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Influence of different media on the frictional contact of radial shaft seals

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Radial shaft seals are used in a broad spectrum of applications. These machine elements are exposed to a variety of intermediate media and ambient media. These substances have been demonstrated to exert a substantial influence on the tribological behavior in the sealing contact. Media can act as a lubricant, reducing friction and wear between the sealing edge and the counter surface. Conversely, some media have been observed to induce an increase in friction and wear. This paper examines the impact of various media on seal friction, exploring potential positive and negative influences in the sealing contact. To this purpose, investigations of the sealing contact are carried out. A test rig is used to record the frictional torque generated by the seal. The tests are carried out based on a minimum lubrication concept, whereby a small amount of the test medium is applied specifically to the sealing edge. This minimum lubrication test rig is used to make conclusions about the lubrication condition and the tribological system in general. In addition to the measurement of frictional torque, the influence of different media on the behavior of the sealing contact is investigated using optical tests. The experimental investigations include dynamic conditions of the tribological system of the radial shaft seal. This enables the documentation of the systems condition prior to operation, during the running-in phase, and after the completion of the running-in process in a state of stationary operation. These tests are used to identify the potential of specific media to either increase or decrease the friction within the system. Furthermore, the influence on wear behavior can be estimated. The different media can have a positive or negative influence on the system depending on the operating status.

1 Introduction

Radial shaft seals (RSS) play a important role in design. They prevent oil from leaking out of a housing, e.g., a gearbox. At the same time, they prevent dirt and moisture from entering the housing. In this way, they prevent early failure of components such as bearings or gears. To meet these requirements, the elastomer seals must be compatible with the lubricants used and the additives required for the optimal function of the gear pairs or bearings.

To minimize wear on the radial shaft seals, the seal is designed to create a thin lubricating film at the contact area. Furthermore, in radial shaft seals, the pumping mechanism ensures that no lubricant escapes from the sealing contact. If a sealing effect against water ingress is also required, both fluids come into direct contact. Depending on the water exposure, mixing of the two fluids at the sealing lip cannot be entirely avoided. Alternatively, the two fluids can be separated from one another by an additional sealing lip, such as a protective lip. In cases of very high performance requirements, additional seals must also be used.

This study examines the influence of additional additives on sealing performance based on measurements of friction torque and lip temperature. The study also examines the effect of water on the tribological behavior of the seal. To better understand the processes occurring at the seal and within the sealing contact, tests are also conducted using a hollow glass shaft and observed via microscope. This allows researchers to observe whether, how, and when water or an added additive enters the sealing gap.

2 State of the art

2.1 Friction of seals

According to Kummer [6] , friction at seals consists of four physical mechanisms: fluid friction, hysteresis friction, adhesive friction, and cohesive friction. In many cases, cohesive friction is neglected in modeling because only minor wear occurs. Adhesive friction plays a particularly significant role at very low relative velocities and when starting from a standstill. At higher speeds, this component of friction is often not taken into account in the model.

Engelke [3] has developed a friction model for RSS that accounts for an initial friction torque and a friction torque dependent on viscosity and speed due to fluid friction. Rocke and Salant [11] has developed a friction model for fluid friction that takes rough surfaces into consideration. Berndt [1] modeled seal friction based on Salant’s model, representing it as a combination of fluid friction and hysteresis friction. In this model, the hysteresis friction components decrease as contact decreases due to an increase in lubricant film thickness. The model demonstrated that roughness on the counterpart surface causes deformation of the seals even with a very thin lubricating film. This allowed a good correlation with measured friction characteristics.

2.2 Additives

Additives are often added to improve the properties of lubricants, e.g., to provide wear protection under extreme pressure (EP), to improve viscosity-temperature behavior, to protect metal components from corrosion, to prevent aging, to improve dispersion properties, to prevent foaming, and much more. Depending on the application, additive concentrations in the oil can range from very low levels [<1%] to as high as 30%. There are also additives that improve friction, such as friction modifiers. According to Möller and Nassar [9] the interactions between the additives and the seals must also be taken into account. It must be determined whether, in addition to their intended effect on gear tooth contact and in rolling bearings, the additives also have a positive or negative effect on the seal and seal friction.

