Influence of dynamic eccentricity on the pumping rate of rotary shaft seals at sub-zero temperatures

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In this paper, the influence of dynamic eccentricity and low operating temperatures on the pumping rate of elastomeric rotary shaft seals is analysed experimentally. For this purpose, function tests and pumping rate measurements were carried out at different dynamic eccentricities up to 0.3 mm (0.6 mm TIR) and oil sump temperatures between +40 and -20 °C with rotary shaft seals made of nitrile rubber (NBR) and fluoro rubber (FKM) in combination with synthetic polyalphaolefin oil FVA PAO1. The function tests and the pumping rate measurements show the application limits of the rotary shaft seals under the combination of dynamic eccentricity and low oil sump temperature.

1 Introduction

Elastomeric rotary shaft seals are complex tribological systems. They prevent lubricants from leaking between rotating (e.g. shaft) and stationary (e.g. gear housing) machine parts. Their sealing performance is essentially determined by the back pumping capability of the system. During the dynamic operation, rotary shaft seals can actively pump leaking fluid back to the fluid side. For the assessment of the pumping capability and the leak-tightness of the sealing system, the pumping rate can be used. The pumping rate measures the pumped fluid volume per time or distance.

In several research projects at the University of Stuttgart, analyses for the assessment of the leak-tightness by means of the pumping rate were performed for mineral and synthetic oils, [1] - [6]. An empirical model for calculating the pumping rate was developed, [2] and [3]. The calculation model is valid for a wide parameter range of the analysed rotary shaft seals. In further publications, the influence of static and dynamic eccentricities [4] and of low temperatures [5] on the pumping rate of rotary shaft seals was separately presented. However, the pumping rate behaviour was not analysed for the combined variation of dynamic eccentricity and low operating temperatures. Elastomer materials lose elasticity at low temperatures. A low elasticity of rotary shaft seals can negatively affect the leak-tightness even at moderate dynamic eccentricity.

2 Basics

In the following sections the sealing mechanism of rotary shaft seals, the pumping rate definition, the dynamic eccentricity and the effects of low temperature are briefly discussed.

2.1 Rotary shaft seal

Rotary shaft seals are dynamic sealing systems. During the dynamic operation, the lubricant enters the contact area between the sealing edge and the rotating shaft. Thereby, a sealing gap, which is filled with lubricant, is formed between the sealing edge and the shaft surface, Figure 1. Due to the different lip face angles, an asymmetric pressure distribution results in the contact area. Additionally, the rough elastomer surface of the sealing edge deforms elastically in circumferential direction while sliding on the shaft surface. Mainly the combination of these processes in the contact area results in an active back pumping capability, which prevents the lubricant from leaking out of the sealing gap. Furthermore, there are different operating principles explaining the active back pumping capability of rotary shaft seals in more detail, [7] - [9].

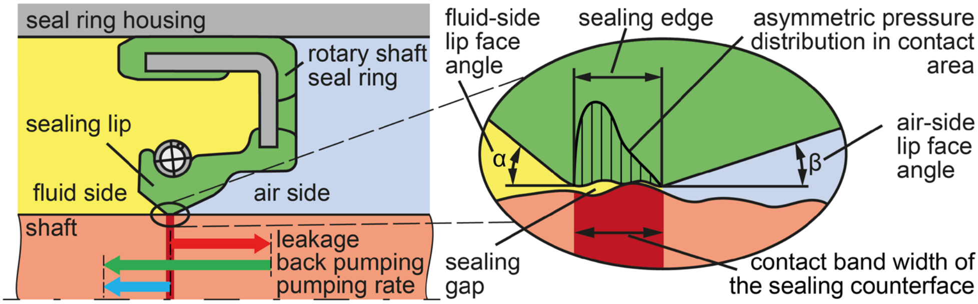

Figure 1: Sealing mechanism of rotary shaft seals according to [7]

2.2 Pumping rate

The active back pumping capability can be observed by offering oil to the rotary shaft seal on the air side. The offered oil is pumped from the air side to the oil side. The quotient of the pumped lubricant quantity and the elapsed time equals the pumping rate, which describes the back pumping capability quantitatively. Pumping rate measurements can show the influence of individual system parameters on the leak-tightness of rotary shaft seals, [1] - [6]. There are several test methods to measure the pumping rate of a sealing system, e.g. [1] - [7]. All these methods are based on two measuring principles. Either the amount of pumped lubricant (mass or volume) for a certain period of time (principle 1) or the time required to pump a certain amount of lubricant (principle 2) is measured. The pumping rate can be normalised for the comparison of sealing systems with different shaft speeds or with different shaft diameters. In this work, the pumping rate is given in µl/m as the pumped lubricant volume per sliding distance on the shaft surface according to equation (1), where Δm represents the mass of the pumped lubricant, D the diameter of the shaft, Δt the pumping time, ρ the density of the lubricant and n the shaft speed in rpm.

