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Tribological behaviour of elastomer shaft seals lubricated with novel water-containing lubricants

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In response to global climate change and the demand for low-carbon technologies, novel lubricants are essential for improving powertrain efficiency and reducing emissions. Therefore, current research increasingly focuses on water-containing lubricants, which offer potential for loss reduction and enhanced thermal management in powertrains and transmissions, while also providing sustainability advantages over conventional lubricants. However, their compatibility and interaction with dynamic sealing systems under operating conditions has to be carefully evaluated.
Under dynamic conditions, a lubricating film forms between the elastomeric sealing lip of a radial lip seal and the counterface. Its thickness, primarily influenced by lubricant viscosity, is critical for sealing performance: While lower viscosities and the corresponding thinner films may result in a reduction of the viscous friction losses, excessively thin films may fail to fully separate surface asperities, leading to increased wear as well as elevated Coulomb type friction and hysteresis-related friction in the elastomer. Beyond viscosity effects, the lubricant's chemical and physical properties can influence the elastomeric material and, thus, the functionality of radial lip seals. In water-containing lubricants, evaporation of the water phase represents an additional challenge due to resulting changes in fluid composition.
This work aims to enhance the understanding of how water-containing lubricants affect the tribological behavior of elastomeric radial lip seals. A range of water-containing and conventional PG-based lubricants with a kinematic viscosity of 220 mm²/s at 40 °C are used to investigate the effects of formulation on the frictional behavior of radial lip seals over a wide range of sliding speeds. Additionally, long-term experiments are conducted to investigate the influence of water-containing lubricants on seal aging, sealing performance, and wear.

1 Introduction

Modern mechanical systems – from high-performance transmissions to electric powertrains – impose ever-greater demands on lubricants. To meet these challenges, the development of next-generation lubricants must address requirements like maximizing efficiency, minimizing wear, and ensuring environmental compatibility. A key challenge in this field is the reduction of friction and wear, which directly impacts energy consumption, component longevity, and operational reliability in mechanical systems. Recent trends in lubricant research have shifted toward water-containing lubricants, particularly those based on polyalkylene glycol-water mixtures.

One of the most compelling benefits of such lubricants is their ability to achieve superlubricity in elastohydrodynamically lubricated (EHL) contacts, with coefficients of friction (CoF) below 0.01, outperforming conventional lubricants in terms of friction reduction and, therefore, wear protection. Published studies have demonstrated up to an 82 % reduction in friction in single gear stages compared to conventional, e.g. PAO-based, gear lubricants. [1], [2]This phenomenon is attributed to the formation of hydration layers within the contact zone and the lubricant's low pressure-viscosity coefficient, which results in a lower effective viscosity under high-pressure conditions. [1], [3], [4]

In addition to their tribological performance, the higher specific heat capacity of water-containing lubricants facilitates improved heat dissipation in mechanical systems. In powertrains and electric vehicle applications, this property allows the lubricant to function not only as a lubricant but also as a heat transfer agent, potentially simplifying cooling system architectures. [2], [5]

From an environmental and safety perspective, water-containing lubricants present several advantages over conventional mineral or synthetic lubricants. Their non-flammable nature makes them ideal for use in explosion-proof environments, while their formulations are more environmentally friendly, exhibiting lower toxicity and improved biodegradability compared to petroleum-based alternatives. Additionally, water is an abundant and cost-effective resource, further enhancing the economic viability of these lubricants. [6]

While demonstrating notable tribological improvements in gear contacts, particularly their ability to achieve superlubrication, the behaviour of water-containing lubricants in sealing systems, such as radial lip seals, remains largely unexplored [7]. Their integration into sealing applications may present a challenge as certain elastomeric material, such as fluorocarbon rubber (FKM) and polyacrylate rubber (ACM), exhibit incompatibility with aqueous environments [8], potentially leading to swelling, hydrolytic degradation, or premature failure. Furthermore, the presence of water exacerbates corrosion risks in metallic components [6].