Friction can also be directly influenced by changing the viscosity. Teichert and Kröger [12] demonstrated an adaptive adjustment of the lubricant’s viscosity in a minimal-lubrication concept for radial shaft seals without spring. In this experiment, lubrication was initially performed with a high-viscosity oil, and then a low-viscosity oil was injected. In a second step, high-viscosity oil was injected into the seal contact again; see Fig. 1. The coefficient of friction drops to a much lower value, which closely matches the steady-state coefficient of friction during initial lubrication with the low-viscosity oil. To verify this effect, the high-viscosity oil was then injected again. The coefficient of friction did not fully return to its original value, suggesting that some of the low-viscosity oil remained in contact.

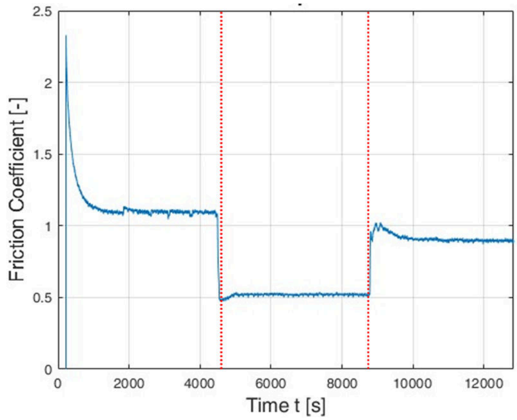

Figure 1: Friction coefficient versus time of a radial shaft seal at circumferential velocity of 1 m/s; first high viscose oil (ISO VG 460) was used, at the marked time oil with small viscosity (ISO VG 32) and later with high viscosity (ISO VG 460) are injected [12].

2.3 Sealing against water ingress

To prevent moisture and dirt from entering the housing, a grease-lubricated protective lip is often used on the shaft seal, positioned in front of the sealing lip. Freudenberg [5] also recommends a second radial shaft seal for applications with heavy contamination. Other recommended solutions include, for example, axial protective lips in contact with a centrifugal protection disc, radial shaft seals with two protective lips, or cassette seals.

The manner and amount of water acting on the seal have a significant influence on the sealing contact. This can involve individual water droplets, a surrounding water bath, or even a jet of water. Experiments using an external water bath were conducted, for example, by Wennehorst [14] and subsequently by Ottink [10]. With an external water bath, Ottink observed significantly lower temperatures at a sealing contact of a special bearing seal and a significantly reduced friction torque. Analyses of the lubricant on the bearing behind the seal revealed a small increase of the water content in the lubricant.

3 Experimental setup

A test rig, see Figure 2, based on the minimal lubrication concept is used to conduct the experiments. The test rig was developed in-house at the Institute for Machine Elements, Design, and Manufacturing [1]. The test rig is driven by an electric motor, whose shaft is connected to an intermediate shaft via a bellows coupling. The intermediate shaft is supported by a bearing block to ensure precise concentricity. At the end of the intermediate shaft is a chuck in which the shaft journal is clamped. The counter surface for the radial shaft seal (RSS) is mounted on this journal. The RSS is seated in a flange connected to a torsion sensor via a thermal insulating body. Thus, the frictional torque transmitted to the RSS by the driven shaft is detected at the seal flange. The mounting direction of the RSS can be freely selected. On the outward-facing side of the RSS, the seal lip temperature is measured non-contact via a pyrometer. Additionally, lubricant or other substances can be precisely applied to the seal lip using a syringe. A syringe pump is used to dispense small quantities for minimal lubrication. This enables different lubricants to be injected in varying amounts while the test rig is in operation, allowing the direct impact on the friction torque to be observed.