$$pumping\ rate = \frac{\Delta m}{\pi \cdot D \cdot \Delta t \cdot \rho \cdot n} \tag{1}$$

2.3 Dynamic eccentricity

The geometrical tolerances within a sealing system can influence its leak-tightness. The actual variations of form, orientation, location and run-out determine the extent of the static and dynamic misalignment. Standards like [10] and [11] and manufacturer catalogues (e.g. [12]) give users information on the acceptable geometrical tolerances. In this paper, the dynamic eccentricity is considered in more detail. Dynamic misalignment or dynamic run out (DRO) is the coaxiality variation of the geometrical shaft axis in relation to the rotational axis of the shaft, Figure 2. In this work, the dynamic eccentricity ε_{dyn} corresponds to the dynamic misalignment. The double amount of ε_{dyn} represents the total indicator reading (TIR).

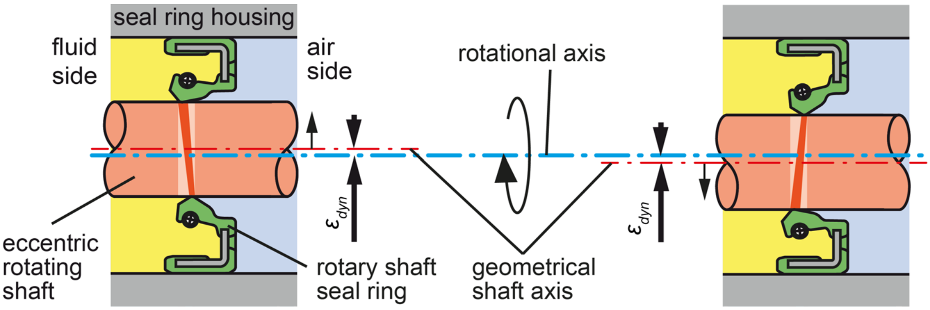

Figure 2: Dynamic eccentricity ε_{dyn} according to [7]

In case of dynamic eccentricity, the shaft performs a reciprocating motion in radial direction during rotation. The amplitude of the motion corresponds to the double amount of the dynamic eccentricity ε_{dyn}. The frequency of the motion depends on the shaft speed. The sealing lip is forced to follow this reciprocating motion of the shaft surface. In case of dynamic eccentricity and high shaft speeds, there is a risk of the sealing lip lifting off from the shaft surface due to the viscoelasticity of the elastomer, [13]. The sealing lip will no longer be able to follow the shaft motion, which may result in leakage. According to analyses by Ishiwata and Hirano [14], the limit of the sealing lip's ability to follow the shaft surface is proportional to the overlap between the rotary shaft seal and the shaft. Schuck [15] variates the frequency with which the sealing lip moves in radial direction by changing the shaft speed. The results in [15] show a strong dependence of the leakage behaviour on the shaft speed. The leakage increases up to a certain speed. As the speed continues to increase, the leakage drops to a low level. Britz [16] assumes that the sealing lip behaves like a reciprocating wedge. A model experiment is shown, where a reciprocating wedge is positioned between two chambers filled with fluid. In the model experiment, the fluid is pumped in the direction of the converging gap. The model proves, that fluid can be pumped through a reciprocating wedge. By transferring the result of the model experiment to rotary shaft seals, it shows that the radially reciprocating sealing lip can pump the fluid from the air to the fluid side.

In an earlier publication [4], the influence of static and dynamic eccentricity on the pumping rate of rotary shaft seals was experimentally analysed at 40 °C. The static and dynamic eccentricities were varied full factorial between 0.0 and 0.3 mm at moderate shaft speed (circumferential speed of 6.5 m/s). Only in some cases a clear influence of the static and dynamic eccentricity on the pumping rate can be recognised. The dynamic eccentricity tends to have a stronger influence on the pumping rate than the static eccentricity. Depending on the oil-elastomer combination, the relationship between the two eccentricities types and the pumping rate differs.

2.4 Effects of low temperature

At low temperatures, the elasticity of elastomer materials decreases as the glass transition temperature is approached or is even passed below. Lower elasticity can reduce the ability of the sealing lip to follow the shaft surface and influence the active back pumping capability of the rotary shaft seal. As a result, even a small dynamic eccentricity (dynamic run out) can cause leakage at low temperatures. The exact range of the glass transition temperature depends on the actual elastomer compound material and also on the load frequency, [17]. Standards like [10] and [11] and manufacturer catalogues (e.g. [12]) provide users information on the minimum specified operating temperature for rotary shaft seal materials.

