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Wiper–Rod Seal Interactions in Hydraulic Systems: Effects on Oil Film Retention and Dust Ingress Prevention

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Wipers are critical components that serve as the first line of defence against external contamination in a hydraulic sealing system. Often, they are undervalued components, but wipers are critical to keep up the performance level of the system, especially considering the interaction between individual components, particularly the rod seal. Even well performing individual sealing system parts can result in unexpected interaction, leading to poor lubrication, increased friction, accelerated wear and even reduced system reliability. Conversely, well matched sealing systems reduce friction forces, extend service lifetime and reduce energy consumption. This study investigates different wiper designs in different dimensions of performance in extensive test bench experiments and combines finite element analysis to evaluate dust exclusion and lubrication film retention, identifying synergistic effects on component combinations that deliver superior overall performance for demanding applications.

1 Introduction

Hydraulic cylinders frequently operate in harsh environments characterized by dust, debris, moisture, and varying weather conditions. These external influences pose a significant threat to the functional reliability and service life of hydraulic systems. Wipers, also referred to as scrapers, excluders, or dust seals form the first line of defense by preventing contaminants from entering the hydraulic cylinder. The dynamic sealing area along the piston rod and the static sealing area between the wiper and the cylinder head must keep particles and moisture out of the system. Beyond contamination exclusion, modern wipers must ensure sufficient lubricant film retention by allowing oil to be pumped back into the system during rod retraction. Otherwise, lubricant loss and external leakage may occur. Furthermore, the wiper is often responsible for venting an intermediate pressure that may evolve between the rod seal and the wiper. Figure 1 is showing a schematic overview of a hydraulic cylinder.

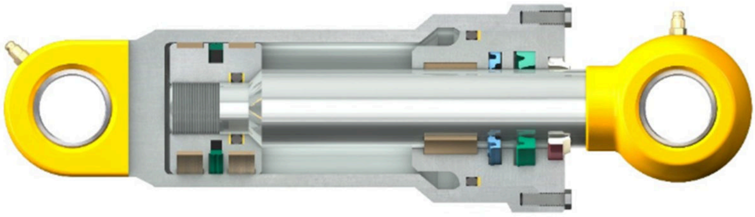


Figure 1: Schematic overview of a double acting hydraulic cylinder [1]

2 Theoretical background

Hydraulic cylinders can be equipped with different types of wipers; this paper only refers to double-lip press-in wipers made from polyurethane (TPU). They are designed with a steel retainer ring that provides a robust static sealing on the outside surface, the internal lip and the dust lip are connected to the steel and maintain a sealing force by tension as well as bending the seal lips (see figure 2). This provides a robust preload situation even under misaligned conditions between the rod and the head [1].

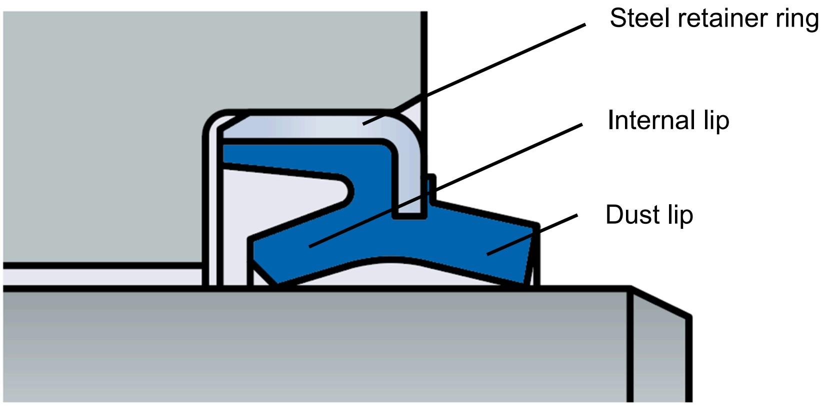


Figure 2: Typical double-lip press-in wiper design [1]