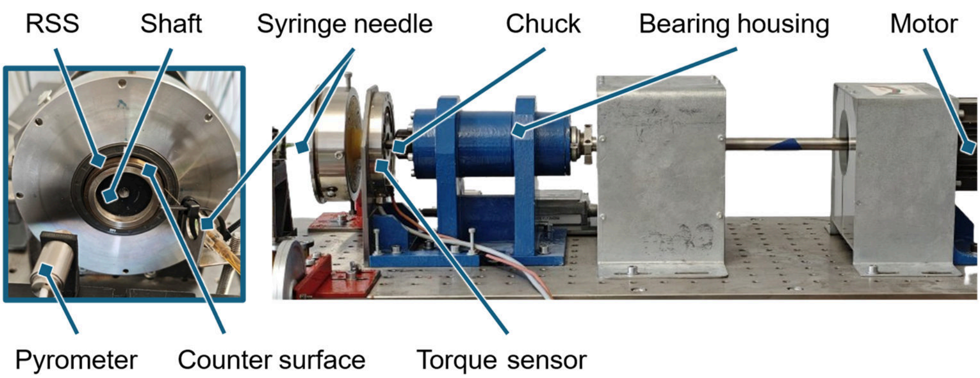

Figure 2: RSS test rig for friction torque measurement at IMKF

In addition to the setup for measuring friction torque, the test rig can also be modified to visualize the sealing contact using a microscope. The microscope setup is shown in Figure 3. In this configuration, the steel shaft journal is replaced with a transparent glass hollow shaft. This allows the sealing contact to be observed via an angled mirror located inside the glass shaft. The visualization setup is intended to provide a better understanding of the tribological behavior in the sealing contact. Once the test rig is modified in this way, neither friction torque measurement nor temperature measurement can be performed.

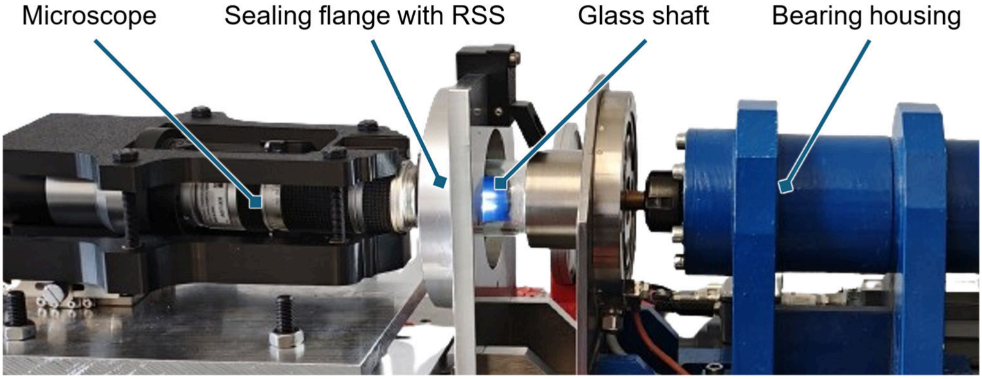

Figure 3: RSS test rig with microscope

3.1 Test material

The tests use HMS5 RG radial shaft seals from SKF. According to DIN 3760, these are radial shaft seals of type A 45 x 60 x 7, made of NBR (nitrile butadiene rubber) [2]. In addition to the substances being tested, the reference oil FVA3A is used as the intermediate substance. This oil has a kinematic viscosity of 90.02 mm²/s at 40°C and 10.41 mm²/s at 100°C. The density of the FVA3A oil is 884.1 kg/m³ [13]. The counterface consists of a INA inner ring of type IR40x45x20-EGS. This is made of rolling-bearing steel and is ground to be free of twist. For the tests, the inner ring is shrink-fitted onto the shaft journal, which is clamped in the chuck. Since the shaft journal can be moved axially within the chuck, multiple tests can be performed on different contact lines on a single inner ring. Subsequently, the used inner ring can be removed and a new inner ring shrink-fitted.

4 Experimental procedure

As part of this research, tests have been conducted to determine the short-term effect of various intermediate media on friction behavior at the sealing contact. The medium being tested was injected onto the sealing contact using a syringe. To ensure comparable test conditions across individual experiments, a running-in process was first performed on new RSS. For this purpose, the counterface was coated with the test oil FVA3A prior to mounting the RSS. During the running-in process, a circumferential speed of 4 m/s was maintained for a period of 2 hours. Afterward, the actual friction tests were conducted. The objective of the friction tests was to investigate the influence of different intermediate fluids on the short-term friction behavior of the RSS.

4.1 Preliminary test of oil additives

In a preliminary test, different additives available in retail stores that let consumers modify the properties of their oil were evaluated. Table 1 lists the additives that were used.

