Observations on Particle Wiping Behaviour of Hydraulic Wipers

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The sealing mechanism of reciprocating seals has been described quite accurate in the literature and validated by several testing procedures. Nevertheless, the behaviour of most of the times not pressurized wipers cannot be described when particles are added into an oil film.

To describe the mechanism of particle retraction during rod motion, a series of tests with different parameters have been performed. In this paper, these results will be summarized showing -among others- the effects of particle sedimentation on the wiping mechanism. Also, a numerical approach to explain what particles do in the wiping area will be presented.

1 Introduction

In several previous papers the importance of keeping abrasive particles out of hydraulic systems has been presented [1,2,3,4,5]. Such particles are responsible for wear of components leading to costly repairment and sometimes and even worse, to complete damage of very expensive machinery. Nearly 70% of machines and industrial equipment fails due to debris particles in the system. With this background it is of huge economic importance to gain detailed understanding of dirt ingress into systems and to develop effective solutions. In hydraulic systems, the rod of hydraulic cylinders in motion are relevant sources for system pollution and hydraulic wipers are the elements responsible to keep particles out of the system while still ensuring an oil conveyance to avoid leakage. In previous studies, the mechanics of ingress mechanism based on friction between particle and rod and wiper material was presented [7]. Also the filtering effects and change of particle size distribution of hydraulic wipers has been observed [5]. Nevertheless, there is still work needed to fully understand how particles are behaving in a small sealing gap and which design parameters would let wipers perform best.

To go further in this matter, a series of wipers was tested, and the particle ingress was analysed. Further, the particle motion in a sealing gap FEA description was improved.

2 Testing Set Up and Test Procedure

From the different testing set ups used in diverse studies, the presented tests results have been taken from a vertical test arrangement (**Fig. 1**). The wiper's lip is assembled towards the fluid in the chamber which contains a mixture oil with standard sand in a weight ratio of 1:2 (HLP 46 oil: Arizona sand class 2). The fluid's pressure in the chamber is atmospheric pressure and the temperature is room temperature. The fixture with the wiper is held on a frame and the rod is driven in horizontal motion with constant velocity. Standard sand with constant statistic amount of different particle sizes is used in these tests, so that reproducibility is given.

The advantages of this set up is the usage of multiple rods and wipers in parallel in one test that allows higher data amount. The assembly is quite close to the wipers' field application, so results may have a higher practical value. Also, the set up and change of wipers and rods is relatively easy and quick. Disadvantages from this set up is the low accuracy of particle tracking during test, which leads to a poor validation of simulation methods due to the chosen particles (Arizona sand) and non-flooded conditions on both sides of the wiper lip. The rod wear with the chosen Arizona sand was significant so for each test new rods were needed.

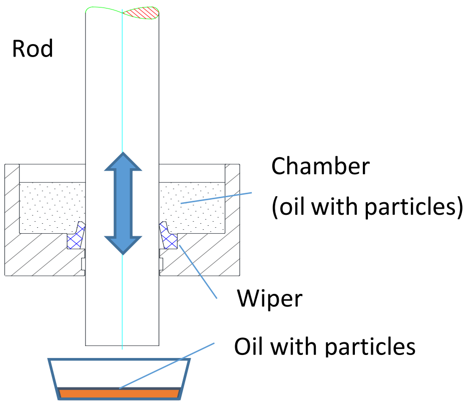


Figure 1: Wiper test arrangement with vertical rod

With this test set up keeping rod diameter constant, the only the variables are the wiper lip geometry and the rod velocity. Hydraulic wipers are available in several geometric and material variations. In these test series, wipers from different manufacturers and designs were analysed, whereas double lip wipers -such with an additional sealing lip towards the oil side of the cylinder- were also modified to oserve secondary effects of that additional lip in the particle motion observation (**Table 1**). The wipers' materials were mostly TPU materials, some of them including a metal case for installation in an axially open space according DIN ISO 6195 Type B, others without metal case for a snap in assembly in axially partially closed installation spaces according to other types in the DIN ISO 6195 standard.

The rods were changed after each test, each test using hard chrome plated standard rods with 50 mm diameter and standard rod surface roughness as delivered by the supplier.

Table 1: Wipers used for testing and material

Wipers with metal insert		**Wipers without metal insert**	
Double lip wiper	Single lip wiper	*Double* lip wiper	Single lip wiper
W5o  *W5m* 	*W1* 	*W7o*  *W7m* 	*W3* 
W6o  *W6m* 	*W 2.1* 	W8o  W8m 	
	W2.2 	W9o  W10o 	

The first half of the test was done during 40,000 cycles with clean hydraulic oil, where the first 20,000 cycles half of this cycles at an instroke / outstroke velocity ratio of 1, the other 20,000 cycles with an instroke/outstroke velocity ratio of 3. Each stroke was 0.2 m. After the first 40,000 cycles, the test procedure was repeated with an oil/particle ratio of 1:2. See **Table 2**. In total, the wipers were tested over 80,000 cycles (32 km distance).

