with compressors incorporating PRL technology used in oil-free air conditioning chillers was commissioned in the early 2000s, and the chillers work well and are still in operation. Today, there is a lot of interest in PRL technology globally, and in recent years, also magnetic bearings became a viable technology enabling oil-free chiller operation [19].

Pure refrigerant lubricated bearings from SKF offer several benefits:

- Oil-free operation
- Increased chiller efficiency
- Less maintenance and no oil disposal
- Increased service life
- Lower lifecycle costs

According to a recent case study done by SKF, which was also verified with some key customers, for a medium size chiller running 5000 hours per year, with 280 kW average drive power and electricity cost of 0.20 US$/kWh, the drive energy cost savings over a 20 year period are in the order of 200,000 US$ when changing from hydrodynamic to oil-lubricated ball bearings, and another 100,000 US$ when changing to PRL bearings.

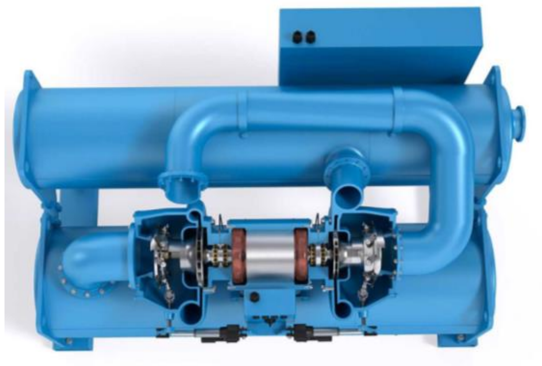

Figure 8. Illustration of a chiller with a sectional view of the two stage centrifugal compressor using PRL bearing technology [4].

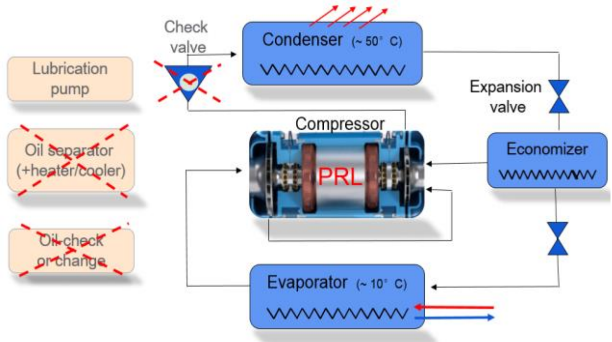

Figure 9. Diagram of the thermodynamic cycle process of a PRL chiller.

3.2.2 Cryogenic fluids like liquefied gas

Cryogenic pumps are used for handling various liquified gases such as petroleum (LPG), ethylene (LEG), natural gas (LNG), nitrogen (LN2), or hydrogen (LH2), see Figure 10. To keep these fluids in the liquid state temperatures down to -200 °C and below are required. The bearings are flushed by the working fluid which provides cooling and lubrication. Generally, the loads acting on the bearings are rather low, since load balancing systems are incorporated in the pump design. Standard "cryogenic bearings" consist of rings and balls made of 440C stainless steel. Typical failure modes of such bearings are fractured (riveted) cages, severe ring fracture, and ball spalling.

For increased reliability and life of the pump, high performance ball bearings are recommended for the use in such pumps: high-nitrogen, martensitic, stainless steel rings with special heat treatment, ceramic balls, and fibre-reinforced polyetheretherketone (PEEK) cage (robust single piece design), see **Error! Reference source not found.**. Those special bearings provide significantly increased MTBF compared to standard bearings, together with overall reduced maintenance and associated cost due to extended pump service life and reduced unplanned downtime. An additional benefit of the use of ceramic rolling elements is electrical insulation to prevent electrical erosion caused by variable speed drives and high frequency currents.

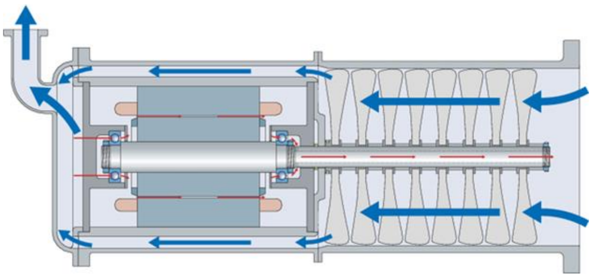

Figure 10. Typical canned cryogenic motor pump, in which the rolling bearings are lubricated by a liquid gas like LNG (Liquid Nitrogen Gas).