Furthermore, the viscosity of the lubricant increases as the operating temperature decreases. Depending on the oil-elastomer combination, the viscosity of the lubricant influences the pumping rate strongly, [2]-[5]. The pour point can be used for the minimum application temperature of liquid lubricants. The pour point is the lowest temperature at which a sample of an oil product barely flows under certain standard conditions during a cooling process. The pour point is determined according to ISO 3016 [18] and specified in oil manufacturers' catalogues and data collection catalogues (e.g. [19]).

In another earlier publication [5], the influence of low temperature on the pumping rate of rotary shaft seals was experimentally analysed. For this purpose, pumping rate measurements were carried out at oil sump temperatures between +40 and -20 °C. Depending on the oil sump temperature, slight changes in the pumping rate were observed.

3 Experimental approach

This section describes the pumping rate measurement method, the test rig and the test conditions which were used.

3.1 Method of pumping rate measurement

The pumping rate was measured according to [4] and [5] with an inversely mounted rotary shaft seal ring, Figure 3. The inverse assembly results in a continuous pumping of lubricant to the fluid side. The pumped lubricant can be collected in a beaker and weighed. From the pumped lubricant quantity and the pumping duration, the pumping rate is then determined according to equation (1).

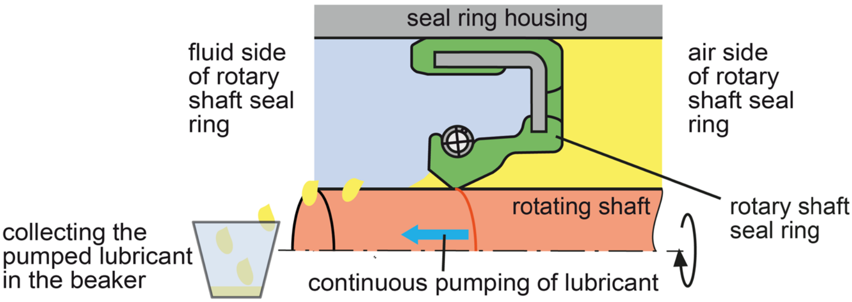

Figure 3: Pumping rate measurement with inversely mounted rotary shaft seal

3.2 Test rig

Figure 4 shows the test rig prepared for a pumping rate measurement at low temperature. Via a control computer, different test conditions can be set. The test shaft sleeve is mounted on a shaft adapter and connected to the drive shaft via a collet chuck with a hollow taper shank (HSK, [20] and [21]). The drive shaft is driven by a motor via a drive belt. The test seal ring is pressed into a holder that is mounted at the oil chamber. The aluminium housing walls of the oil chamber contain heating cartridges and circulating channels filled with cooling fluid. The oil is thus heated or cooled indirectly via a large surface without being thermally damaged, even at high heating or cooling power. The oil sump temperature is measured by a temperature sensor inside the chamber. For tests in the sub-zero temperature range, the oil chamber was equipped with a thermal insulation to improve the thermal efficiency. For cooling, an external temperature control system Julabo Magnum 91 was connected to the cooling circuit of the oil chamber. An additional front chamber with silica gel grain is mounted on the air side of the oil chamber to reduce the air humidity and to avoid icing at the air side of the test seal ring. Both, the oil chamber and the front chamber are not airtight and allow pressure equalisation.