2.1 Lubrication Film thickness

During outstroke the rod sealing system is creating a lubrication film with a thickness h, which is mainly defined by the operating conditions and the rod seal geometry. Based on the Reynolds equation the following formula for the determination of the lubrication film thickness can be used [2].

$$h = \sqrt{\frac{2 \cdot \eta \cdot v}{9 \cdot \left({dp}/{dx}\right)_{max}}} \qquad (1)$$

The contributing factors are

- dynamic viscosity η of the hydraulic fluid
- relative speed v of the piston rod to the sealing edge
- max pressure gradient $\left({dp}/{dx}\right)_{max}$ within the contact pressure distribution of the sealing contact. This gradient considers the combination of sealing geometry, material and pressure of the medium.

This formula is valid to determine the lubrication film thickness in each single sealing contact, which can be the buffer seal, the rod seal but also the internal lip of the wiper as well as the dust lip of the wiper acting in the opposite direction. It can also be used during instroke and outstroke conditions.

Typical values for lubrication films on hydraulic piston rods are in the magnitude of the surface roughness of the piston rod. Measured values are in the nm-range and can also vary significantly by adjustment of the tip radius of the sealing edge [3].

2.1.1 Rod seal design as a source for the lubrication film

When the primary hydraulic pressure is acting in one chamber of the hydraulic cylinder and forces the piston to perform an outstroke there is a secondary lower pressure level in the non-working chamber of the cylinder to better control the movement of the system. This so-called back pressure is resulting into a contact pressure profile beneath the rod seal, which is responsible for the creation of the lubrication film and its thickness during the movement of the piston rod. Too thin lubrication films create increased wear of the sealing elements; thick lubrication films create tendencies to system leakage but also decrease the system friction during instroke.

2.1.2 Internal wiper lip design

The lubrication film on the piston rod passes next through the internal wiper lip. The calculated lubrication film thickness from this lip should be at least on the same level as from the rod seal to avoid accumulation of fluid between the two elements.

An internal pressure less wiper lip wears less than the pressurized rod seal and therefore increasing the service lifetime of the system when the rod seal starts to leak. If the lubrication film thickness created by the internal wiper lip would be too small, oil would be collected between rod seal and wiper, which requires at a certain point venting that can either be achieved through a vent hole in the internal lip or an integrated venting system in the hydraulic cylinder head.

2.1.3 Lubrication film retention

The dust lip of the wiper needs to be able to allow the same lubrication film to re-enter the hydraulic cylinder during instroke that leaves the system during outstroke.

A simple mathematic volume calculation indicates that a lubrication film that is only 1 nm thinner during instroke than the created film during outstroke would create already 250 mm³ leakage on an 80 mm piston rod during 1000 strokes of 1 m. This is equivalent to 6 drops of oil. Such values are not acceptable and have to be avoided.

As a result of this the contact pressure distribution of the dust lip must allow a thicker lubrication film to re-enter the system than provided from the rod sealing system during outstroke. Many wipers on the market show a large radius of the dust lip tip to avoid an oil ring at the reversal point of the cylinder (see figure 3).

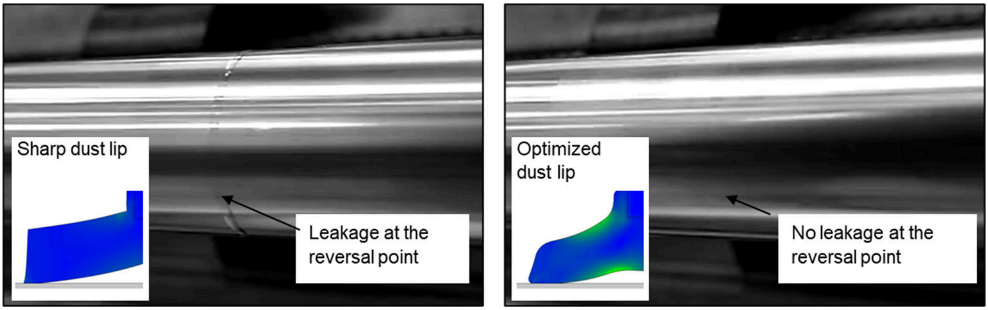


Figure 3: Reversal point comparison between different dust lip designs

Too large dust lip radii open the path for contamination to enter the system during instroke.

