TRIBOLOGICAL PROPERTIES OF HYDRAULIC CYLINDER PISTON SEALINGS IN WATER AND OIL HYDRAULICS

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ABSTRACT

Hydraulics is indispensable in everyday life because of its ability to work with large forces. Hydraulic cylinders are an important hydraulic element and contain different types of seals. This work presents an investigation of the influence of three different shapes and materials of piston seals in a hydraulic cylinder on the friction force. The friction was tested in two hydraulic fluids, water and mineral oil, at six different piston rod travel speeds on a test rig prepared for this purpose. It was found that the proportion of the friction force in mineral oil is between 60 % and 85 % of the friction force generated by the same piston seal in water. However, a long-term test carried out on a test rig provided data on the leakage of the piston seal before the start of the long-term test, after 50 km of travel, and after 100 km of travel of the piston rod at full load.

Keywords: hydraulic, cylinder, piston seals, friction, mineral oil, water, long-term test

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1. INTRODUCTION

Among the most important components of the hydraulic cylinder, which make motion of parts of machines, are the seals, whose task is to prevent the undesirable flow of fluids between the chambers and to prevent the penetration of hard particles. Thus, the main task of the seals is to ensure a sufficiently large sealing force, while the frictional force resulting from the sealing force is also important. There are two types of seals, static and dynamic seals. Static or stationary seals seal the gap between two parts facing each other, while dynamic seals seal the gap between two parts moving toward each other. In this study, dynamic seals in hydraulic cylinders are discussed. In seals friction causes heat generation, leakage and wear. Seals are required to withstand high pressures and long life at competitive price [1].

Yanada et. al. [2] experimentally investigated the behaviour of hydraulic actuators controlled by servo valves with respect to different sealing materials, different external load amplitudes, and different cylinder dimensions. Friction tests were conducted to determine a more accurate friction model. They developed a more accurate dynamic friction model that includes fluid friction dynamics. They demonstrated that hydraulic actuators with HNBR seal material produce a higher frictional force than those with FKM and NBR material. Moreover, they proved that the frictional force exhibits the characteristic Stribeck effect.In their research, Márton et. al. [3] presented a practical method for measuring the friction of seals in hydraulic cylinders. The method is based on measuring the chamber pressures in cylinder and measuring the velocity of piston rings. The friction force is measured at a constant speed of travel of the piston rod. If we have a system with no external load and the piston moves at a constant speed, the friction force can only be calculated from the pressure difference.

In the work of Ottestad and colleagues [4], a method for reducing static friction ("stick-slip" effect) between the piston seals and the cylinder tube is presented. Static friction is reduced by introducing relative rotation of the piston to the hydraulic cylinder tube when the piston is at rest. The relative rotation of the piston is achieved by additional cylinders, which through the mechanism ensure the rotation of the piston rod and thus the piston. The additional cylinders are controlled by a servo valve that ensures extremely high switching speeds. The results show that the static friction is reduced in a small interval around zero speed. Thus, outside this interval, the usual Coulomb friction is present.

In the work of G. K. Nikas [5] and G. K. Nikas et al. [6], an investigation was carried out (experimental setup and mathematical model) of elastomer seals with rectangular piston rod cross-section was carried out. The operating pressure range of the oil is between 3.4 and 34.5 MPa, and the temperature range is between -54 °C and +135 °C. They found that the frictional force was 27% to 53% higher when the piston rod was pulled out than when it was pulled into the cylinder tube. This was true not only for piston seals with rectangular cross-sections, but also for piston rod U-seals. They also found that lower pressures and lower speeds lead to minimal leakage and increased friction.

In 2021, Pan et. al. [7] experimentally investigated the frictional force generated by a single seal as a function of velocity, external load, seal diameter and seal shape. The friction force was determined using the principle of measuring chamber pressures in cylinder. The resulting friction force shows a characteristic Stribeck effect when the piston rod is pulled out and retracted into the cylinder tube. Initially, the frictional force decreases with increasing speed, then the frictional force increases almost linearly with increasing speed. In the following, it was demonstrated that for the same material and shape of the seal, the frictional force increases as the diameter of the seal increase. A comparison of different seal types showed that the KGD seal type achieves the highest frictional force. In addition, the KGD seal is the least sensitive to changes in external load or pressure compared to the other two piston seal types (YB and KD). braking, which is true both when the piston is pulled out and when it is pulled into the cylinder tube.

Wang et al. [8] experimentally investigated the influence of the surface roughness of the piston rod in cylinder when sealing with an O-seal under different operating conditions. The results showed that the roughness of the piston rod surface has a great influence on the behaviour of the seal and therefore should not be ignored. The pull-out and pull-in frictional forces and leakage are increased when the roughness of the piston rod surface is greater. The resulting frictional force generates heat, which increases the temperature in cylinder.