Table 1: Additives

Number	Additive	Brand/Manufacturer
1	Hydraulic System Additive	Liqui Moly
2	MoS_2 – Anti Wear	Liqui Moly
3	Stop Up	Errecom

As these additives are sold commercially, information about their exact composition and ingredients is not published. Additive 1 is an additive for hydraulic systems designed to protect sealing materials and reduce friction. It is also intended to reduce wear and corrosion [7]. Additive 2 is a molybdenum sulfide additive primarily designed to protect against wear by forming a high-load-bearing lubricating film on metal surfaces. This is also intended to reduce friction [8]. Additive 3 is a leak-stop additive. It is designed to stop micro-leaks in seals by restoring the original properties of seals that have already been in use [4].

The preliminary test, see Figure 4, have been conducted at a constant circumferential speed of 4 m/s too. The additives were injected one after another by hand onto the oil side of the seal. To ensure comparability, the first additive was not injected until the RSS had completed a warm-up phase. During the warm-up, small amounts of FVA3A oil were injected onto the oil side of the seal several times to ensure that the sealing contact remained continuously lubricated with oil. After 11 minutes, Additive 1 was injected. Since the injection was performed manually in this preliminary test, no defined volume could be preset. The volumes involved, were in the range of 100 µl to 3 ml. After injecting the first additive, a short period was observed to see how the friction torque was affected. After this, the sealing lip was flushed with FVA3A oil so that the base oil would once again be the primary lubricant in the sealing contact. Since this was a preliminary test, there was no cleaning of the seal and counterface, which would have been time-consuming, because of a new warm-up phase which would be required. Thus, Additive 2 could be injected at 21 minutes. Here, too, the sealing contact was subsequently flushed again with FVA3A oil. At 38 minutes, Additive 3 was injected, which remained in the sealing contact until the end of the test.

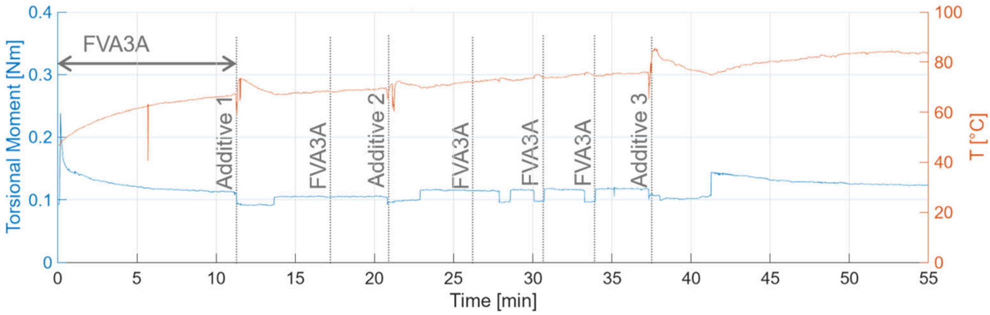

Figure 4: Diagram torsional moment and temperature while injection of different additives (Preliminary test)

Figure 4 illustrates the friction torque curve for the present experiment. It indicates that the injection of specific additives can influence friction. Particularly at the 11-minute mark, it is clearly visible that the friction torque drops significantly after the injection of Additive 1. Similar changes in friction torque are also observable as the experiment continues. However, since the system was not cleaned between experiments, it is not possible to assess the influence of the individual additives independently of one another. Furthermore, due to the imprecise, manual addition of lubricant and additives, it cannot be ruled out that the friction state is influenced not only by the increased fluid volume directly or indirectly via a change in temperature. It is therefore necessary to conduct an isolated analysis of the individual additives.

4.2 Effect of additive 3 on seal friction

To examine the effect of the additives on friction individually, a test is performed with Additive 3, since the preliminary test had shown that, following injection of the additive, the friction torque first decreased and then increased. In this test, see Figure 5 - Test 1, the liquid was precisely dosed using a syringe pump. At the start of the test, 100 µl of FVA3A oil were applied to the oil side of the seal. After a 30-minute warm-up phase, Additive 3 was added in 2 µl increments every 5 minutes. Thus, theoretically, the manufacturer's recommended concentration of 60 ml per 1 liter of oil should been reached after 3 additions [4]. In reality, this concentration cannot be set exactly, since only a certain amount of oil can collect beneath the sealing lip of the RSS, which depends on the surface tension of the fluid, the rotational speed and the interfacial effects between the fluid and the surfaces of the friction partners. Accordingly, the injection of 2 µl of additive was repeated in 5-minute intervals for 30 minutes.