Based on the above stated the design of a dust lip and its contact pressure distribution is always a trade-off.

2.2 Contamination exclusion

Wiper lips allow a certain lubrication film to enter; it likewise can also be an area of ingress for contamination. Sharp wiper lips are expected to keep more contamination out than rounded lips. However, the handling of particles cannot be described by formulas and therefore require testing to understand differences between good and bad wiper designs related to contamination exclusion.

2.3 Friction Force

Systems with increased lubrication film thickness show less friction. The basis for such behavior is created from the rod seal during outstroke when the rod is wettened with hydraulic fluid and leaves the hydraulic cylinder.

The friction force of the rod sealing system is typically dominated by the behavior during instroke of a double acting cylinder, where the rod sealing system is pressurized with the working pressure. The wiper must allow all available lubrication film to enter the hydraulic system during that movement to keep friction forces low.

For low-friction performance of a sealing system at the same time with leak tightness and long service lifetime due to contamination exclusion it is paramount that the sealing system is balanced and the single components match to each other.

3 Experimental setup and performed simulations

Different test setups are required to investigate the handling of the lubrication film and the contamination exclusion. Those tests were set up with a rod diameter of 50mm and different rod seal packages, using asymmetrical rod seals from the same type but different wipers.

3.1 Ingression test and test rig

The ingression test rig (see figure 4) was built to evaluate the wiper's capability of preventing particle contamination in a comparative way. The test setup is using a 50 g mixture (equal by weight) of standard hydraulic oil and Arizona coarse test dust (acc. ISO 12103-1) that is introduced into a funnelled vertical test chamber above the test wiper. Any fluid and dust that passes the wiper is collected beneath the test cell. The test duration is 8 hours (=10800 cycles at 0.25 m/s). The accumulated fluid is centrifuged after completion of the test to separate and quantify the dust particles that were not excluded from the wiper.

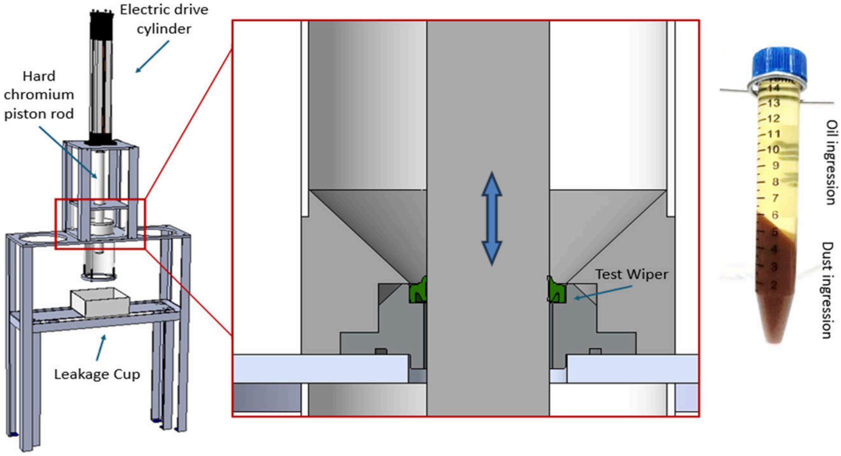


Figure 4: Setup of the ingression test rig (left), example of centrifuged oil/sand mixture (right)

3.2 Linear test rig and test cycles

The experiments were conducted using the reciprocating seal test rig LP3 (see Figure 5). The system consists of a test chamber that moves on a piston rod back and forth driven by an electric unit. The test chamber is pressurised by a hydraulic pressure unit and simulates a hydraulic cylinder. This configuration requires two rod sealing systems to be tested simultaneously. In case of different conditions (speed & pressure) in each direction only one seal can be considered as test seal side for leakage evaluation, the other sealing system will always be just used as a balance side, related friction forces are within the test data and cannot be separated. Balance sealing systems in this paper are always having the same rod seal without a wiper. (see Figure 5).