Special bearings as the one shown in **Error! Reference source not found.** have been used for over 10 years in highly process critical installations: Process pumps, in-tank pumps, loading pumps. Some hundred cryogenic process pumps have already been upgraded to this new technology [20]. The wide spread of temperatures such a pump is exposed to (between ambient down to minus 200 degrees Celsius and below) requires special internal bearing clearances and application specific computations to account for the thermal expansion.

Figure 11. Special hybrid deep groove ball bearing for cryogenic pumps, with a special PEEK cage and nitrogen steel rings according SKF VC4444 specification.

3.3 Diesel pumps in locomotives

Hybrid deep groove ball bearings with a single piece PEEK cage are successfully applied in special diesel transfer pumps for locomotives. The motor pumps have a canned design where both the motor and pump are enclosed in a sealed housing, which implies that no separate oil-cycle is present, and the bearings are lubricated solely by the diesel fuel. The benefit for the customer is a simple and maintenance free pump design.

3.3.1 Water-glycol lubrication

Nitrogen-stainless steel hybrid bearings - both roller and ball bearings - are also applied in reciprocating hydraulic fluid pumps, where the HFC hydraulic fluid, a water-glycol mixture, is lubricating the bearings. The special challenge in such applications is again the thin film thickness created by water-glycol – as compared to conventional lubricants - and potential stress cracking and corrosion caused by the high content of water.

3.3.2 Liquid ethylene (C_2H_4)

Because it is a base compound for the production of polyethylene plastics, Ethylene (C_2H_4) is one of the most widely used media in chemical industry. Transport of ethylene is often done in liquefied cryogenic stage at -100 °C, whereby the pumps are submerged and the bearings run in the liquid ethylene. Such pumps enable a high power density due the effective cooling and are intrinsically safe due to the submerging into the pumped liquid. In addition, the polymerization of ethylene to polyethylene is traditionally done in high-pressure chemical reactors, where the gas goes through a rotating mixer in which catalysers are injected and the gas is converted to polyethylene. Motors and mixers run with bearings lubricated by the high-pressure gas and the liquid polyethylene product. After careful analysis and choice of bearing materials, heat treatment, geometry and tolerances, SKF supplied hybrid bearings with PEEK cages and above presented nitrogen stainless steel with a modified treatment for higher dimensional stability according SKF specification VC4444 for the cryogenic pump, and similar bearings for the reactor mixer.

3.4 Vacuum and dry-running applications

Basically, hybrid ceramic bearings with PEEK cages possess good properties for the use in low to medium level vacuum applications, i.e. when it is still possible to use special vacuum greases. However, in some equipment with high vacuum and extreme cleanliness requirements as for example in semiconductor lithography, aseptic environments, or space and research, or for very high temperatures, it is not possible to apply any liquid refrigerant.

For such conditions, a special self-lubricating coating named TripleM™ was developed, tested, and successfully applied. This hard PVD (Physical Vapour Deposition) coating gives much higher wear resistance and adhesion, as well as much lower outgassing compared to, for instance, typical MoS_2 lubricants or coatings, and coating precision is in the order of +/- 0.2 µm. Further features of the TripleM™ coating are: extremely low friction coefficients in the order of 0.02; better performance in humid environments compared to MoS_2; high temperature stability up to 350 °C; and some (limited) corrosion protection. One reason for the good coating performance is a special gradient coating structure, leading to good adhesion to the steel surfaces and high toughness as illustrated in Figure 12. The life testing result in Figure 13 indicates the superior performance of hybrid bearings coated with TripleM™ compared to normal steel bearings or coated steel bearings.

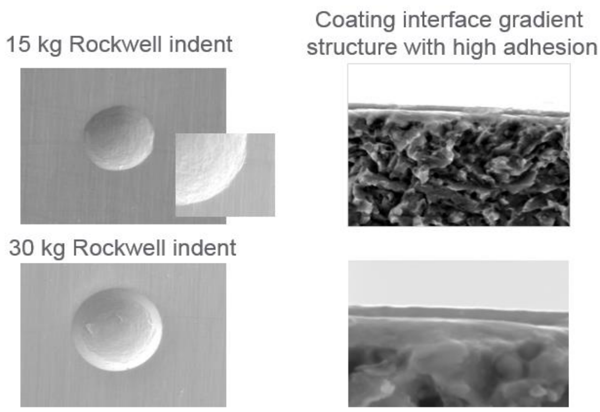

Figure 12. Indentation test on a bearing steel surface coated with TripleM™ coating for dry running (vacuum) applications, with a coating thickness of about 1 µm.

Beside semiconductor applications, the TripleM™ coating was also successfully applied in an oil-free industrial dying machine using hot $C0_2$ gas.