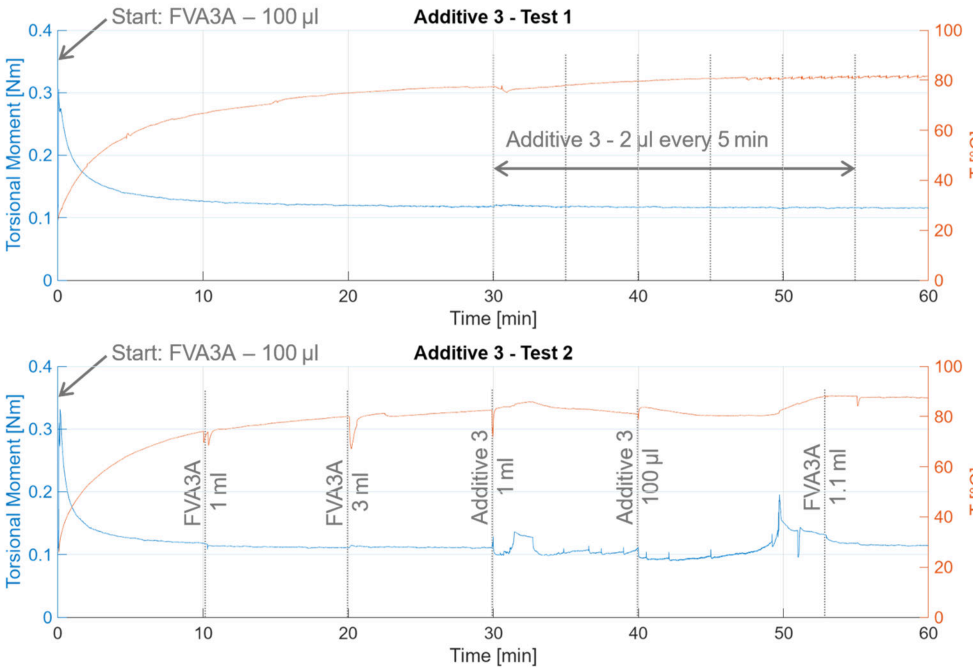

Figure 5: Tests with Additive 3; Test 1: Small amount of Additive 3 injected every 5 min; Test 2: Different amount of FVA3A oil and Additive 3 injected

Figure 5 shows that the injection of the additive has no detectable effect on friction. Because the preliminary test, in which significantly larger amounts of the additive were used, did show a change in the friction torque, a second test have been conducted to investigate Additive 3. This time, larger quantities of the additive were injected. To increase the chance that the injected additive reaches the sealing contact, the seal was installed in reverse for this test, so that the injection occurs on the air side and thus enters the sealing contact via the pumping effect of the RSS. To rule out the possibility that any changes in friction torque are caused solely by the injected volume, the injection volume of the FVA3A oil was also varied. At the start of the test, 100 µl of oil were dispensed onto the oil side of the RSS. After 10 minutes, FVA3A oil was added again, this time in a volume of 1 ml. After 20 minutes, another 3 ml of FVA3A oil were added. At 30 minutes, 1 ml of Additive 3 was then added. Figure 5 - Test 2 shows that the friction torque is influenced by the addition of the additive. Subsequently, at 40 minutes, another 100 µl of Additive 3 were added. At the 53-minute mark, an additional amount of FVA3A oil was injected into the system.

4.3 Friction tests with water

Since radial shaft seals can come into contact with ambient media such as water, which can then enter the sealing contact, preliminary tests were conducted to determine the effect of water on friction behavior. These tests have shown that water coming in touch with the sealing contact can also effect the friction torque. Therefore, friction tests have been conducted in which water is injected onto the RSS. In these tests, a circumferential speed of 4 m/s was maintained too.