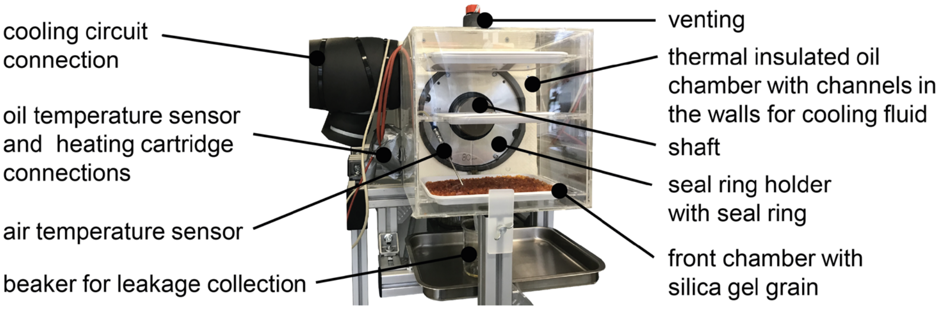

Figure 4: Test rig chamber

3.3 Test conditions

The pumping rate was measured with an inversely mounted rotary shaft seal ring, Figure 3. The duration of each pumping rate measurement was 10 hours. The whole pumping rate measurement duration was used as the pumping time for calculating the pumping rate according to equation (1). The nominal diameter of the sealing system was 80 mm. The test shaft was rotating with 1552 revolutions per minute, which corresponds to a circumferential speed of 6.5 m/s. The rotating speed and direction were constant during the test. For each individual measurement a new sealing system with a new rotary shaft seal ring and a new running track on the shaft surface was used. According to the previous works ([3] - [5]), the seals were not run in before the pumping rate measurement. According to [5], the oil level was completely filled with oil. Before each measurement the sealing system was tempered to the desired temperature while the shaft did not rotate. The tempering period was between 30 and 180 min depending on the desired temperature. Then the shaft drive was switched on and the measurement was performed.

3.3.1 Rotary shaft seal rings

Standard rotary shaft seal rings (dimensions 80x100x10 mm) with trimmed sealing edges made of fluoro rubber 75 FKM 585 (BAUMX7) and nitrile rubber 72 NBR 902 (BAUX2) from the manufacturer Freudenberg Sealing Technologies were used. The recommended minimum operating temperature is -25 °C for the FKM seal rings and -40 °C for the NBR seal rings, [12]. Seal rings from one batch were used for each elastomer material.

3.3.2 Lubricant

The synthetic polyalphaolefin reference oil FVA PAO1 was used. The FVA PAO1 oil is standardised by the FVA (German Research Association for Drive Technology). Figure 5 shows the viscosity-temperature behaviour of FVA PAO1. The oil viscosity decreases with increasing temperature. The pour point of FVA PAO1 is -58 °C, [19]. The oil used for the FKM seal rings was from another batch as for the NBR seal rings.

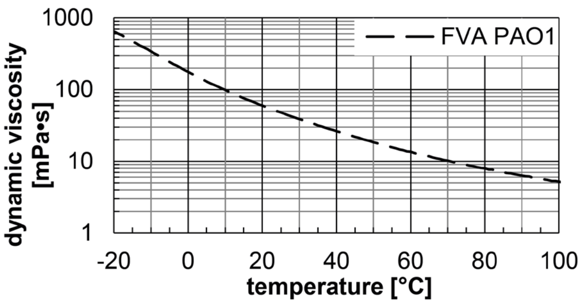

Figure 5: Dynamic viscosity of FVA POA1 [5]

3.3.3 Shafts

Plunge ground shaft sleeves made of 100Cr6 from the same manufacturer were used as test shafts in order to minimise the shaft surface influence on the pumping rate. All shaft sleeves were subjected to a comprehensive surface analysis, which includes 2D and 3D roughness measurement, microlead and macrolead evaluation and the thread method. All used shafts sleeves are inconspicuous concerning lead and have very similar 2D and 3D roughness parameters to each other, which are within the standard specifications. The surface roughness R_z of the shaft sleeves was between 1,88 and 2,33 µm.

3.3.4 Test settings for dynamic eccentricity and oil sump temperatures

According to [4], the dynamic eccentricity ε_{dyn} was varied in steps of 0.1 mm between 0.0 and 0.3 mm. In order to vary the dynamic eccentricity, shaft adapters were used, which take up the shaft sleeves eccentrically to the axis of rotation.

For the FVA PAO1 oil, -20 °C was determined as the minimum oil sump temperature that can be maintained at the shaft speed of 1552 rpm for the entire duration of the pumping rate measurement, [5]. The oil sump temperature was varied in steps of 10 K between -20 and +10 °C. Additionally, +40 °C was used. This results in twenty possible combinations of the dynamic eccentricity and oil sump temperature. All these combinations have been analysed in this work.

3.4 Function tests

To prove the functionality of the sealing systems at each dynamic eccentricity and low temperatures, function tests were carried out with both seal types. The function tests were performed with correctly installed seal rings under the same conditions as the pumping rate measurements. For each dynamic eccentricity, the oil sump temperature at which the sealing system was leak-tight was determined. For this purpose, the first function test was carried out at the lowest temperature of -20 °C for each dynamic eccentricity. In case of leakage, a further function test at the next higher temperature was performed. The temperature was increased stepwise until the sealing system was leak-tight and passed the function test. Once the sealing system was leak-tight, no further function tests were performed for the corresponding dynamic eccentricity. The sealing systems at further higher oil sump temperature levels are less critical and therefore to be assumed as leak-tight.