Table 2: Test program

v_{in} / v_{out} Ratio: velocity [m/s]	v_{in} / v_{out} = 1 0.3 / 0.3	v_{in} / v_{out} = 3 0.3 / 0.1	v_{in} / v_{out} = 1 0.3 / 0.3	v_{in} / v_{out} = 3 0.3 / 0.1
Medium	Oil HLP 46	Oil HLP 46	Oil /Sand 1:2	Oil /Sand 1:2
Cycles	20,000	20,000	20,000	20,000
Total cycles	20,000	40,000	60,000	80,000

All wipers were dimensionally characterized, and their measured geometry was used to run FEA and calculate the contact pressure distribution of the wiper lip against the rod. The FEA material data was chosen from available FST material data, so an assumption on material behaviour on non FST wipers was done based on manufacturers data.

3 Test results

3.1 Test phase without particles

During the first half of the test duration, the medium is pure and clean HLP 46 mineral oil. And the only test variation in this phase is the velocity of the rod. The results show an inlet rate that increases with the instroke/outstroke velocity ratio, something that we would have expected and is completely according to the seal lip behaviour known from seals. **Figure 2** shows the inlet rate during this test period. The inlet rate stabilizes after 10,000 cycles at an instroke / outstroke ratio of 1 with a 0.3 m/s stroke velocity. Reducing the outstroke velocity to generate an instroke/outstroke velocity ratio of 4 increases the inlet rate.

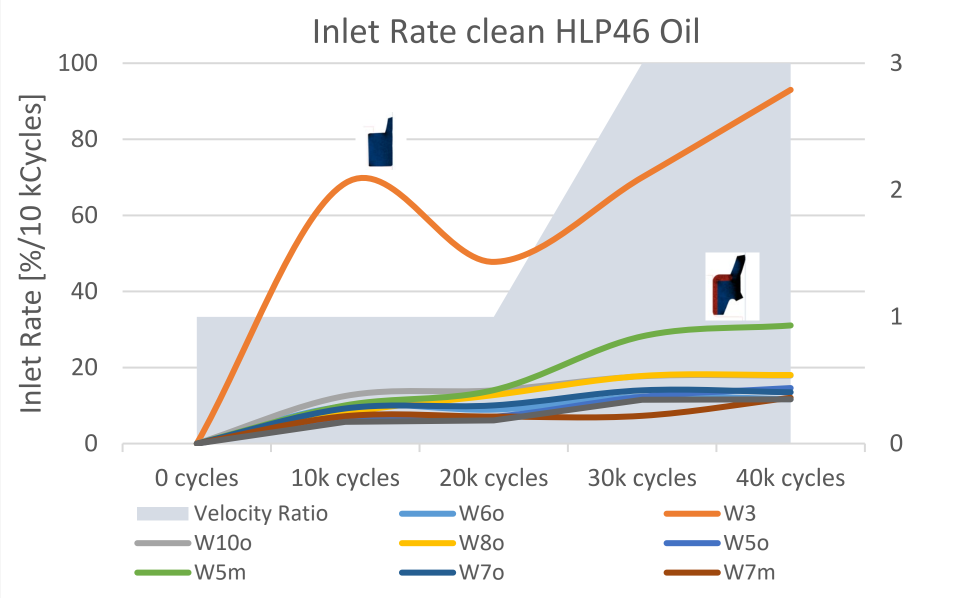


Figure 2: Inlet Rate of different wipers in clean oil

With exception of wiper W3, which is the only one in the group of wipers made from a NBR material, and the wiper W5 modified, all other wipers show a very similar oil inlet behaviour. Wiper W3 is constantly conveying oil into the system at significantly higher rates compared to the TPU wipers. Wiper W5m lets at a higher velocity ratio up to twice more oil into the system than other wipers.

The difference between the inlet rate of the tested wipers depends on the pressure gradients at the wiper's lips. (See **Fig. 3**). This is in accordance to Blok's theory, where the viscosity, stroke velocity ratio and pressure gradients will define the oil film thickness on the rod and in that way the oil flow depending on the instroke and outstroke conditions [8]. **Figure 3** shows the general trend of inlet rate vs. the wiper's gradients difference at different stroke velocity ratios. The wiper's pressure gradients were obtained by FEA, where for proprietary TPU materials own known material data was used, where for external TPU materials an assumption was used, also for the NBR material for Wiper W3.