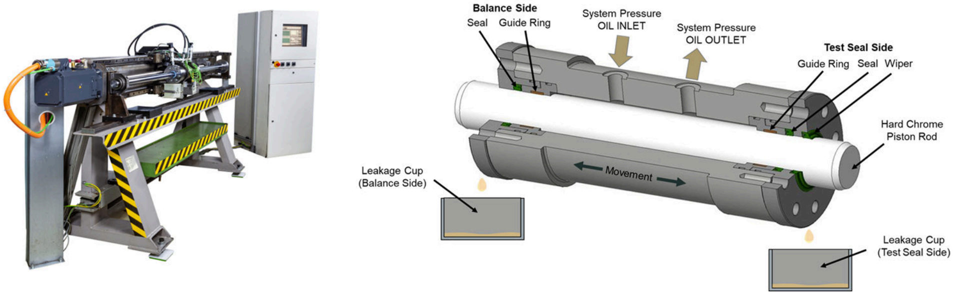


Figure 5: Reciprocating hydraulic seal test rig (LP3) and sectional view of the test cell

The test rig is equipped with a load cell to measure the friction force of the total system. System pressure is monitored and controlled via a pressure transducer installed directly within the test chamber, while the oil temperature is measured at the outlet port. Leakage will be collected in cups during the test runs and measured after the test run.

3.2.1 Short term back-pumping test

The interaction between the wiper and the rod seal has been screened by a 500 m test program using application parameters tending towards leakage, see Table 1.

Table 1: Application parameters short term back-pumping test

	Outstroke	Instroke
Pressure	30 [bar]	100 [bar]
Speed	0,5 [m/s]	0,25 [m/s]
Hydraulic oil	HLP46 at 38 [°C]	

Higher outstroke speed at lower pressure, which is normally equal to a lower value of the maximum pressure gradient of the rod seal, and low temperatures (increased viscosity) result in a system that creates a rather high lubrication film thickness. Slower instroke speeds at increased pressure only allow less fluid to enter through the dust lip. Therefore, this test setup is leakage sensitive.

3.2.2 Speed variation back-pumping test

To better understand and simulate different operating conditions this testing program evaluates the back-pumping capability considering different speed profiles and a longer test duration of 90km at typical hydraulic fluid temperature, see table 2.

Table 2: Application parameters speed variation back-pumping test

	Outstroke	Instroke
Pressure	50 [bar]	250 [bar]
Speed 0km-30km	0,25 [m/s]	0,50 [m/s]
Speed 30km-60km	0,25 [m/s]	0,25 [m/s]
Speed 60km-90km	0,50 [m/s]	0,25 [m/s]
Hydraulic oil	HLP46 at 60 [°C]	

Leakage and friction forces are evaluated during the single steps and showcase some possible operating conditions of a hydraulic cylinder.

3.3 FEA-Simulations

To further investigate the functionality of the rod sealing system, an internally developed FEA-simulation software for structural mechanical simulations was utilized for simulations.

3.3.1 Simulation setup

The sealing lips were simulated with hyperelastic material models, the housing and the piston rod were defined as rigid bodies (see Figure 6). Special attention was paid to the contact pressure distribution between the sealing or rather wiping lips at the dynamic sealing surface of the piston rod.