4 Results

Table 1 shows an overview of the function tests and their results. Leak-tight sealing systems are marked with “+”. The air side of their sealing contact was completely dry. Sealing systems with “○” were slightly wetted with oil on the air side of the sealing contact at the end of the function test. These sealing systems were characterised as borderline. Sealing systems with “-” have not passed the function tests due to leakage. Sealing systems with “*” were not subjected to a function test. These sealing systems are assumed as leak-tight. Two or more pumping rate measurements were performed for each borderline (“○”), leak-tight (“+”) and assumed as leak-tight (“*”) sealing system. For sealing systems with leakage (“-”) at the function tests, no pumping rate measurements were carried out. A total of 21 function tests and 75 pumping rate measurements were carried out. Part of the test runs with FKM seal rings were performed by Falkenecker [22].

Sealing systems with FKM and NBR seal rings were leak-tight at the lowest temperature of -20 °C without eccentricity (ε_{dyn} = 0.0 mm). Therefore, no further function tests were carried out at higher temperatures without eccentricity. Sealing systems with NBR seal rings are leak-tight up to lower temperatures than FKM at each eccentric set-up (ε_{dyn} values between 0.1 and 0.3 mm). This means that the NBR seal rings have a higher elasticity and thus a better shaft followability than FKM seal rings at sub-zero temperatures. This also corresponds to the lower recommended operating temperature of NBR seal rings compared to FKM seal rings, [12].

Table 1: Overview of the function tests

		ε_{dyn} [mm]								**Explanation**
		FKM				**NBR**				function test
		0.0	**0.1**	**0.2**	**0.3**	**0.0**	**0.1**	**0.2**	**0.3**	“+” – leak-tight
ϑ [°C]	**-20**	+	○	-	-	+	○	-	-	“○” – borderline
	-10	*	○	○	-	*	+	○	○	“-” – leakage
	0	*	+	○	-	*	*	+	+	no function test
	10	*	*	+	+	*	*	*	*	“*” – assumed to be leak-tight
	40	*	*	*	*	*	*	*	*	

Figure 6 shows the pumping rate as the arithmetic mean of all measurements for each elastomer for leak-tight sealing systems. This average pumping rate indicates the level of measured pumping rates. The pumping rate for FKM seal rings is more than twice as high as for NBR. For the oil-elastomer combination FVA PAO1 and FKM, the pumping rate is similar to the earlier publication [5]. For FVA PAO1 and NBR, the pumping rate is significantly lower compared to [5]. The high difference between the pumping rates at similar operating conditions was also observed in the earlier publication and may be caused by various factors, [4].

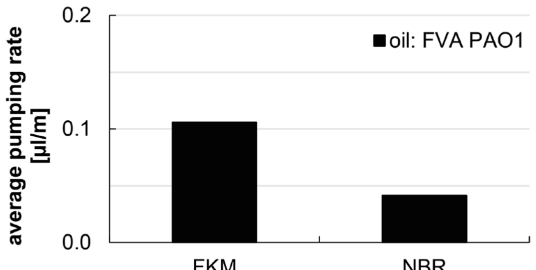

Figure 6: Influence of the elastomer on the pumping rate for leak-tight sealing systems

For each elastomer and each combination of the dynamic eccentricity and the oil sump temperature, there are at least two measured pumping rates, which were combined into an arithmetic mean. These arithmetic means are represented in Figure 7 and Figure 8. The average deviation of the individual pumping rates from the arithmetic mean values for each “leak-tight” combination of the dynamic eccentricity and the oil sump temperature is ≈ 10 % for FKM seal rings and ≈ 15 % for NBR seal rings.

4.1 Result for FKM seal rings

Figure 7 shows the result of pumping rate measurements for the sealing systems with FKM seal rings. For the sealing systems without eccentricity (ε_{dyn} = 0.0 mm), the pumping rate at -10 °C decreases slightly with decreasing temperature. As the temperature continues to fall, the pumping rate returns to the previous level. The pumping rates with ε_{dyn} = 0.0 mm are slightly higher than with ε_{dyn} values between 0.1 and 0.3 mm. For ε_{dyn} values between 0.1 and 0.3 mm the pumping rates are approximately similar with decreasing temperature until the borderline temperature from the function tests (Table 1). The pumping rates drop to almost zero at the borderline temperatures according to Table 1. The pumping rate drops between 0 and -10 °C for ε_{dyn} = 0.1 mm and between +10 and 0 °C for ε_{dyn} = 0.2 mm. For ε_{dyn} = 0.3 mm the system behaviour abruptly changes from leak-tight at +10 °C to leaking at 0 °C (Table 1). Therefore, no further pumping rate measurements were carried out.