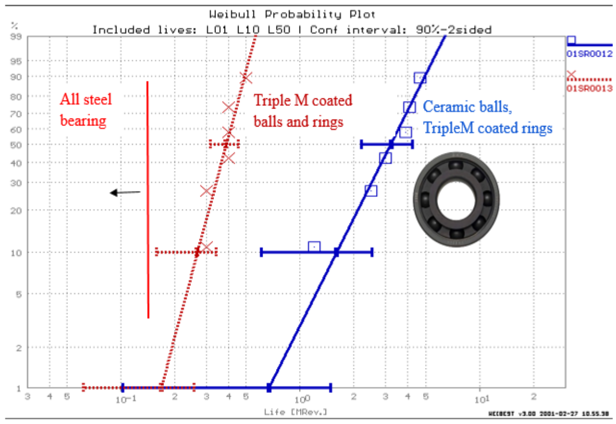

Figure 13. Life testing results (Weibull curves) for different bearing executions under dry running conditions (bearing size 6205, C/P=10, 6000 rpm, no lubricant, run in air at room temperature).

4 FUTURE APPLICATIONS

The above described advance in technology and the many years of field experience under extreme applications open possibilities for new applications of the presented rolling bearing technologies.

4.1 Hydrogen gas handling

When it comes to compression of hydrogen (H_2), conventional rolling bearings may function well in screw compressors if the hydrogen is dry and pure. Still, issues with corrosion and cracking are known to happen in hydrogen applications due to water condensation, related to the high thermal conductivity of H_2 rich gases and to dew point reduction [17]. Similar as explained above for sour gas compressor bearings, the use of stainless high-nitrogen steel hybrid bearings offers a viable solution for such cases, as demonstrated by the comparison in Figure 14 and Figure 15.

Figure 14. Corrosion, frosting, and spalling of a ball bearing made from conventional steel in an oil-flooded screw compressor. Service-life was below 1000 hours when run in H_2-rich process gas [17].

Figure 15. High-nitrogen stainless steel inner ring in the same H_2-rich application as in Figure 14, after about 8000 hours [17].

4.2 Liquid $C0_2$ lubrication

Because of safety and sustainability reasons, some cooling or refrigeration systems use one or more of the so-called "natural five" refrigerants: ammonia (NH_3), carbon dioxide (CO_2), water (H_2O), hydrocarbons (HC) and air. They are applied for heating, drying, hot water supply, air conditioning and freezing over a wide temperature range from -100 to +200 °C [21]. CO_2 has a relatively low environmental impact per weight unit, as its GWP index is only about 1/4000 compared to hydrofluorocarbons (HFC) and chlorofluorocarbon (CFC) substitutes. And CO_2 is safer, non-toxic, non-flammable and provides high cooling capacity [21]. Nevertheless, its relatively high quantity in Earth atmosphere makes CO_2 the major greenhouse gas.

An example is given: freezing systems for super-low temperatures of -80 °C are used to kill bacteria in sushi grade fish. A chiller manufacturer uses ammonia (NH_3) as refrigerant in the primary cycle to cool CO_2 which is flowing in a secondary cycle. By this, NH_3, which is both toxic and flammable, is eliminated from the chambers containing the food. To avoid (oil) leakage and contamination in this chiller, the CO_2 pump bearings are lubricated by liquid CO_2, without the use of any oil. This is a challenging bearing design task as the viscosity and pressure viscosity index of liquid CO_2 is not favourable for lubrication, and only special hybrid bearings as described above have the capability to cope with such conditions.

5 CONCLUSIONS

Appropriate lubrication is a key factor for reliable operation of rolling element bearings. Most importantly, suitable lubricants - usually mineral oils or greases - must possess a certain viscosity and viscosity-pressure index. For applications with very low viscosity oil, or where the oil is diluted or contaminated by other media, hybrid ceramic bearings have been successfully applied since many years.

However, due to regulations and new targets in the area of sustainability, safety, and new energy sources, more and more applications are arising where either the oil-dilution rates are extremely high, or the requirement is oil-free operation and rolling bearing lubrication by liquid gases, or even dry running like in vacuum or hot gas applications. In such applications, the separating film between the rolling contact surfaces becomes extremely thin or even hardly existing and bearing failure modes are not dominated by classical sub-surface fatigue, but by high stressing of the rolling contact surfaces. In applications with acidic media, corrosion, (hydrogen) embrittlement, and stress cracking pose additional challenges to bearing design.