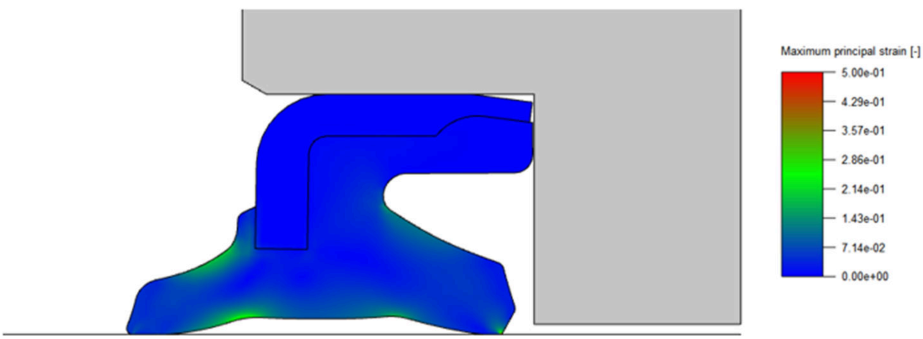
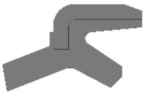
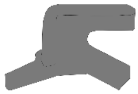
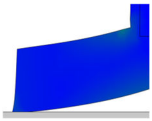
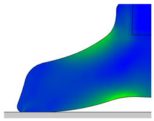
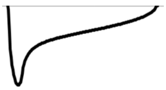
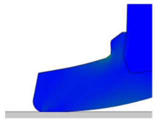
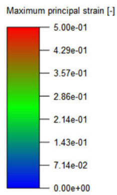
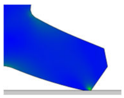
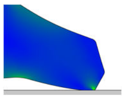
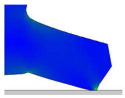


Figure 6: FEA simulation of a Wiper

3.3.2 Investigated geometries

The FEA-simulations were performed on the measured geometries of three different wipers. The dust lip differences are resulting into contact pressure distribution variations, see table 3. The simulation of the internal lips did not show significant differences; therefore those results are not further discussed.

Table 3: Overview of investigated wipers with differences on the dust lip

	Wiper #1	Wiper #2	Wiper #3	
Wiper geometry				
Dust lip and schematic contact pressure distribution	 	 	 	
$f_{W\#,D}$	1,07 [N/mm circ]	2,46 [N/mm circ]	0,98 [N/mm circ]	
Internal lip and schematic contact pressure distribution	 	 	 	
$f_{W\#,I}$	1,70 [N/mm circ]	2,89 [N/mm circ]	1,41 [N/mm circ]	

Wiper #1 represents wipers with a sharp dust lip. Those wipers are used when contamination exclusion is prioritized and small amounts of leakage are accepted. Wiper #3 has a rather large dust lip radius and therefore allows a lot of fluid to enter during instroke of the hydraulic cylinder; leakage will be appearing very late in the service lifetime of the system. Wiper#2 is a solution in between that reduces the ingress to a certain level. The maximum contact pressure gradient is between wiper #1 and wiper #3.

The area between the contact pressure distribution and the x-axis is representing the contact force. The highest value was simulated on wiper#2 and the lowest level on wiper#3, very similar to wiper #1. The specific contact force values on the dust lips ($f_{W\#1,D}$, $f_{W\#2,D}$ and $f_{W\#3,D}$) as well as on the internal lips ($f_{W\#1,I}$, $f_{W\#2,I}$ and $f_{W\#3,I}$) in Table 3 are also showing the same indication.

4 Experimental results

The different tests have been performed with all described wipers (see 3.3.2). This chapter connects the experimental results to the theoretical FEA-Simulations.

4.1 Results from short term and ingression testing

The different wiper designs shown in Table 3 have been investigated first in terms of ingression and short term back-pumping. The results can be seen in Figure 7.