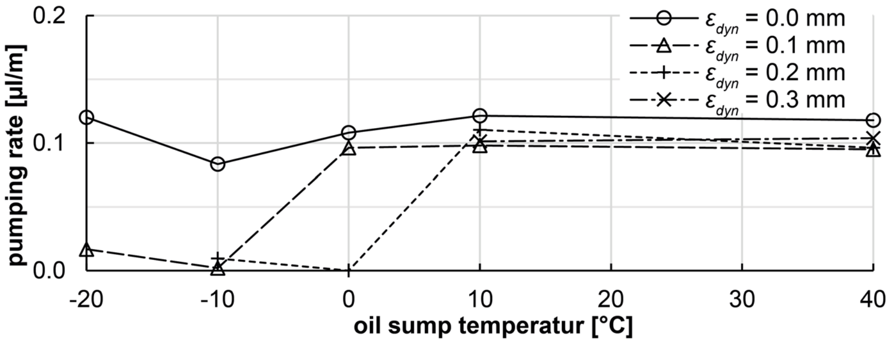

Figure 7: Influence of dynamic eccentricity and oil sump temperature for FKM

4.2 Results for NBR seal rings

Figure 8 shows the result of pumping rate measurements for the sealing systems with NBR seal rings. The pumping rates of the NBR seal rings show a similar behaviour to those of the FKM seal rings.

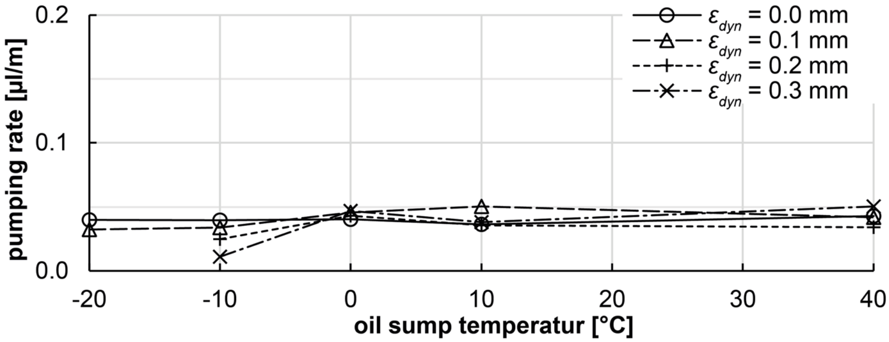

Figure 8: Influence of dynamic eccentricity and oil sump temperature for NBR

Compared with each other, the pumping rates of the NBR seal rings are at a similar level with decreasing temperature up to the borderline temperature from the function tests. For the borderline temperatures according to Table 1, the pumping rate decreases. For ε_{dyn} = 0.1 mm the pumping rate decreases slightly at -20 °C. At -10 °C, the pumping rates drop for ε_{dyn} = 0.2 mm by almost half and to almost a quarter for ε_{dyn} = 0.3 mm.

4.3 Visual observation of the sealing gap

Additionally, the sealing gap between the sealing edge and the shaft surface was visually observed from the airside during the tests (Figure 9). For this purpose, the inside of the oil chamber was equipped with LED lights. Already after dry assembly of the sealing system, a thin, circumferential thread of light was visible from the outside, independent of dynamic eccentricity. Figure 9 (G) shows this thread of light on a sealing system prepared for a pumping rate measurement with ε_{dyn} = 0.3 mm. This sealing system was dry assembled and contained no oil in the oil chamber at the time of recording. The shaft was not rotating without the oil.