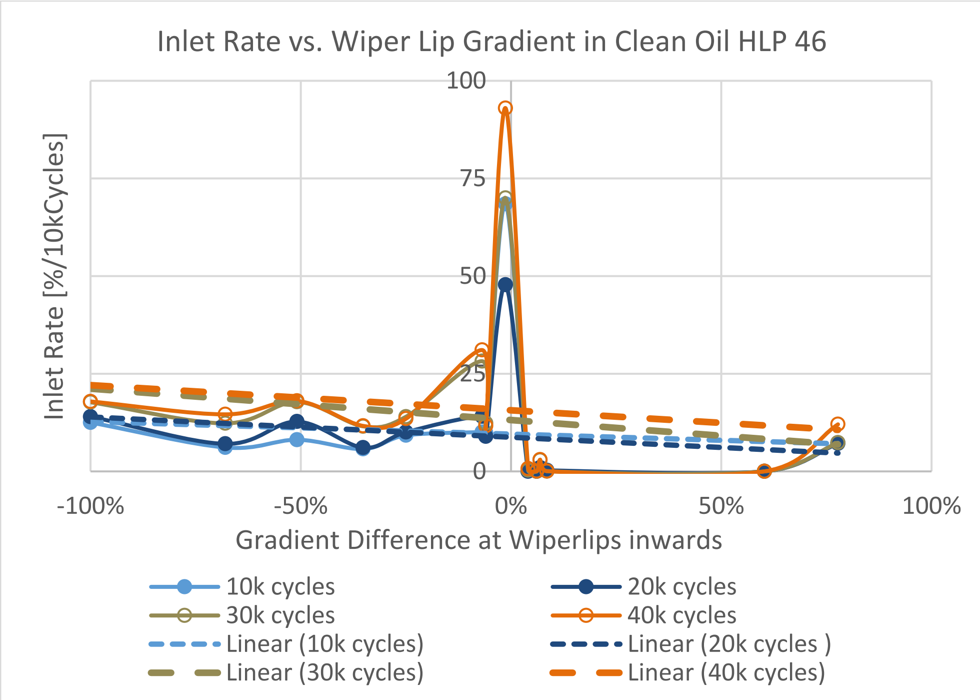


Figure 3: Inlet Rate of different wipers in clean oil, Inlet rate vs. gradient difference

Positive gradient differences should not show any inlet rate, which is mostly observed. Single values show a higher inlet rate at higher velocity ratios, as shown in Fig. 2. Also here, the NBR wiper W3 shows a different behaviour and does not fit into the general trend. We see a reduction of inlet rate with a higher pressure gradient difference in the wiper's lips. Also, room for discussion delivers the inlet rate of the wiper with the highest gradient difference, which is similar to a wiper with negative gradient difference.

3.2 Test phase with oil with sand

In the second phase of the test, the oil was changed by a mixture of 100 g oil with 200 g Arizona sand while leaving the same wipers and rods from the first phase unchanged. Adding sand has a strong effect on inlet rate. Not only the amount of inlet is reduced, also the concentration of the sand particles are filtered, something already observed and reported in [5]. In **Figure 4** the inlet rate is shown over the cycle time and different velocity ratios. In difference with the tests without sand, we see an inlet rate reduction with the stroke distance. This is significant at a higher velocity ratio and after 30k cycles, also at a velocity ratio of 1 some wiper shows the same behaviour.

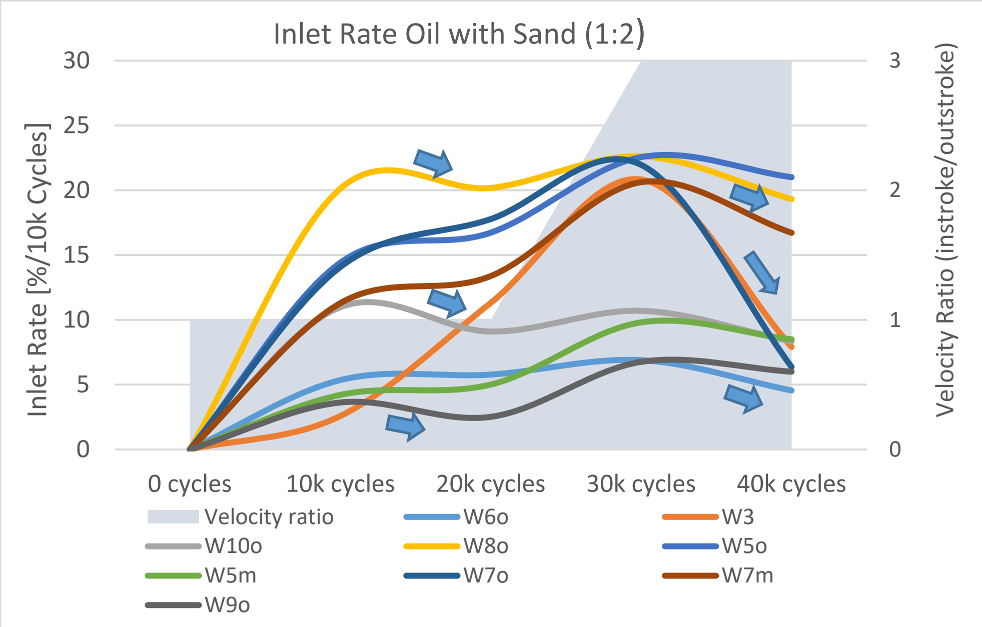


Figure 4: Inlet Rate of different wipers in oil with sand

In terms of effectivity, we see a differentiation between the wiper types after reaching 10 k cycles and 30 k cycles. The increasing inlet rate reaches a maximum and then decays for some wipers with the test duration (see arrows in **Figure 4**). Increasing the velocity ratio increases the inlet rate which again with the test duration decays. For some wipers (W3, W7o) the changes during the cycles are much more accented compared with the other wipers tested.