It is shown in this paper for several (mixed-)media lubrication applications that rolling bearing systems can successfully operate under such extreme conditions by applying a combination of high-tech materials (ceramics, high nitrogen steel, PEEK), detailed application analysis, special (jet) lubrication design and also cleanliness specifications. In addition, a test rig with unique analysis and observation possibilities for PRL (pure refrigerant lubricated) bearings is presented.

The following successful application cases were briefly discussed: sour gas and acid gas compressors; chillers with heavy oil-dilution or even pure refrigerant lubrication; cryogenic pumps with liquid gas lubrication; bearing lubrication by diesel, water-glycol, or liquid ethylene; and dry running applications in vacuum or with hot gases like CO_2. Ongoing developments e.g. in the field of material science provide future potential for even tougher rolling bearing conditions like water lubrication.

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7 REFERENCES AND BIBLIOGRAPHY

[1] Trane, 2019. What drives chiller efficiency?, *Trane Engineering Newsletter* 48-1.

[2] Morales-Espejel G. E., Gabelli A. 2015. A major step forward in life modelling, *SKF Evolution* No. 4.

[3] Morales-Espejel, G. E., Hauleitner, R., Wallin, H.H. 2017. Pure refrigerant lubrication technology in oil-free centrifugal compressors, *SKF Evolution*, No. 1 2017, 26-30.

[4] Wallin, H.H., Morales-Espejel, G. E. 2002. Hybrid Bearings in Oil-Free Air Conditioning and Refrigeration Compressors, *SKF Evolution magazine*, No. 2 2002, 28-30.

[5] Habchi, W., Vergne, P., Eyheramendy, D., et al., 2011, Numerical investigation of the use of machinery low-viscosity working fluids as lubricants in elastohydrodynamic lubricated point contacts, *J IMechE, Part J, J. Eng. Tribology*, 225: 465–477.

[6] Forster, T., Hauleitner, R. 2011. Systematic Approach for Friction Reduction on Rolling Bearings, *ÖTG Symposium*, Österreichische Tribologische Gesellschaft, Wiener Neustadt, Austria, 1: 185-193.

[7] 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.

[8] SKF, 2018. Bearings in twin screw compressors, SKF publication 14510.

[9] Jacobson, B.O., Morales-Espejel, G.E., 2006. High Pressure Investigation of Refrigerants HFC245fa, R134a and R123, Proceedings of *International Compressor Engineering Conference*, Purdue University, paper 1789, 1-8.

[10] Vergne, P., Fillot, N., Bouscharain, N., Devaux, N., Morales-Espejel, G.E. 2015. An Experimental and Modeling Assessment of the HCFC-R123 Refrigerant Capabilities for Lubricating Rolling EHD Circular Contacts, *IMechE, Part J, J. of Eng. Tribology*, vol. 229(8), 950-961.

[11] 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, *IMechE*, Part C, *J. of Eng. Tribology*, vol. 229(2), 244-253.

[12] Hauleitner, R., Morales-Espejel, G.E., Meeuwenoord, R., et. al., 2018. Rolling Bearings Lubricated with Refrigerant", Proceedings of *International Compressor Engineering Conference*, Purdue, No. 2556.

[13] ISO 15243:2017, Rolling bearings -- Damage and failures -- Terms, characteristics and causes, ICS 21.100.20.

[14] Schöppl, O., 2012. Developments in ceramic bearing balls, *SKF Evolution Magazine* 1 2012, 25-29.

[15] SKF, 2016. SKF hybrid bearings for extreme application conditions, *SKF publication* 16651.

[16] Hauleitner, R., Morales-Espejel, G.E., Arvidsson, M. 2017. Tribological Aspects of Rolling Bearings Lubricated with Refrigerant. Proceedings of *World Tribology Conference*, Beijing, China.

[17] Kahlman, L., 2013. Oil-Flooded Screw Compressors: Predicting MTBF under Various H2S, C02 and H2-rich Conditions for Rolling Bearings Designed for Process Gas Use, Proceedings of *Gas Machinery Conference,* Albuquerque.

[18] Morales-Espejel, G.E., Gabelli, A., Vieillard, C. 2001. Hybrid Bearings Lubricated with Pure Refrigerants. *SRM Technical Screw Compressor Conference*, Stockholm.

[19] SKF, 2015. Evolving chiller performance – SKF solutions for centrifugal compressors in chillers, SKF publication 15693.

[20] Kahlman, L., 2018, New Rolling Bearing Technologies for LNG Pumps and Vapour Recovery Units, *LNG18,* Perth Australia.

[21] "Natural Five", Mayekawa Mfg. Co. Ltd, www.mayekawa.com/activities/natural5/.