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## Frictional characteristics of elastomeric radial lip seals at extremely low temperatures

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A novel, low-temperature radial lip seal test rig was set up, allowing for simultaneous non-contact, telemetric measurements of both radial lip seal contact temperature and seal friction torque. Extreme cooling of the sealing contact zone down to below  $-50\text{ }^{\circ}\text{C}$  was achieved by continuously feeding carbon dioxide snow pellets into the bore of a hollow seal counterface adaptor. In this work, the frictional characteristics of single test seals that were wetted were investigated.

Experiments were conducted with plain radial lip seals made of NBR and FKM, respectively, using two polyglycol oils with different viscosity grades of VG 220 and VG 46, respectively. Starting from a stationary state at 200 rpm (0.84 m/s) with contact temperatures in the range of  $45\text{ }^{\circ}\text{C}$  to  $60\text{ }^{\circ}\text{C}$ , the sealing contacts were cooled down, finally reaching steady state seal contact temperatures as low as approx.  $-50\text{ }^{\circ}\text{C}$ . Thus, during cool-down of the sealing systems, both seal elastomers pass through the glass transition, and both lubricants pass through their pour points. In contrast to warm operating conditions, where speed-step dependent seal friction changes could be accurately predicted based on soft micro-elastohydrodynamic asperity lubrication theory, speed step experiments at such extremely low temperatures revealed that there was no viscous friction response, i.e., the seal friction was due to Coulomb-type friction. While showing larger fluctuations, the overall level of this Coulomb-type friction was comparable to the steady-state seal friction measured under warm operating conditions. When warming the systems up, the original lubrication mode was reestablished.

### 1 Introduction

Although elastomeric radial lip seals are used at extremely low temperatures, their behaviour under these conditions has not been sufficiently explored. Especially during operation at temperatures below the glass transition point ( $T_g$ ) of the elastomer as well as the pour point of the lubricant, the properties of the sealing system (e.g., the seal's elastic modulus or lubricant's viscosity) change drastically, preventing the prediction of the seal's behaviour.

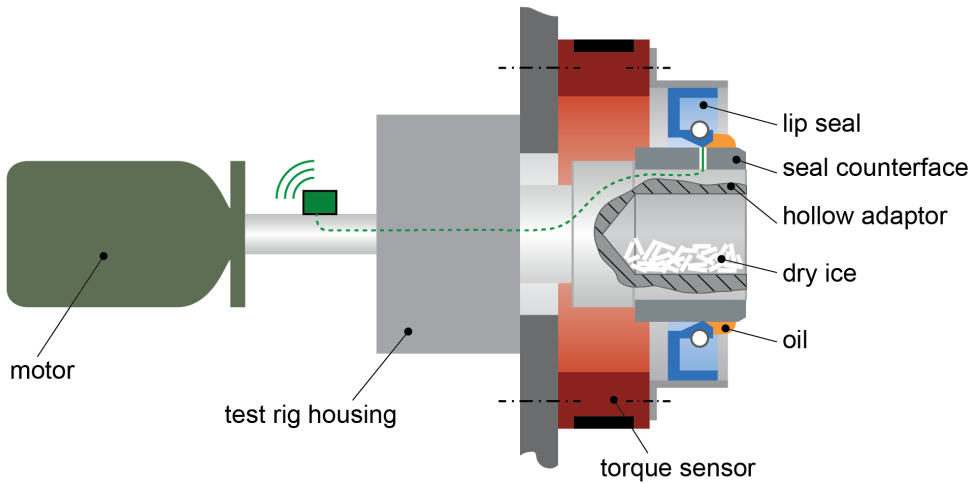
The aim of this study, which was originally presented in [1], is to introduce a method for the characterization of the friction losses of cooled down elastomeric seals and to discuss the behaviour of different combinations of elastomers and lubricants.

## 2 Experimental setup

This section describes the experimental equipment and tested materials in this study.

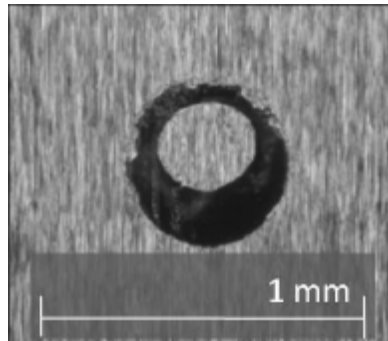
### 2.1 Low-temperature test rig

To investigate the functional behaviour of radial lip seals with regard to friction torque and contact temperature, a novel low-temperature functional test rig was developed and built, see Figure 1.