This study aims to investigate the behaviour of radial lip seals under the influence of water-containing polyglycol lubricants, with a focus on the following key questions:

- How does the use of water-containing lubricants influence the tribological performance, leakage behaviour, and long-term durability of radial lip seals?
- What challenges arise from the interaction between water-containing lubricants and sealing systems?

2 Materials and Methods

2.1 Radial Lip Seals

To investigate the behaviour of radial lip seals under the influence of water-containing lubricants, experiments were performed using standard single plain lip radial lip seals, i.e., without dust excluder lip or hydrodynamic aids, (according to ISO 6194-1) with a nominal shaft diameter of 35 mm, manufactured from acrylonitrile-butadiene rubber (NBR).

2.2 Lubricants

Two lubricants were evaluated in this study:

1. A commercially available polyalkylene glycol (PAG)-based gear oil, classified as ISO VG 220, used as a reference lubricant
2. A water-containing lubricant on a PAG basis, also formulated with a viscosity class of ISO VG 220

2.3 Seal Friction Measurement

In order to characterize the frictional behaviour of a sealing system, the seal pump rate test rig as shown in Figure 1 was used. A high-precision torque measurement shaft (KTR-Dataflex 16/10) with a measuring range up to 2 Nm was installed between the electric motor and the test rig bearings (spindle bearings), thereby measuring the total friction torque of both the bearings and the test seal. During data post-processing, the bearing friction component was subtracted using a pre-determined correction table to isolate the seal-specific friction torque. The test seal was installed in a mounting fixture, with the oil side submerged in an oil sump maintained at the shaft centreline level. The sump was vented to atmospheric pressure and the oil temperature was measured using a thermocouple and controlled via cartridge heaters integrated into the housing wall. An integrated sight glass provided visual access to the oil sump and the oil side of the test seal, enabling the observation of any changes in the lubricant – such as phase separation – throughout test duration. Data acquisition was performed at a sampling rate of 1 kHz for all key variables, including friction torque, oil sump temperature and rotational speed. The raw signals were downsampled by averaging every 100 samples. Subsequently, the processed data were stored at a rate of 5 Hz.

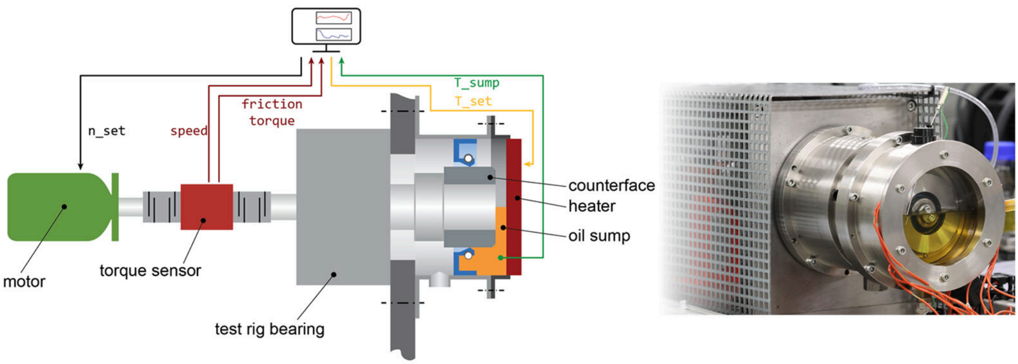

Figure 1: Test setup used for friction torque measurements

The sealing systems were evaluated across a range of sliding speeds following the procedure outlined in Figure 2. To minimize water evaporation, the oil sump temperature was set to 40 °C throughout the experiments. It should be mentioned that the actual operating temperature could exceed the target setpoint as a result of frictioninduced heating within the sealing contact due to the absence of an active cooling system. Each test began with a one-hour preconditioning phase at the lowest set speed (200 min^{-1}) to establish thermal steady-state. Subsequently, the speed was incrementally increased in steps of 200 min^{-1}, with each speed step being held constant for three hours to ensure steady-state conditions. The testing sequence progressed from 200 min^{-1} to 2000 min^{-1}, followed by a final stage at 2728 min^{-1} (equivalent to a sliding speed of 5 m/s). After reaching the maximum speed, the rotational velocity was decreased symmetrically in the same step-wise manner, resulting in a total runtime of 64 hours per test.