Plotting the oil with sand inlet rate versus the pressure gradient differences in the wipers is shown in **Figure 5**. The linear approximation delivers a lower inlet rate with higher gradient differences, but looking closer at the single values, we see a strong difference between the wipers. The inlet rate of the wiper with the lowest and with the highest gradient differences show nearly the same levels at a velocity ratio of 1.

The main reason for this inconsistency may be the wear effect on the wipers' lips. Wear will change continuously the shape of the contact zone and so the contact pressure distribution.

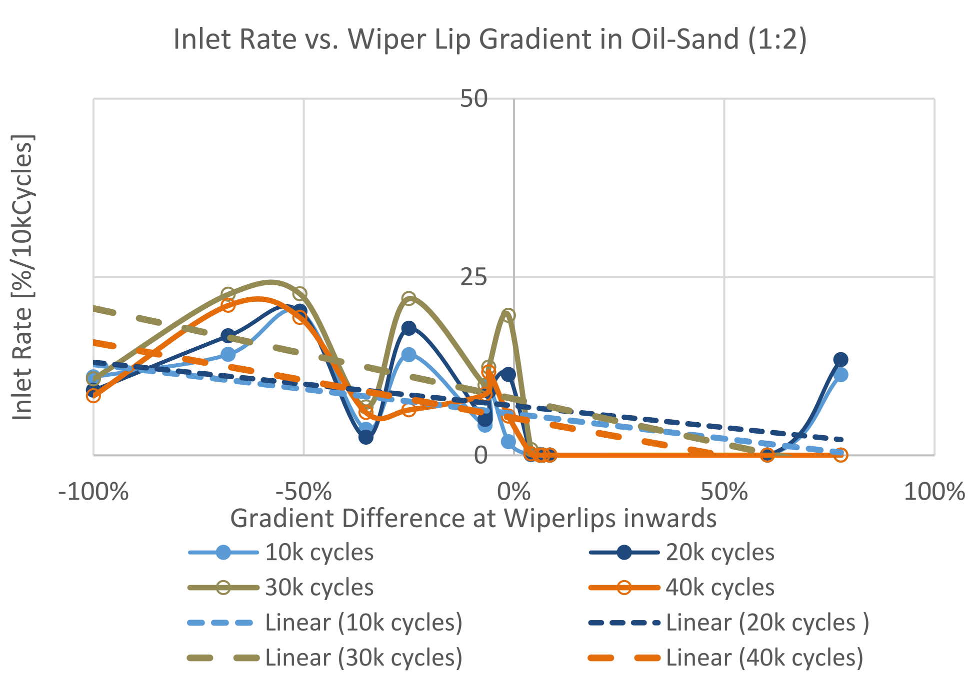


Figure 5: Inlet Rate of different wipers in oil with sand, Inlet rate vs. gradient difference

In **Figure 6** the contact zone of wiper lips after the test is shown. Here the change of shape shows that the date in Figure 5 is only valid for a status where wipers do not show any wear. Wear depends strong on wiper material. The wear causes not only axial scratches but seems to affect some materials unsteadily in circumferential direction. Wear on the NBR material is dramatically higher than that of the TPU materials with the tested parameters.

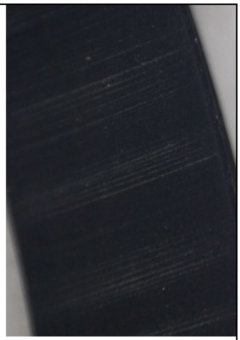
			
Regular wear, fine scores	Regular wear, medium scores	Irregular wear	Strong wear on whole contact
TPU	TPU	TPU	NBR

Figure 6: Wiper lip wear

Additionally to the filtering effect of particles reported in [5], which was also observed in these tests, a sedimentation of particles in the wiper lip area was observed. This leads to a change of particle concentration in oil after the test. **Figure 7** plots the inlet rate vs. the particle concentration in the oil that passes the wiper, which increases for all wipers in the test. At the end of the test, oil passing by is more a stick mass rather than a fluid. **Figure 8** shows exemplary the different inlet oil concentration and inlet mass measured at one rod during the test.