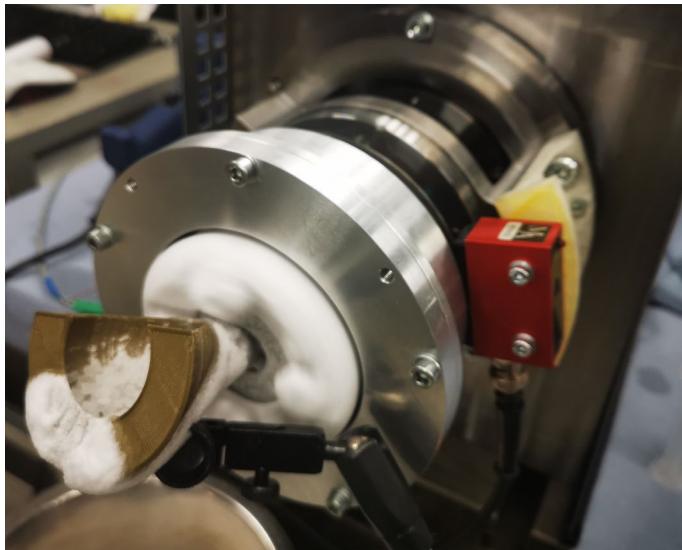


*Figure 1: schematic illustration of the low-temperature test rig*

In this work, a single test seal was mounted on the seal counterface in such a way that the sealing edge was placed on a miniature thermocouple cemented into and ground along with the counterface. This thermocouple, which had a diameter of approximately 0.4 mm, enables a direct measurement of the temperature inside the contact zone of the seal. A similar approach to measure the contact temperature is also described in [2], see Figure 2. The temperature signal is then transmitted telemetrically to the data acquisition system. To cool the sealing contact area, dry ice pellets approximately the size of a grain of rice were continuously fed into the hollow adaptor of the counterface by means of a feeding device consisting of a funnel and a covering disc, as seen in Figure 3. The contact zone in this design is cooled directly via the counterface so that, depending on the sliding speed, extreme contact temperatures of below  $-50\text{ }^{\circ}\text{C}$  could be achieved. To lubricate the sealing system, oil was applied manually to the oil side using a syringe. The seal itself was mounted in an adaptor that was connected to a torque measuring flange. By measuring frictional torque using this technique rather than at the drive shaft, systematic errors resulting from additional friction in the test rig bearings are eliminated.



*Figure 2: Miniature thermocouple ground along with the counterface, [2]*



*Figure 3: Low-temperature test rig during an experiment*

Although two identical test seals with an oil-filled inner gap in between may be evaluated in this setup, an arrangement with only one seal was studied in this work. By using this method, the oil-filled ring gap is avoided, the churning losses of which – caused by the oil's increasing viscosity as temperature drops – would significantly impede the measurement of the seal friction. As a result, the measured friction torque can be directly associated with the friction occurring in the seal lip.

## **2.2 Investigated elastomers and lubricants**

The experiments were conducted with plain radial lip seals with a nominal diameter of 80 mm made of NBR and FKM, respectively, using two polyglycol (PG) oils with different viscosity grades of VG 220 and VG 46, respectively.

In order to understand the characteristic behaviour of the sealing system, it is necessary to have information on the behaviour of its components. The temperature-dependent dynamic properties complex shear modulus ( $G^*$ ) and loss factor ( $\tan(\delta)$ ) of both elastomers were obtained by means of dynamic mechanical analysis at the Deutsches Institut für Kautschuktechnologie e.V. (DIK, Hannover). This analysis revealed a glass transition temperature ( $T_g$ ) of  $-28\text{ °C}$  for NBR and  $-12\text{ °C}$  for FKM at a frequency of strain oscillation of 0.1 Hz. At this temperature,  $\tan(\delta)$  reached its peak value, indicating a viscoelastic behaviour of the elastomer.

According to the datasheet of the lubricants, the pour points of PG ISO-VG 46 and PG ISO-VG 220 are  $-40$  and  $-35\text{ °C}$ , respectively. At these temperatures, the oils lose their viscous behaviour.

### **3 Experimental results**

Without yet cooling the sealing contact, the manually performed tests began at 200 rpm rotating speed (approx. 0.84 m/s). After the contact zone reached a steady-state temperature, dry ice was continuously fed into the hollow counterface adaptor. Once the contact temperature stabilised, the speed was gradually reduced to 2 rpm. Thereafter, the speed was gradually increased back up to the initial speed again, depending on the observed sealing contact behaviour. Finally, the cooling of the sealing contact was terminated so that a steady-state condition at 200 rpm was re-established at the end of the test. By comparing the corresponding temperatures and seal friction torques with the initial steady-state, conclusions can be drawn about wear effects as well as damage to the sealing systems.