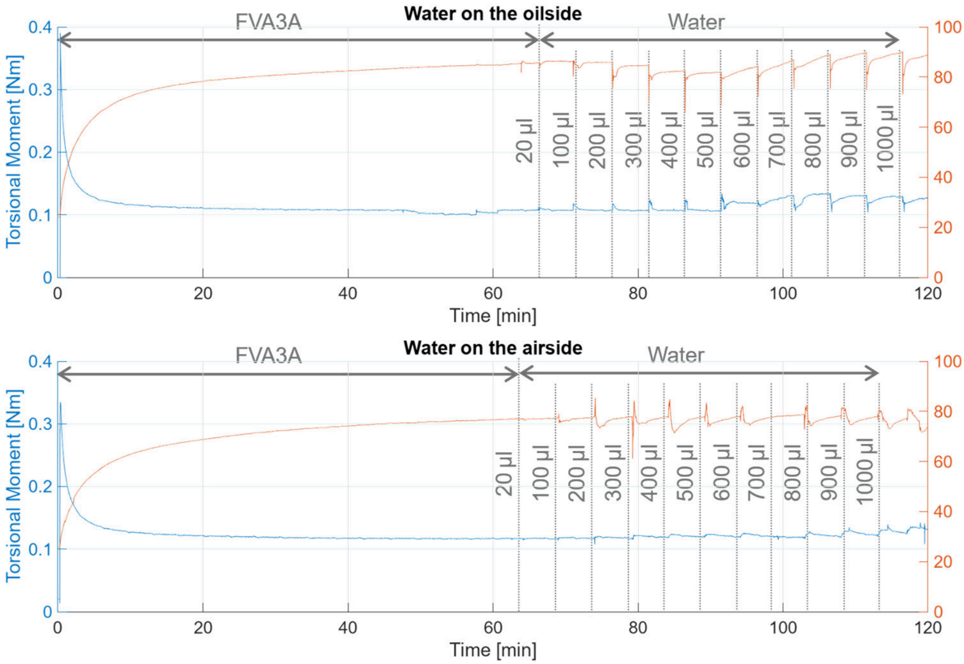

Figure 6: Different amounts of water injected to the RSS; Top diagram: Water is injected on the oilside; Bottom diagram: Water is injected on the airside

After a 65-minute warm-up phase, during which the sealing contact was lubricated with oil, water injection began. One pump stroke was performed every 5 minutes, with the volume started at 20 µl and increased with each stroke up to 1 ml. In the first friction test with water, see Figure 6 – Top diagram, the installation direction of the RSS is chosen such that the fluid was injected on the oil side of the RSS. In the second test, see Figure 6 – Bottom diagram, injection took place on the air side. It can be seen in both tests that the addition of water has an short-time and potentially long-time effect on the friction torque. The shape and magnitude of the change in friction torque also vary over several pump strokes. But this does not correlate clearly with the increasing volume of water that was injected. A comparison of the two tests reveals that injection on the oil side shows a significantly greater influence on the friction torque than injection on the air side. This is supported by the fact that the gap between the sealing lip and the counter surface is shorter on the oil side due to the different sealing lip angles and opens wider. This allows the water to come more easily to the contact area. However, this assertion is countered by the principle that the pumping effect of the radial shaft seal should transport the liquid from the air side to the oil side. Consequently, when injecting on the air side, there should be a greater probability that the water will reach the sealing contact.

4.4 Visualization of additive tests

Since the friction behavior observed in the additive tests cannot be conclusively explained based on the measurement data, the visualization setup was used. To investigate how the lubricant behaves beneath the sealing lip, the injection of the oil or additive was recorded using the microscope. For better visualization and due to manufacturing-related constraints, a RSS from the manufacturer Freudenberg was used. This is the BAUM type. The RSS has dimensions of A38 x 52 x 7 and is also made of NBR. To create good contrast during visualization, the black colored Additive 2 was used in addition to the nearly colorless FVA3A oil. According to the manufacturer's instructions, the additive was added to the FVA3A oil at a ratio of 5%, turning it black. Thus, the unmodified base oil appeared under the microscope in the color of the seal (blue), and the additive-oil mixture appeared dark (black). At the start of the visualization test, base oil was first injected onto the oil side of the RSS while it is rotating, see Figure 7 – 1 to 3. Subsequently, as in the friction tests, the base oil was also injected onto the air side of the RSS, see Figure 7 – 4 to 6.