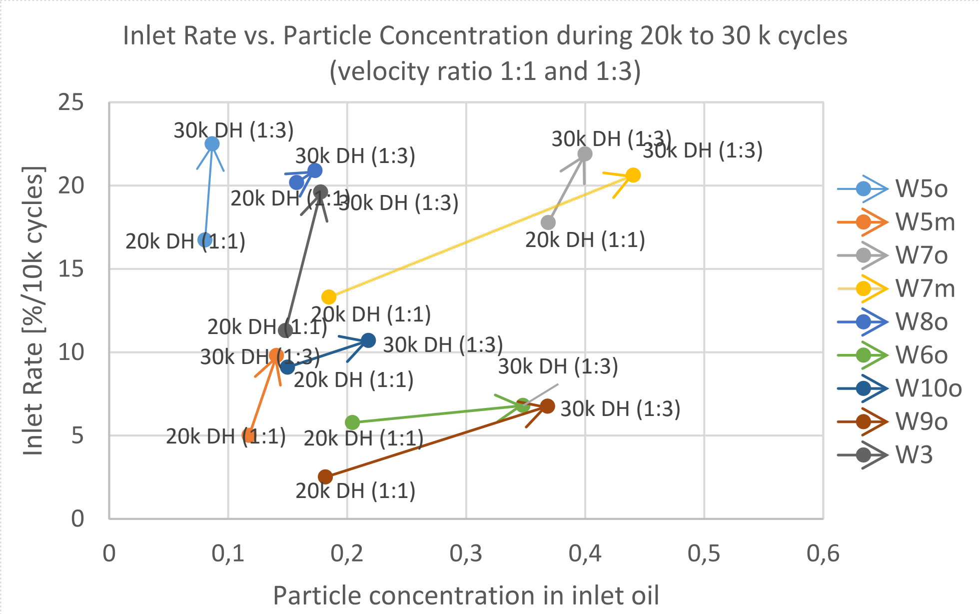


Figure 7: Particle concentration increase in inlet oil

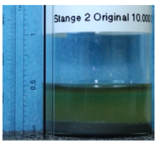
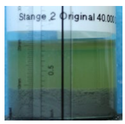
Oil inlet rate and particle concentration exempleary one rod, W10o				
Cycles	10 k	20 k	30 k	40 k

Figure 8: Inlet oil at different test cycles

3.3 Test result discussion and conclusions

The tests with pure oil (**Fig. 2 and 3**) can be explained with the known conveyance rules known from hydraulic seals. The inlet rate depends on the fluid film thickness on the rod during outstroke and instroke. And it depends on the oil's viscosity, stroke velocity and maximal pressure gradient between wiper lip and rod [6,8].

One wiper type (NBR material) shows significant higher oil inlet than the other wipers. This is due to a contact of the wipers' heel against the rod, as FEA analysis show. The stress gradient difference is nominal nearly cero, during motion the wiper's cross section rocks in the gland, leading to higher differences as calculated with a static FEA model.

The second test phase, where sand is added to oil reveal a complex wiper conveyance behaviour. The inlet rate is not significantly different, also, it is not constant, it decays during the lifetime at a constant velocity. And we do not see a clear correlation between inlet rate and pressure gradient difference of the wipers lips, this seems to be wiper specific. So, additionally to the design, the wipers' material properties may have a big impact.

The question is why it decays instead of increasing, when we see the wiper lips are wearing. One possible explanation for this observation could be, that during the test lifetime, we observe a sedimentation of sand in the wiper lip's contact area to the rod. Sedimentation increases with the time, and a higher particle concentration leads to a filter effect of particles and oil.

So not only the wiper material and lip's shape does influence the inlet behaviour, also the particles in the oil and its agglomeration process directly in the wiping area has a strong effect. This may be completely different with different fluid/particles combinations.

4 Particle simulation in sealing gap

A simulation software is developed to investigate the behaviour of particles in the lubricating film of a wiper. The calculation consists of three parts. First, a structural mechanical simulation of the wiper in the installed state is carried out. This provides the deformed geometry and the contact stress in the sealing zone. Nonlinear material behaviour and large deformations are taken into account. The results of this simulation form the basis for an elasto-hydrodynamic calculation (EHL - calculation). Dependent on the rod speed and the fluid viscosity one obtains the lubricating film and the fluid pressure.

For the third simulation part, a computational domain is built up around the particle. The boundary conditions are provided by the previous elasto-hydrodynamic calculation. Figure 9 shows the computational domain for the particle within the sealing gap.

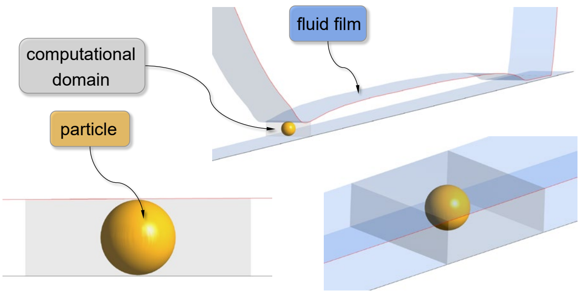


Figure 9: Computational domain

By solving the Reynolds differential equation, one obtains the pressure in the entire computational domain. Knowing the pressure, one can calculate the shear stresses acting on the particle. Figure 10 shows the pressure and the shear stresses as an example.

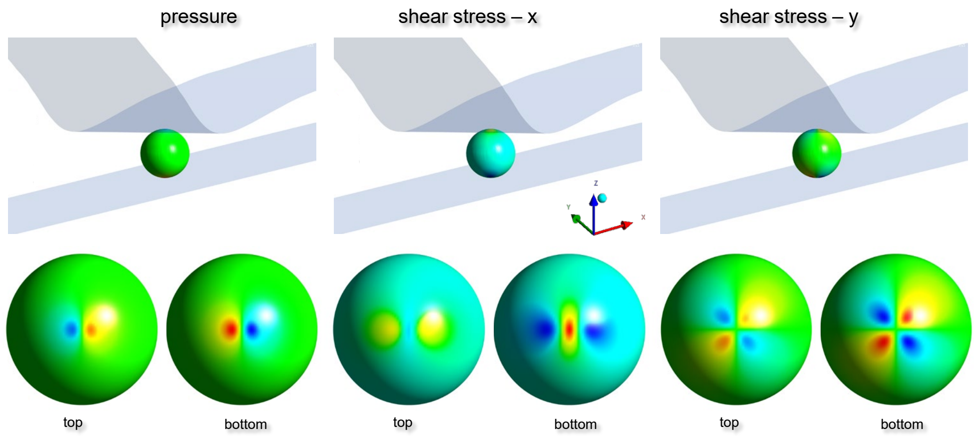


Figure 10: Pressure and shear stresses acting on the particle

By knowing the forces, the translational and rotational velocities of the particle can be calculated. To determine the particle path, an explicit Euler method is used.