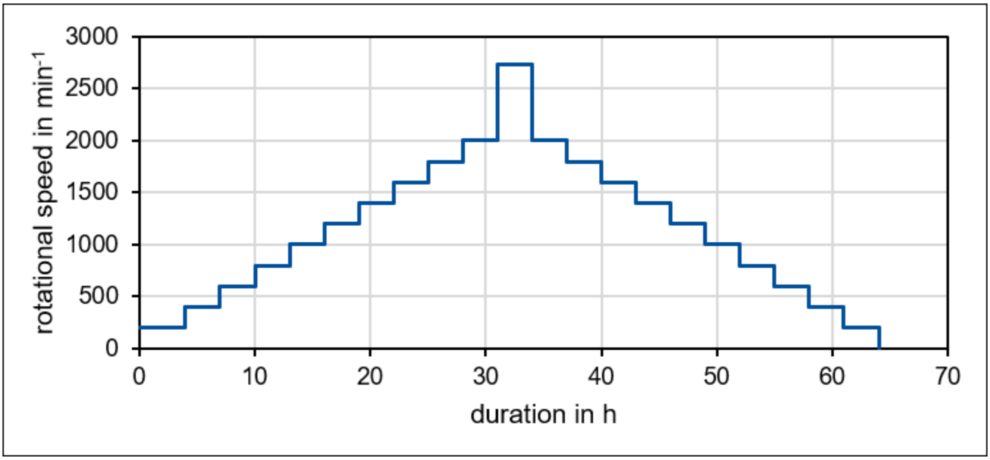

Figure 2: test procedure for measuring seal friction

2.4 Seal Leakage Behaviour

To investigate whether water-containing lubricants impair the functional performance of dynamic sealing systems, experiments were conducted using an endurance seal test rig (validated for compliance with Flender testing specifications) as shown in Figures 3 and 4. In this setup, the test seal was installed in a dedicated mounting fixture, with the test head being filled with about 1 litre of lubricant to the shaft centreline level. The counterface was connected to the electric motor via an adapter, enabling rotation at the specified speed. Temperature control was achieved using jacket heating on the test head, with the setpoint of 40 °C maintained through feedback from a PT100 resistance thermometer. Thereby, the test seals were operated for 10 days at a constant rotational speed of 2728 min^{-1}, which is the equivalent to a sliding speed of 5 m/s. Potential initiation and progression of leakage was continuously monitored using cameras, which captured images of the radial lip seal at regular intervals of a few seconds. This approach generated a time-lapse sequence that was subsequently analysed to assess leakage behaviour throughout the test duration. Images were acquired at regular intervals of a few seconds. This approach generated a time-lapse recording that was subsequently analysed to assess leakage patterns and progression rates over the entire duration of the experiment.

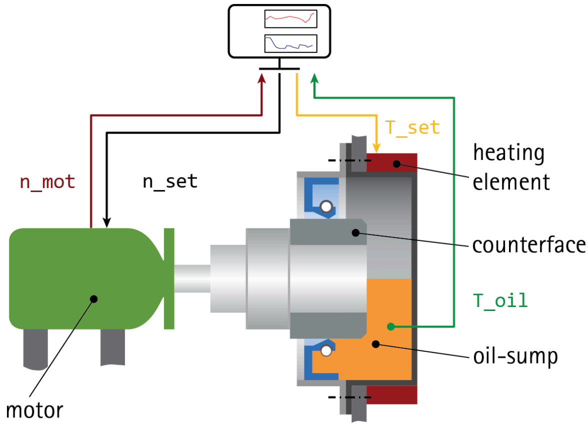

Figure 3: Schematic overview of the endurance seal test rigs used for investigating leakage behaviour