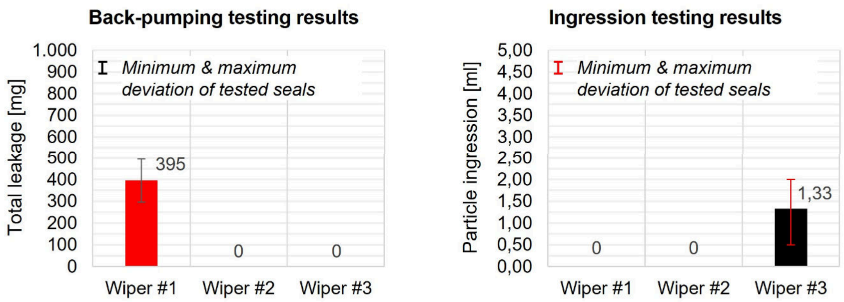


Figure 7: Results of short term back-pumping test (left) and ingression test (right)

The short term back-pumping test results show a very good correlation to the expectation from the theoretical FEA simulation. Wiper #1 with the sharp dust lip is creating very high leakage during the back-pumping test but does not allow ingression to enter the system during the ingressions test. Wiper #3 with the large radius does not create any leakage but allows a significant amount of particles to enter the system. Combining both good results, no leakage and no ingression intake is possible by optimization of the dust lip geometry of wiper #2.

Simulation results only show the capability of allowing lubrication film to re-enter the system, the ability of particle ingression intake cannot be estimated by simulation. There was no information in simulation that the wiper#3 will not be able to avoid contamination ingression.

4.2 Results from speed variation back-pumping test

This test has been performed with the different wiper designs according to table 3 in combination with an asymmetric u-cup, but also with a u-cup only and without a wiper to better understand the system performance. This gives further insights, for example if the complete lubrication film from the outstroke is able to re-enter the system during instroke. The results have been summarized in figure 8 and figure 9.

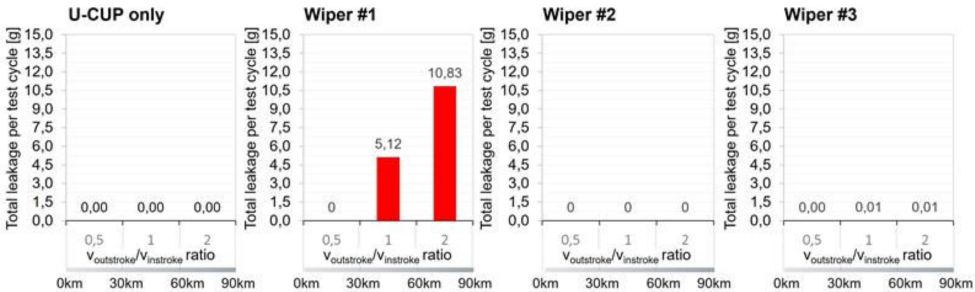


Figure 8: average leakage results speed-variation back-pumping test

The leakage results are expected to increase when the outstroke speed or the outstroke to instroke speed ratio is increasing. The only test setup that shows measurable leakage is equipped with wiper#1, all other systems are leak tight.

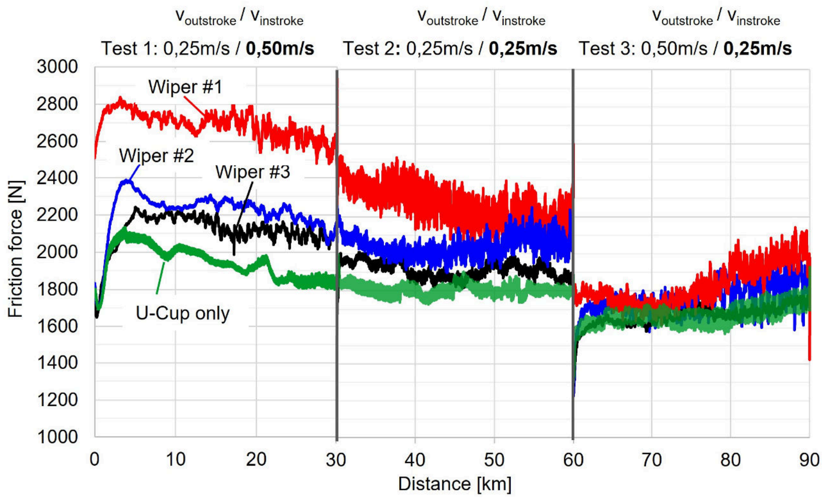


Figure 9: Instroke friction results speed-variation back-pumping test

The diagram shows only the friction force during instroke of the test seal package, because outstroke friction forces are only influenced by the speed. All packages are showing very similar outstroke friction forces. Therefore these results do not provide insights to the wiper-rod interaction and are not shown here.