If the particle is larger than the lubricating film, there is also contact to the counter-parts. The simulation software takes also into account that the particle deforms the wiper and at the same time itself undergoes deformation. The rod is assumed to be rigid. Figure 11 shows an example of the particles in the lubricating film and the corresponding deformations.

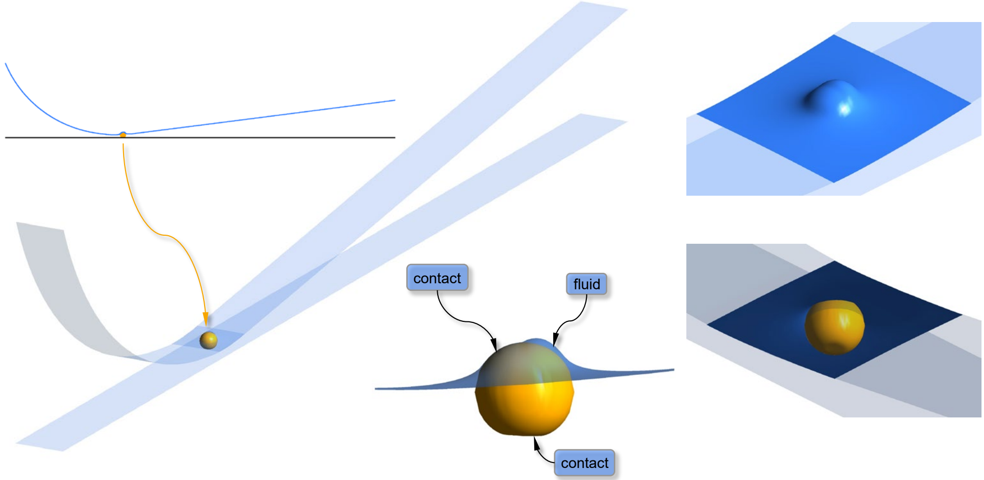


Figure 11: Deformations of the wiper and the particle

The contact- and friction forces that occur are taken into account in the force balance for the particle.

In Figure 12 the results of the structural and elasto-hydrodynamic simulation for the wiper W7m are displayed.

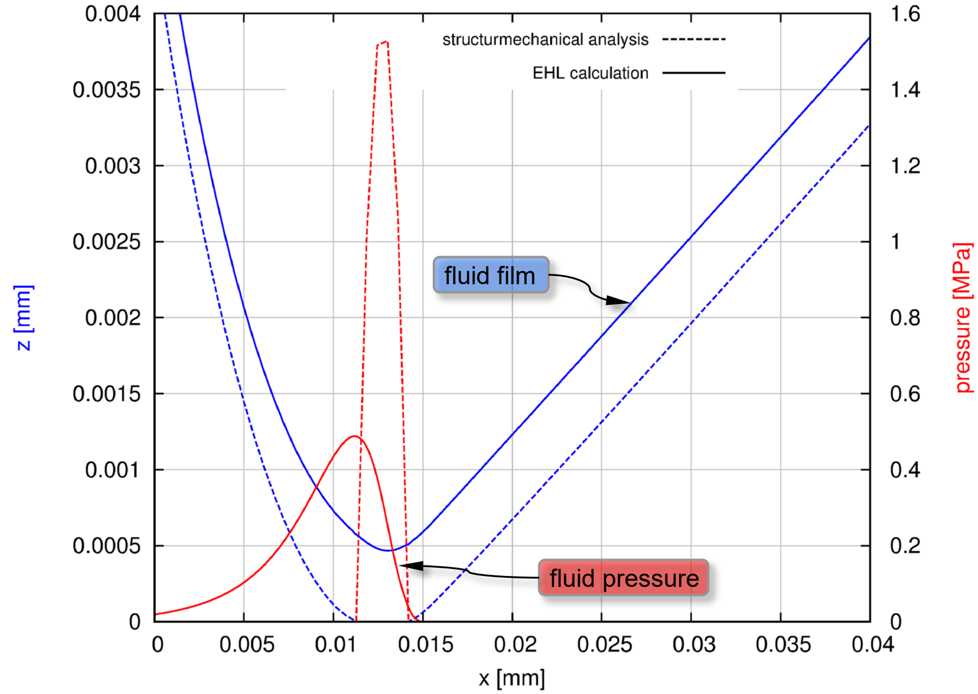


Figure 12: Structural and EHL simulation results

Figure 13 shows the streamlines resulting from the elasto-hydrodynamic calculation. The streamlines are identical to the paths of infinitesimal small particles. On the left side one can see a backflow area.