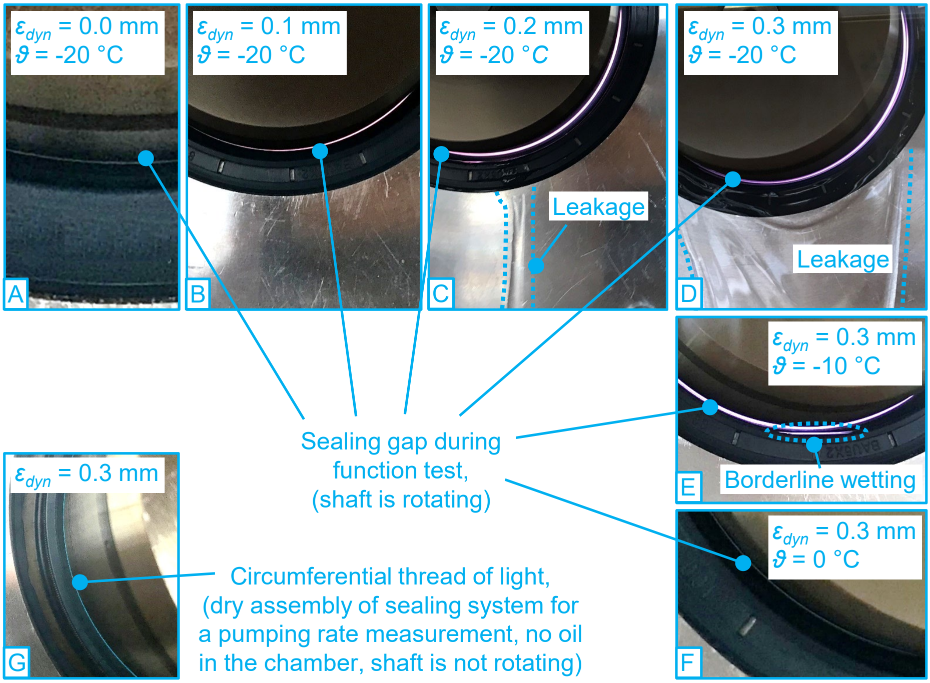

Figure 9: Visual observation of the sealing gap of NBR seal rings

During the functional tests at high dynamic eccentricity and low oil sump temperature, the sealing systems show a large rotating light gap (Figure 9 (C, D)). At -20 °C, the light gap and leakage increases with increasing dynamic eccentricity (Figure 9 (A - D)). With a remaining dynamic eccentricity of ε_{dyn} = 0.3 mm, the light gap and the leakage decrease with increasing temperature (Figure 9 (D - F)). Therefore, the results shown in Table 1 for the NBR seal rings correspond to the visualisations in Figure 9. A high rotating light gap means a local lifting of the sealing lip from the shaft surface, which can lead to leakage and thus to failure of the system.

5 Summary and conclusion

In this paper, the influence of dynamic eccentricity and low operating temperatures on the pumping rate of elastomeric rotary shaft seals was analysed experimentally. For this purpose, function test and the pumping rate measurements were carried out at different oil sump temperatures between +40 and -20 °C and different dynamic eccentricities up to 0.3 mm (0.6 mm TIR). The experimental analyses were performed with rotary shaft seals made of nitrile rubber (NBR) and fluoro rubber (FKM) in combination with synthetic polyalphaolefin oil FVA PAO1.

The function tests show the application limits of the seal rings under the combination of dynamic eccentricity and low oil sump temperature. Leak-tight sealing systems pass the function tests with a dry sealing contact at the air side. At function tests with operating conditions at the application limit, the air side of the sealing contact is slightly wetted with oil. These sealing systems are characterised as borderline. The application limit is exceeded as soon as the sealing system shows leakage during the function test. Sealing systems with NBR seal rings are leak-tight up to lower temperatures than FKM at each eccentric set-up.

Under the operating conditions at which the sealing systems pass the function tests, the pumping rates are relatively constant for each elastomer. The pumping rates for FKM seal rings are more than twice as high as for NBR. There is no clear influence of the dynamic eccentricity on the pumping rate for each oil sump temperature. Similarly, there is no clear influence of the oil sump temperature on the pumping rate for each dynamic eccentricity. Similar behaviour has been shown in earlier publications for various dynamic eccentricities at an oil sump temperature of +40 °C [4] and for sealing systems without eccentricity for low oil sump temperatures [5].

At the borderline operating conditions, the sealing systems show an abrupt reduction of the pumping rate. Therefore, the results of the function tests agree with the results of the pumping rate measurements. For the FKM seal ring, the pumping rate reduction is even almost to zero. The back pumping capability of the sealing system is severely impaired at the borderline operating conditions and the sealing system is no longer reliable. The elastomer elasticity reduces with temperature decrease. Low elasticity reduces both the ability of the elastomer sealing edge to deform elastically in circumferential direction and to follow the shaft surface in radial direction.

The dynamic eccentricity was varied in steps of 0.1 mm and the oil sump temperature in steps of 10 K (below 10 °C). With these relatively coarse steps, the borderline operating conditions were reached abruptly. For the pumping rate measurements, a slow approach to the borderline operating conditions was not observed. Performing further measurements with reduced steps in dynamic eccentricity and temperature, the borderline operating conditions could be resolved more accurately.

6 Nomenclature

Variable	*Description*	*Unit*
D	Diameter	m
Δm	Mass	kg
n	Speed	rpm
$pumping\ rate$	Pumping rate	µl/m
Δt	Time	s
ε_{dyn}	Dynamic eccentricity	mm
ρ	Density	kg/m³

7 References

[1] Remppis, M; Bauer, F.; Haas, W.: *Measurement of the Pump Rate of Radial Lip Seals During Long Term Tests.* Proceedings of the VII. Iberian Conference on Tribology (IBERTRIB), Porto, Portugal, June 20-21 2013, ISBN 978-972-752-156-2.