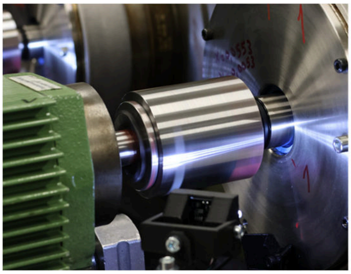
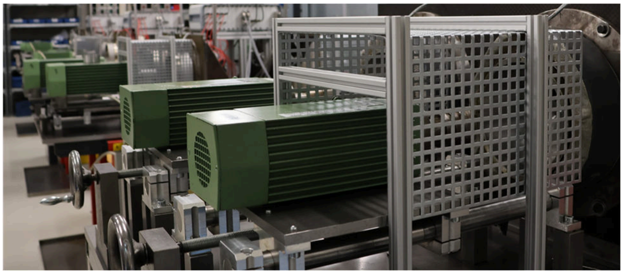

Figure 4: Images of the endurance seal test rigs. In the left image, the camera observing leakage is visible

2.5 Analysis of Sealing Systems and Lubricants

Following each test, both the sealing lip and lubricant properties were analysed using various analytical techniques.

To characterize wear on the sealing lip, a 3D optical profilometer (Keyence, VR-6000) was utilised to scan the entire circumference of the lip, see Figure 5. This method enabled precise measurement of the wear band width and facilitates detection of surface damage in the contact zone, including grooving, cracking and deposits. Furthermore, lubricant samples were analysed via Fourier Transform Infrared (FTIR) spectroscopy (Bruker Optik GmbH, INVENIO-R). This method provides detailed information on chemical changes that occurred during the experiment due to interaction with the sealing system.

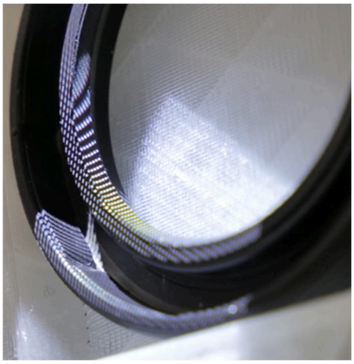

Figure 5: Light strips projected onto the sealing lip by the 3D optical profilometer

Lubricant samples were analysed via Fourier Transform Infrared (FTIR) spectroscopy. This method provides detailed information on chemical changes that occurred during the experiment due to interaction with the sealing system.

3 Results and Discussion

3.1 Frictional Behaviour

This section examines the frictional behaviour of radial lip seals when exposed to water-containing lubricants compared to a conventional reference lubricant. The analysis aimed at identifying differences in friction torque and their dependence on operating parameters such as speed and temperature. Thereby, differences were observed in the frictional behaviour of sealing systems when comparing the reference lubricant (PAG-oil) to the water-containing PAG-based lubricant, as shown in Figure 6. The friction torque of the sealing system lubricated with the reference lubricant (Figure 6, blue) exhibited stable behaviour and reached steady-state conditions across all operating points. Furthermore, the friction torque values demonstrated high repeatability when returning to previously tested rotational speeds. Despite increasing rotational speeds, the friction torque did not exhibit a proportional increase beyond a certain point. This friction torque plateau correlated with thermal effects. Due to self-induced heating from the radial lip seal, the oil sump temperature deviated from the target setpoint of 40 °C with measured increases initiating at 1600 min^{-1} and peaking at 51 °C during maximum-speed operation (2728 min^{-1}).