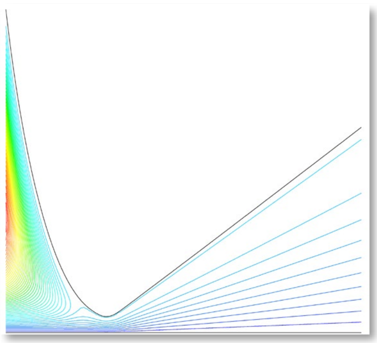


Figure 13: Streamlines within the sealing gap

Particles with different distances to the rod were placed in the lubricating film for the simulation of the particle paths. The results for particles with a diameter of 0.25 µm are shown in Figure 14. A particle (orange) and the streamlines of the undisturbed flow (black) are shown also.

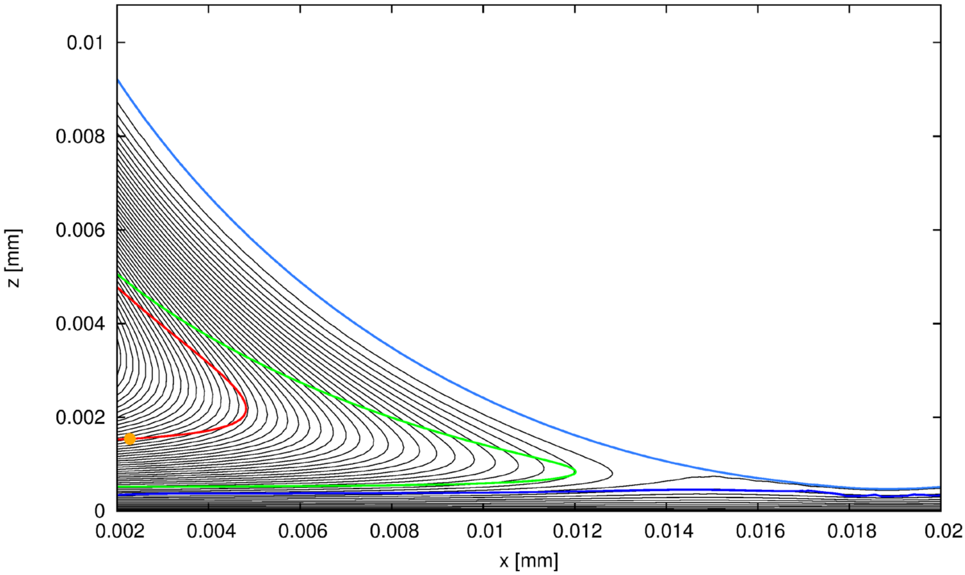


Figure 14: Particle path (Diameter 0.25 µm)

With a large distance to the rod, the particle very quickly gets into the backflow area and does not reach the sealing edge (red line). It more or less follows the streamlines of the undisturbed flow. The deviations to the streamlines are due to the size of the particle, since it influences the flow in its neighbourhood. A particle closer to the rod initially moves to the sealing edge, but also gets into the backflow area(green line). Only particles very close to the rod are drawn under the sealing edge (blue line). The particle has no contact to the counterparts.

Figure 15 shows the situation for a particle with a diameter of 1 µm. Again, the particles with larger distance to the rod gets in the backflow area and are not drawn under the sealing edge (red and green lines).

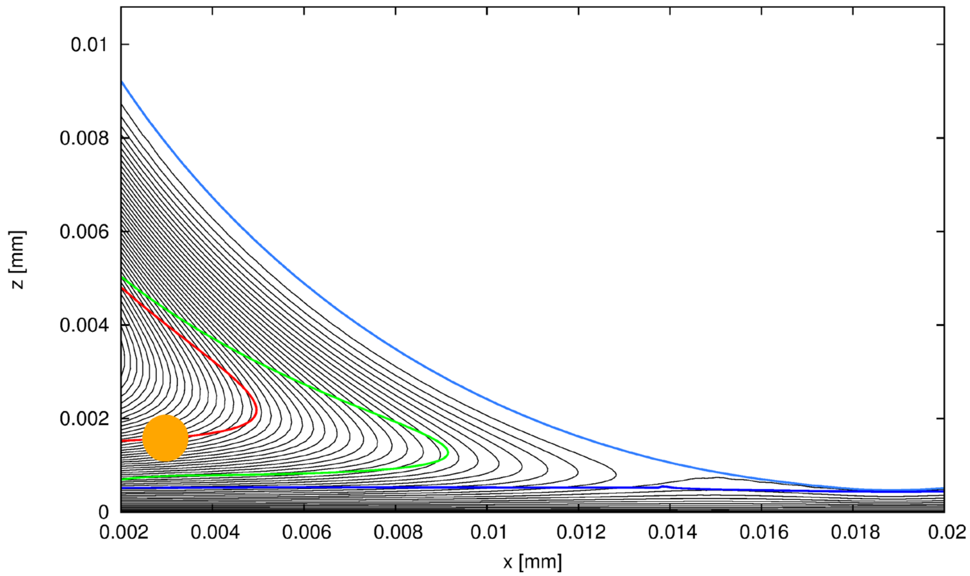


Figure 15: Particle path (Diameter 1.00 µm)

Now the particle very close to the rod has contact to the counterparts. Figure 16 illustrates the situation in the cross section at two different positions of the particle. On can see the deformation of the particle and the wiper (blue line). In addition, the path of a point at half of the radius (red line) is shown. One can recognize the rotation of the particle with different speeds, caused by the different forces acting on it during its movement.