[2] Remppis, M.: *Untersuchungen zum Förderverhalten von Dichtsystemen mit Radial-Wellendichtringen aus Elastomer.* University of Stuttgart. Ph.D. thesis. 2016. ISBN: 978-3-936100-68-6.

[3] Bekgulyan, S.; Bauer, F.; Haas, W.: *Rechnerische Abschätzung der Dichtgüte von Radial-Wellendichtringen durch Kenntnis der Systemparametereinflüsse II.* Abschlussbericht, FVA, Forschungsvorhaben Nr. 617 II, FVA-Heft 1259, IGF-Nr. 17938 N/1, Frankfurt/Main, August 2017

[4] Bekgulyan, S.; Feldmeth, S.; Bauer, F.: *Influence of static and dynamic eccentricity on the pumping rate of radial lip seals*. 25th International Conference on Fluid Sealing, BHR Group, Manchester, March 4-5 2020, pp. 79-91, ISBN: 978-1-85598-177-5.

[5] Bekgulyan, S.; Feldmeth, S.; Bauer, F.: *Influence of Low Temperature on the Pumping Rate of Radial Lip Seals*. Machine and Industrial Design in Mechanical Engineering. KOD 2021. Mechanisms and Machine Science, vol 109,. Springer, 2022, ISBN 978-3-030-88464-2 / 978-3-030-88465-9, DOI: https://doi.org/10.1007/978-3-030-88465-9_12

[6] Sommer, M.; Haas, W.: *A new approach on grease tribology in sealing technology: Influence of the thickener particles.* Tribology International 103, Elsevier, Aug. 2016, S. 574-583, ISSN 0301-679X, DOI: https://doi.org/10.1016/j.triboint.2016.08.002

[7] Bauer, F.: *Federvorgespannte-Elastomer-Radial-Wellendichtungen. Grundlagen der Tribologie & Dichtungstechnik, Funktion und Schadensanalyse*, Springer Vieweg, Wiesbaden, 2021, ISBN 978-3-658-32921-1

[8] Müller, H. K.; Nau, B. S.: *Fluid sealing technology. Principles and applictions,* New York: M. Dekker, 1998, - ISBN 9780585128573.

[9] Müller, H.K.: *Concepts of Sealing Mechanism of Rubber Lip Type Rotary Shaft Seals.* 11th Int. Conf. on Fluid Sealing (BHRA), Cannes 1987, Paper K1.

[10] DIN 3760. *Rotary shaft lip type seals.* September 1996. (in German)

[11] DIN 3761-2. *Rotary shaft lip seals for automobils; applications.* November 1983. (in German, withdrawn in March 2017)

[12] Freudenberg Sealing Technologies GmbH & Co. KG: *Simmerring and rotary seals – Catalog (FNST)* – Volume 11. Weinheim. 2015

[13] Kawahara, Y.; Hirabayshi, H.: *A Study of Sealing Phenomena on Oil Seals.* ASLE/ASME Lubrication Conference, Kansas City, 1977

[14] Ishiwata, H.; Hirano, F.: *Effect of Shaft Eccentricity on oil Seal.* Second International Conference on Fluid Sealing, S. 17-32, Cranfield. 1964

[15] Schuck, O.; Müller, H.K.: *Rotary Shaft Seals at Large Dynamic Eccentricities.* 9th Int. Conf. on Fluid Sealing (BHRA), Norwijkerout, 1981, Paper D1

[16] Britz, S.: *Ein Beitrag zur Erfassung der Funktionsprinzipien dynamischer Wellendichtungen unter besonderer Berücksichtigung des Radialwellendichtrings.* Universität Kaiserslautern. Ph.D. thesis. 1988

[17] Jaunich, M.: *Tieftemperaturverhalten von Elastomeren im Dichtungseinsatz.* Technische Universität Berlin. Ph.D. thesis. 2012. ISBN 978-3-9814634-3-9.

[18] ISO 3016. *Petroleum and related products from natural or synthetic sources – Determination of pour point.* April 2019

[19] FVA-Heft 660: *Referenzölkatalog. Datensammlung.* May 2007.

[20] DIN 69893-1. *Hollow taper shanks with flange contact surface – Part 1. Hollow taper shanks type A and C; Dimensions and design.* April 2011. (in German)

[21] ISO 12164-1. *Hollow taper interface with flange contact surface- Part 1: Shanks – Dimensions.* December 2001

[22] Falkenecker, P.: *Pumping rate behaviour of rotary shaft lip seals in eccentric installation and at low operating temperatures.* Bachelor thesis : University of Stuttgart, Institute of Machine Components (IMA), 2018. IMA-2018-94-DT. (in German)

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