When examining the friction curve of the sealing system lubricated with the water-containing lubricant (Figure 6, red), it is evident that the initial friction torque was substantially lower than that of the reference system. However, this advantage shrank over time, as the friction torque exhibited unstable behaviour and failed to reach a steady-state condition, and continued to increase instead. Even upon reducing the rotational speed, the friction torque remained elevated and did not return to the initial levels observed at the start of the test. As with the reference lubricant, the oil sump temperature began to rise at speeds higher than 1400 min^{-1}, though reaching a higher peak of 53 °C at the maximum test speed of 2728 min^{-1}. Despite water-containing lubricants exhibiting a higher specific heat capacity, this elevated temperature can be attributed to increased friction torque.

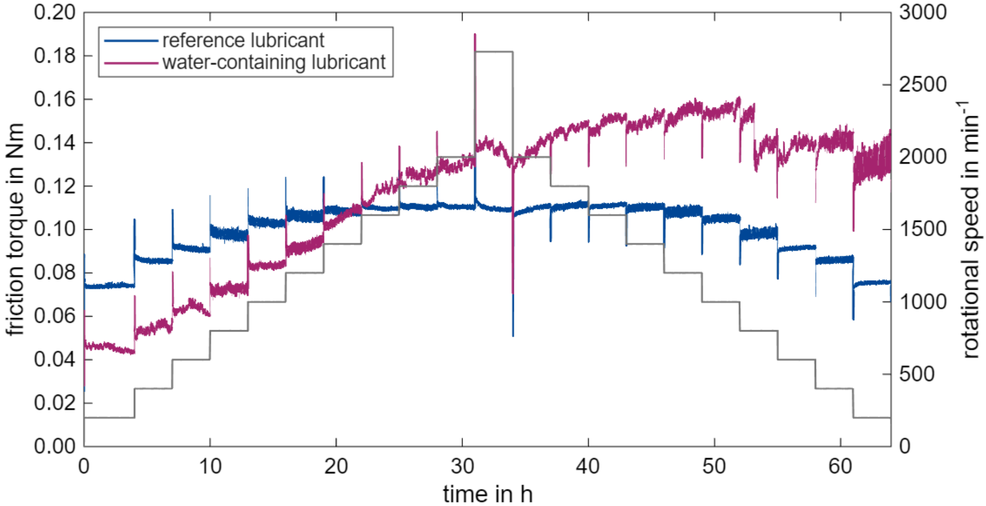

Figure 6: comparison of frictional behaviour of both investigated lubricants

3.2 Leakage Behaviour and Wear

Regarding leakage behaviour, the tests conducted with the PAG reference lubricant revealed no anomalies. All tested systems performed as expected, exhibiting no signs of failure nor leakage.

In contrast to the reference lubricant, sealing systems lubricated with the water-containing lubricant exhibited initial leakage onset after only 8 hours of operation. This leakage persisted continuously throughout the remaining duration of the experiment, resulting in a total leakage volume of approximately 150 ml by the end of the experiment. Therefore, manual lubricant fill-up was required to maintain the shaft centreline level. A series of images captured by the test rig camera is displayed in Figure 7, documenting the progression of leakage over time. Notably, the leaking fluid showed substantial deviation from the original lubricant composition, with visible residue deposits forming at the seal interface and in the collected leakage samples. Additionally, the viscosity of the leakage was substantially higher than that of the original lubricant. FTIR analysis of the original lubricant, the lubricant in the fluid sump after testing, and the leakage revealed no significant changes in chemical composition within the test head. This indicates that the lubricant did not degrade due to excessive heat from the heating elements or water evaporation during the test. Nevertheless, leaked samples showed complete water depletion and oxidative degradation, characterized by decreased C=C peak intensity, which indicates polymer breakdown.