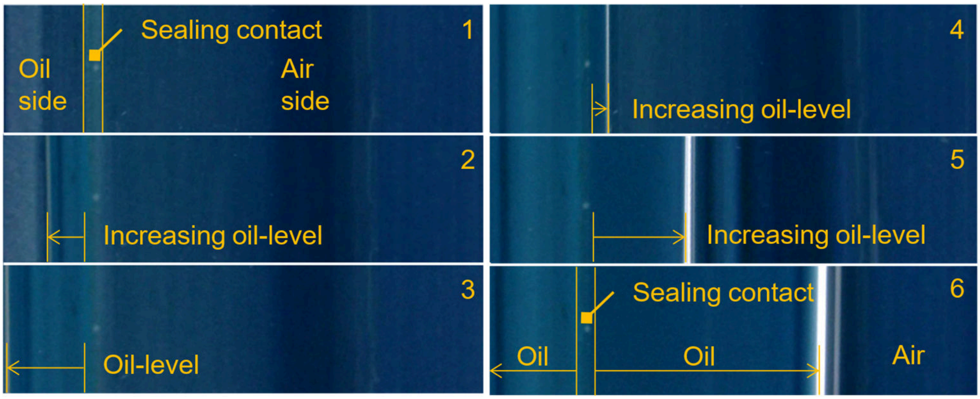

Figure 7: Injecting base oil on both sides of the seal

After both sides of the seal had been covered with oil, the test switched to the additivated oil. Injection took place on the air side of the RSS. A crucial detail here was that the injection needle did not pierce the oil meniscus boundary layer. Instead, the additivated oil was injected outside the oil meniscus, see Figure 8 - 1. After approx. 30 seconds, it was already visible that the additive-enhanced oil began to mix with the base oil in the oil meniscus, see Figure 8 – 2. After 50 seconds, the entire outer section of the oil meniscus consisted of an additive-oil mixture, see Figure 8 - 3. This state persisted for several minutes, and only minor changes were observable. After approximately 5 minutes, it could be seen, that the boundary between the base oil and the oil-additive mixture was becoming increasingly blurred. In addition, there was a slight coloration at the edges of the sealing contact, see Figure 8 – 4. This indicates that the base oil, which is still visible as blue within the oil meniscus, already contained a certain proportion of additive. After 15 minutes, the color change at the edges of the sealing contact has become more apparent. Additionally, it could be seen that the oil meniscus was shrinking, see Figure 8 – 5. But there's still a distinct strip visible that mainly contains base oil. On the left side, many base oil is observed.

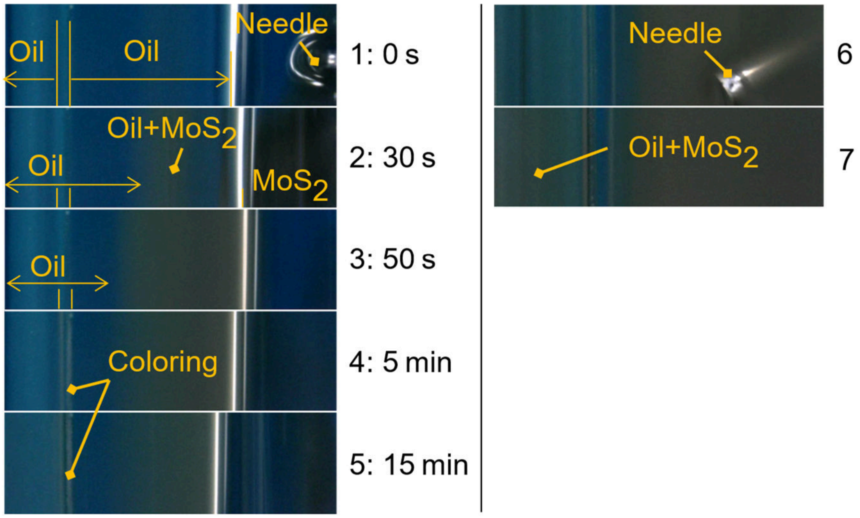

Figure 8: Injecting Additive 2 on the airside of the seal

In a second visualization test, see Figure 8 – 6 and 7, it was investigated whether it is possible to get the oil-additive mixture directly to the sealing contact. During the injection of the oil-additive mixture, the oil meniscus was pierced with the needle, and the oil was applied as close as possible to the sealing lip, see Figure 8 - 6. This ensured that the oil with additives came into direct touch with the sealing contact and, due to the pumping action of the seal, was also transported to the oil side through the seal contact, see Figure 8 - 7.