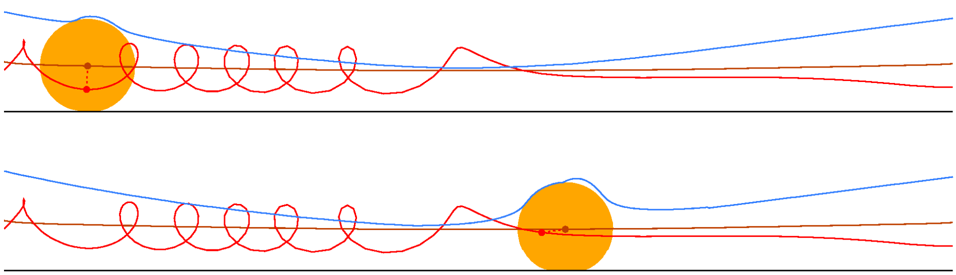


Figure 16: Particle within the sealing gap (Diameter 1.00 µm)

By placing a particle with a diameter of 2 µm in the flow field gives the result shown in Figure 17. Even a particle near the rod will no longer drawn under the sealing edge. The fluid pressure, shear stresses and the contact- and friction forces stops the movement of the particle. The translational velocities vanish. The particle only rotates.

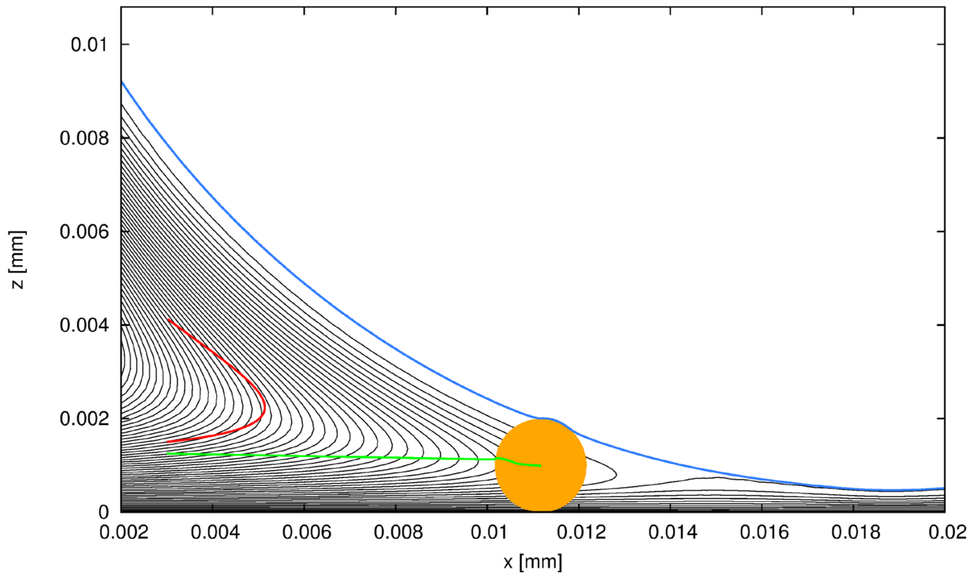


Figure 17: Particle path (Diameter 2.00 µm)

With the help of the simulation, two mechanisms could be identified that prevents that a particle is drawn under the sealing edge. On the one hand there is the backflow area, which is build up in front of the sealing edge and prevents the particles from reaching the sealing edge. On the other hand, there are the forces acting on the particle that stops the movement.

Actually, the roughness of the counterparts has not been taken into account in the simulation. Since the size of the roughness is in the range of the considered particles, they play an important role. Therefore, the simulation software will be expanded in this regard.

5 Summary and Outlook

Different designs and materials of wipers were tested to find out parameters that can be used to design effective wipers. Inlet behaviour of wipers with pure oil is like the conveyance behaviour of seals already known: Velocity and pressure gradient differences in the wipers will define the inlet rate.

Adding particles into an oil changes the mechanism completely and can not be described in terms of parameters used to describe seals conveyance behaviour. Material wear resistance has a big influence as well as sedimentation process of particles in the fluid. Sedimentation seems to lead to a filtering effect reducing the inlet rate but increasing the particle concentration of the mixture passing the wiper lip.

The geometry of the wiper has a significant influence on the contact pressure in the sealing zone. This in turn determines the movement of a particle in the lubricating film. With the help of the developed simulation software, a wiper design is to be found that shows optimal behaviour regarding the movement of particles.

Further investigation is needed to allow a fully comprehension of the particle inlet mechanisms in a sealing gap.

6 References

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