The instroke friction force of the rod seal without wiper (U-cup only) is measured lowest during all speed steps. Wiper#1 is showing the highest friction forces in all three steps, the biggest difference can be identified in step 1.

The instroke friction forces of Wiper #2 and Wiper#3 are slightly higher than the values from U-cup only, but significantly lower than the values from Wiper#1.

4.3 Discussion of the results

The friction diagram shows different behavior in all three steps. Higher outstroke speeds or rather the relation of the outstroke to the instroke speed results as expected into lower friction forces during instroke. The friction force rises significantly when the instroke speed is higher than the outstroke speed. In that case a rounded dust lip on the wiper leads to a lower friction than the sharp lip.

This increase of the instroke friction force is not in relation to the simulated specific contact force at the dust lip. Based on the low contact forces from the wipers the difference in friction force can only come from the rod seal and the lubrication film, that is formed from the dust lip of the wiper.

Even if the wiper is not scraping off hydraulic fluid and reduces the film thickness by creating leakage there is still an impact on the lubrication film that changes the lubrication conditions of the rod seal.

5 Summary and conclusions

The lubrication film on the piston rod is crucial for the overall hydraulic cylinder performance. The film thickness is heavily influenced by the design of the single sealing components, also the dust lip of the wiper is playing a significant role.

Different wipers, especially variations in the dust lip tip geometry have been investigated in FEA-simulation and in experimental setups to investigate contamination ingress, leakage and friction forces.

Simulation results show an increase of the maximum pressure gradient as a result of smaller dust lip radii. Smaller dust lip radii result into a higher probability of leakage and larger dust lip radii can result into contamination ingression.

There is a dust lip radius possible in the investigated sealing setup that can prevent from contamination ingression without showing leakage. The optimum radius is depending on the rod seal behaviour and the operating conditions like temperature of the hydraulic fluid and speed of the piston rod.

The friction force of the rod sealing system during instroke (working pressure level) is higher than during outstroke (back pressure level). During instroke the rod seal is dominating the friction force creation.

The contribution of the contact force of the pressure-less wiper to the friction force can be neglected. The increase of friction force is not in relation to its contact force, the friction force during instroke is more related to the dust lip tip radius and the resulting lubrication film, where small radii result in higher friction forces.

The ratio between outstroke speed and instroke speed is amplifying the differences in the friction forces. Higher outstroke speed result into lubricated conditions where all wiper variants provide very similar friction results. Higher instroke speeds result into starving lubrication conditions where sharp wiper lips significantly increase the friction forces.

Friction forces are more and more moving into focus in the hydraulic cylinder industry. In order to optimize sealing systems for friction an increased lubrication film thickness is required. Rod sealing systems with optimized wiper lip geometries can still have low friction values in combination with very low leakage values and best contamination exclusion but special attention needs to be paid such that the single parts of the sealing systems are aligned in performance.

6 Nomenclature

Variable	*Description*	*Unit*
h	Lubrication film thickness	[nm]
T	Temperature	[°C]
v	Relative speed of the piston rod to the sealing system	[m/s]
$\left({dp}/{dx}\right)_{max}$	Maximum pressure gradient in the contact pressure profile of the lip	[N/mm²m]
$v_{outstroke}$	Speed of the piston rod during outstroke	[m/s]
$v_{instroke}$	Speed of the piston rod during instroke	[m/s]
f_w	Specific contact force of the wiper lip	[N/mm circ]

Index #,i Internal lip

Index #,d Dust lip

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