#### **3.1 Friction torque at very low temperatures**

In each of the experiments, cooling down the system at first resulted in an increase of the frictional losses in the sealing system, which can be explained by the increased viscous friction due to the increasing lubricant viscosity. After reaching a maximum value, the frictional losses start to decrease until they reach a level similar to that observed at the end of the uncooled run-in period, as seen in Figure 4 for an experiment with an NBR-seal and PG ISO-VG 220 as a lubricant.

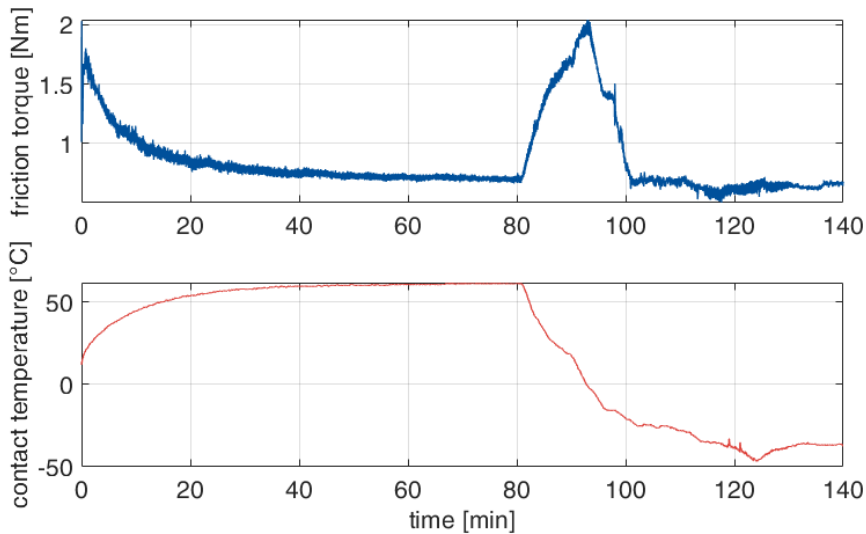


Figure 4: Trend of friction torque during the cool-down phase; NBR, PG ISO-VG 220

The decrease in the friction torque can be explained by the strongly increasing oil viscosity and the loss factor of the elastomer. As cooling continues, the increasing viscosity of the lubricant, combined with the pumping mechanism of the sealing contact, prevents the lubricant from wetting the seal's contact zone, which reduces the viscous friction. Furthermore, once the temperature is lowered below the glass transition temperature, there is a drop in the loss factor, i.e., a decrease in the viscoelastic losses in the elastomer. Both effects result in the observed steep drop of the friction torque after cooling the contact zone down below 0 °C. It is worth noting that the poor lubrication of the sealing contact may cause deeper counterface wear tracks and increased seal lip wear, as observed in long-term tests carried out on a different test rig where the lubricating oil was cooled down to -15 °C [1].

Under the conditions described above, the viscous friction in the contact zone declines and we may therefore attribute the observed friction to largely Coulomb-type boundary friction. This is supported by Figure 5, which shows that, when the rotation speed is altered, the friction does not change, as would be the case when assuming a viscous lubricant behaviour.

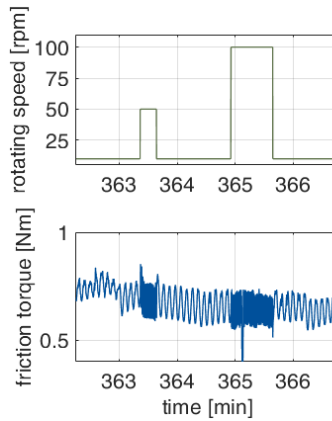


Figure 5: Friction torque in speed step experiment, contact temperature: approx.  $-40\text{ }^{\circ}\text{C}$

Despite the frictional torque maintaining a consistent level, it shows increased fluctuations and instabilities compared to the uncooled state. Notably at extremely low speeds below 20 rpm and contact temperatures ranging from  $-50$  to  $-40\text{ }^{\circ}\text{C}$ , intense vibrations and noise emissions were detected. Interestingly, under these conditions, the frictional torque decreased by more than 50 % compared to the levels observed when no vibrations were present. This effect stopped once the shaft was accelerated to 200 rpm.

### 3.2 Ice build-up and influence of condensate on the lubrication condition

In the course of each experiment, ice formed on the test rig, as shown in Figure 6. At the end of an experiment, while the test rig was heating up again, and soon after this ice started to melt, the friction torque suddenly dropped to a considerably lower level. After a certain period, it returned to its original level. An example for this phenomenon is shown in Figure 7.