4.5 Visualization tests with water

To better understand the tribological behavior in the water tests as well, the visualization test was also repeated with water using the microscope setup. The sealing lip was covered with oil on both sides in the same manner as in the additive visualization test, see Figure 9 - 1. Subsequently, the water was again applied with the needle outside the oil meniscus. In the process, the surface of the RSS became fogged due to the water steam generated by frictional heat, see Figure 9 - 2. After some time, enough water was evaporated, that there are clearly visible steam bubbles on the sealing lip, see Figure 9 - 3. The interface between the oil and water appeared to prevent the water from penetrating the oil meniscus, although, as in the additive tests, it cannot be completely ruled out that a small percentage of the water still entered the oil.

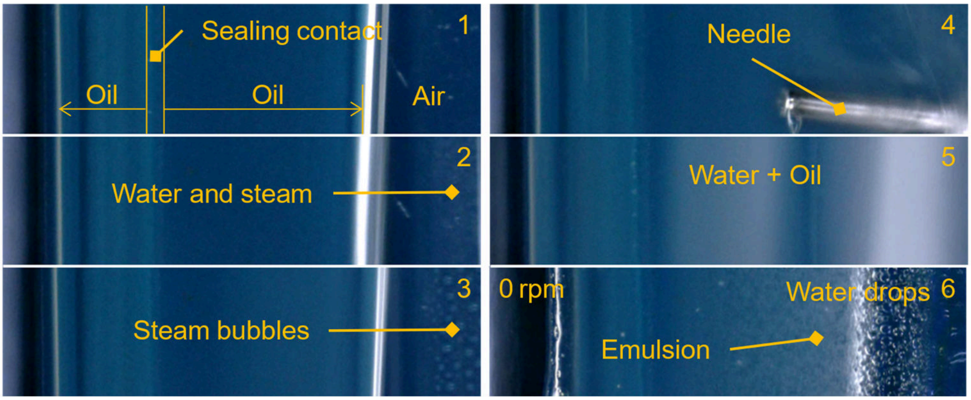

Figure 9: Injecting water on the airside of the seal

Similar to the additive tests, after applying the water outside the oil meniscus, the experiment examined what happens when the water is injected directly into the oil. To do this, the needle was used to pierce the boundary layer of the oil meniscus again, and the water was injected near the sealing lip, see Figure 9 - 4. After injection, it could be seen that the meniscus appeared lighter in color due to the injected water, see Figure 9 - 5. After the shaft rotation had been stopped, it was clearly visible that the oil formed an emulsion with the water, see Figure 9 - 6.

5 Summary and conclusion

The friction tests showed that injecting various substances to the sealing contact can lead to a change in friction behavior. Water causes a temporary and potential permanent increase in the coefficient of friction. The addition of various additives caused both an increase or a decrease in the friction torque. For both the additives and water, the amount injected does not correlate significantly with the magnitude, form, or duration of the change in the coefficient of friction. However, in the additive tests, the injection of very small amounts did not result in any impact on friction. The reasons behind this behavior were identified in the visualization experiments. These showed that the positioning of the needle during injection has a significant influence on whether and how quickly the injected substance reaches the sealing contact. If the oil meniscus is pierced during injection, the substance reaches the sealing contact directly and mixes with the oil. In contrast, when injected in front of the oil meniscus, it was observed that the boundary layer of the oil meniscus significantly slows down or completely prevents the injected substance from reaching the sealing contact. This also helps to better understand the friction behavior. Thus, in tests that show no change in the coefficient of friction, it is possible that the injected medium does not reach the sealing contact at all, or does so only after a significant delay. This also explains the phenomenon whereby the shape of the change in the coefficient of friction can differ with increased injection volume, even though it does not correlate directly with the injection volume, see Figure 6. The increased volume delivered by the syringe pump over the same period of time causes the pressure at the syringe needle to rise. As a result, larger volumes leave the syringe needle at a higher velocity, which could be sufficient to break through the meniscus and reach the sealing contact more quickly. Overall, the results illustrate the complexity of the interactions between the intermediate medium, the oil meniscus, and the sealing contact, and show that, in addition to substance properties, the conditions of substance transport in particular are essential for tribological behavior.

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