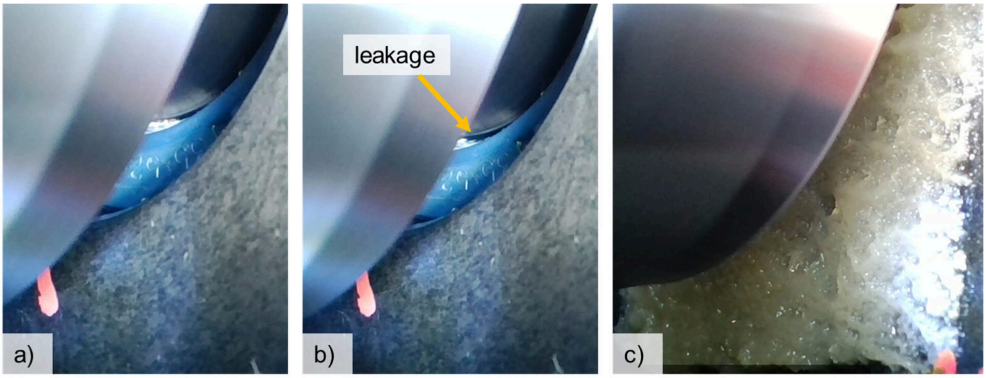

Figure 7: Air side of the radial lip seal, test with water containing lubricant; a) begin of the test, b) leakage onset, c) end of the test

As shown in Figure 8, analysis of the sealing lip revealed elevated wear in the sealing system lubricated with water-containing lubricants, characterized by a wear band of approximately 0.7 mm and severe grooving. In contrast, seals lubricated with the reference lubricant exhibited wear within tolerable run-in limits, with wear band widths of approximately 0.25 mm.

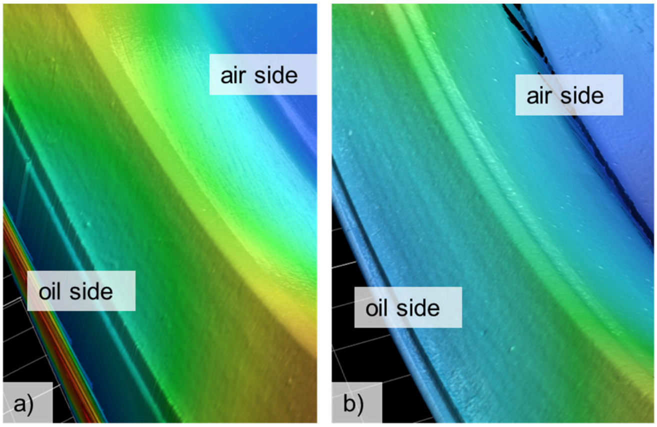

Figure 8: 3D profilometry of sealing lip of the seals used in leakage tests; a) reference lubricant, b) water-containing lubricant

4 Summary and Conclusion

While water-containing lubricants have demonstrated promising friction and wear reduction in highly-loaded EHL-contacts, particularly in gear applications, their performance in elastomeric sealing systems remains unexplored. This study investigates the compatibility of radial lip seals with water-containing lubricants through systematic testing of sealing systems using both a water-containing formulation and a commercial polyalkylene glycol (PAG)-based gear oil as reference.

It has been demonstrated that water-containing lubricants can initially reduce frictional losses in sealing systems. However, the friction torque exhibits unstable behavior, progressively increasing over time and ultimately resulting in inferior performance compared to PAG-based lubricants. Furthermore, experiments revealed that water-containing lubricants lead to leakage in sealing systems. This leakage coincides with chemical degradation of the leaked fluid, suggesting that tribological stresses in the sealing contact zone induce lubricant modification and accelerated degradation, thus disrupting normal sealing functionality. Counterintuitively, seal wear was severe despite leakage-induced lubricant replenishment, suggesting that leakage-related mechanisms (e.g., abrasive wear from contaminants) dominated over potential lubrication benefits.

In order to fully understand the underlying mechanisms responsible for the observed phenomena, future work should focus on investigating the processes occurring within the sealing contact zone. A promising approach involves utilizing a transparent sapphire hollow shaft as the counterface, enabling direct in situ observation of lubricant behavior, particularly to determine whether phase separation (aqueous and PAG phases) occurs under dynamic sealing conditions. [9], [10], [11]

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