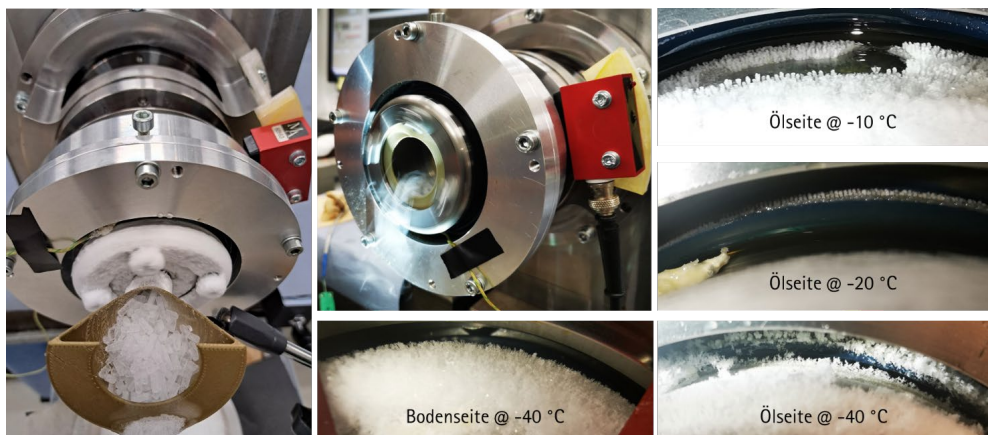


Figure 6: Ice build-up during the experiments

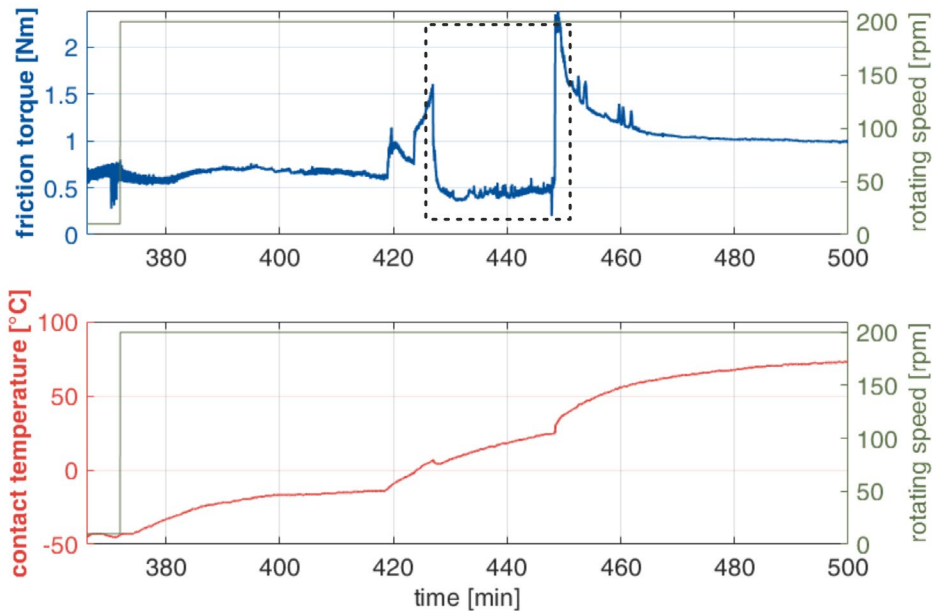


Figure 7: drop in the friction torque during the heat-up phase; NBR, PG ISO-VG 220

This behaviour indicates that water entered into the air side of the sealing contact and mixed with the lubricant within the contact zone, thus lowering its viscosity. After the water was pumped onto the oil side by the seal, the friction torque returned to its initial level and the initial lubricating state was restored.

It deserves attention that this effect was exclusively observed in NBR seals. In contrast, FKM seals did not exhibit a similar behaviour on their own, but the effect could be induced by actively injecting water into the air side of the sealing contact. This effect might, therefore, be related to a different wettability of FKM and NBR seals.

### 3.3 Influence of extremely low temperatures on the seal

At the end of each experiment, the cooling was stopped, allowing the systems to stabilize and return to their initial thermal steady-state conditions. In this state, all experiments showed similar friction torque and contact temperature levels as initially recorded before cooling down the sealing contacts. This indicates that, although having been subject to impaired or even starved lubrication when operated at extremely low temperatures, the lip seals were not damaged during the tests.

## 4 Conclusion

Using a novel low-temperature radial lip seal test rig, the behaviour of radial lip seals made out of NBR and FKM was studied at contact temperatures as low as approx. -50 °C.

It was observed that, following an initial increase during the cooling phase due to the lubricant's increasing viscosity, the friction torque at low contact temperatures finally reached levels comparable to those observed during uncooled steady-state operation, and that the friction of the sealing system evidently transitioned from viscous lubricant friction to Coulomb-type boundary friction.

In addition to this observation, it was seen, that under specific conditions, condensate could enter into the sealing contact and alter the lubrication mode. The impact of water within the sealing contact zone on the lip seals' behaviour will be explored in future research.

## 5 Acknowledgements

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