In 2017, Ma, Wang, and Gu [9] conducted an experimental study of the friction of piston seals in cylinder as a function of different operating conditions. They found that under high-frequency operating conditions, the seal assembly T is the best. Under steady-state operating conditions, the M seal assembly is best.

In 2021, Mahankar and Dhoble [10] studied how medium and high temperatures affect the failure of hydraulic seals, which are mostly made of elastomers. They argue that it is important to have a good understanding of the failure mechanisms in order to improve seal life and reliability. All of the seal wear mechanisms studied are the result of the temperature of the seals and the temperature of the area in which the seal operates. Seal decay and performance degradation occur at moderate to high temperatures but become more noticeable at higher temperatures. Oil viscosity and elasticity of seals are strongly dependent on the operating temperature. On the process of thermal aging of seals, high pressures, improper installation of seals, chemical and thermal influences have a highly degrading and abrasive effect. The process of thermal aging affects the material, mechanical and chemical properties of seals. In many cases, two or more failure mechanisms can occur simultaneously.

In their work, Chen and colleagues [11] presented a method for determining the failure or reduction in functionality of seals in hydraulic cylinder during operation. Acoustic emission signals are caused by an internal leak in the hydraulic cylinder and technique is suitable for measuring internal leakage that is less than 1 l/min. Shanbhag et al. [12] improved the acoustic emission technique. Based on the acoustic emissions, they can distinguish between perfectly worn seals, moderately worn seals, and unworn seals.

In the work of Cristescu et al. [13], an experimental investigation of piston friction force was carried out seals in hydraulic cylinder. They tested a type of seal, the U-seal. They found that the frictional force increases with increasing pressure. However, at high pressures, the frictional force increases more slowly.

Literature suggest multiple studies of performance of the seals and the influencing parameters such as frictional force, hydraulic fluid type, speed of the moving piston rod, temperature generated form friction and surrounding area. Motivation for this study to evaluate the performance of different type and materials of seals in water and oil, to choose the most appropriate seal for the application. New test rig was developed to investigate comparison of different seal types (KGD, YB, KD) on frictional force. A dynamic test was performed to determine the dependence of friction forces on speed and acceleration. Two different hydraulic fluid were used to assess the performance of seals and their suitably application in water and oil hydraulics.

2. EXPERIMENTAL

In the present study, we tested three different cylinder piston seals at two test rigs. On the first one we performed measurements of the frictional force of all three different piston seals, they were lubricated once with tap water and the second time with mineral hydraulic oil ISO VG 46. On the second oil-hydraulic test rig, we then conducted an endurance test for the selected piston seal made of PTFE with bronze additive.

2.1. Tested cylinder piston sealings

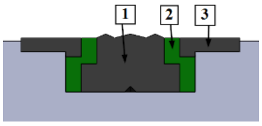
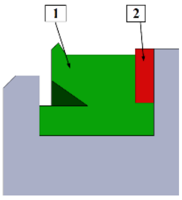
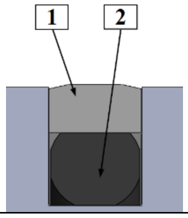
Three different types of piston seals with different geometries and made of different materials were tested, requiring different operating parameters for use (Table 1). Each seal has a different installation geometry, so three different hydraulic cylinder pistons were produced. The following materials were used for the seals: nitrile rubber (NBR), thermoplastic polyurethane (TPU) and polytetrafluoroethylene (PTFE) with bronze. The "YB50 39 4.2" seal made of PTFE with bronze is designed for maximum pressure (600 bar) and maximum sliding speed (15 m/s).

2.2. Friction measurement of piston seals lubricated once with oil and once with water

Frictional force measurements were performed on a single-axis pneumatic-hydraulic test rig (Figure 1). Using a pneumatic cylinder and a pneumatic system (Figure 2), we performed an externally controlled movement of a hydraulic cylinder piston with three various seals. We have a system with no external load and the piston moves at a constant speed, the friction force can only be calculated from the pressure difference.

Table 1: Three tested hydraulic cylinder piston seals

Type of the seal	KGD 50 34	KDA 50 39 9	YB 50 39 4.2
Material	NBR (1), TPE-E (2), POM (3)	TPU (1), POM (2)	PTFE + bronze (1), NBR (2)
Max. pressure	400 bar	500 bar	600 bar
Temp. range	-30 °C…+110 °C	-40 °C…+100 °C	-30 °C…+100 °C
Max. sliding vel.	0.5 m/s	0.5 m/s	15 m/s

Shape of the seal	(S1)  	(S2)  	(S3) 

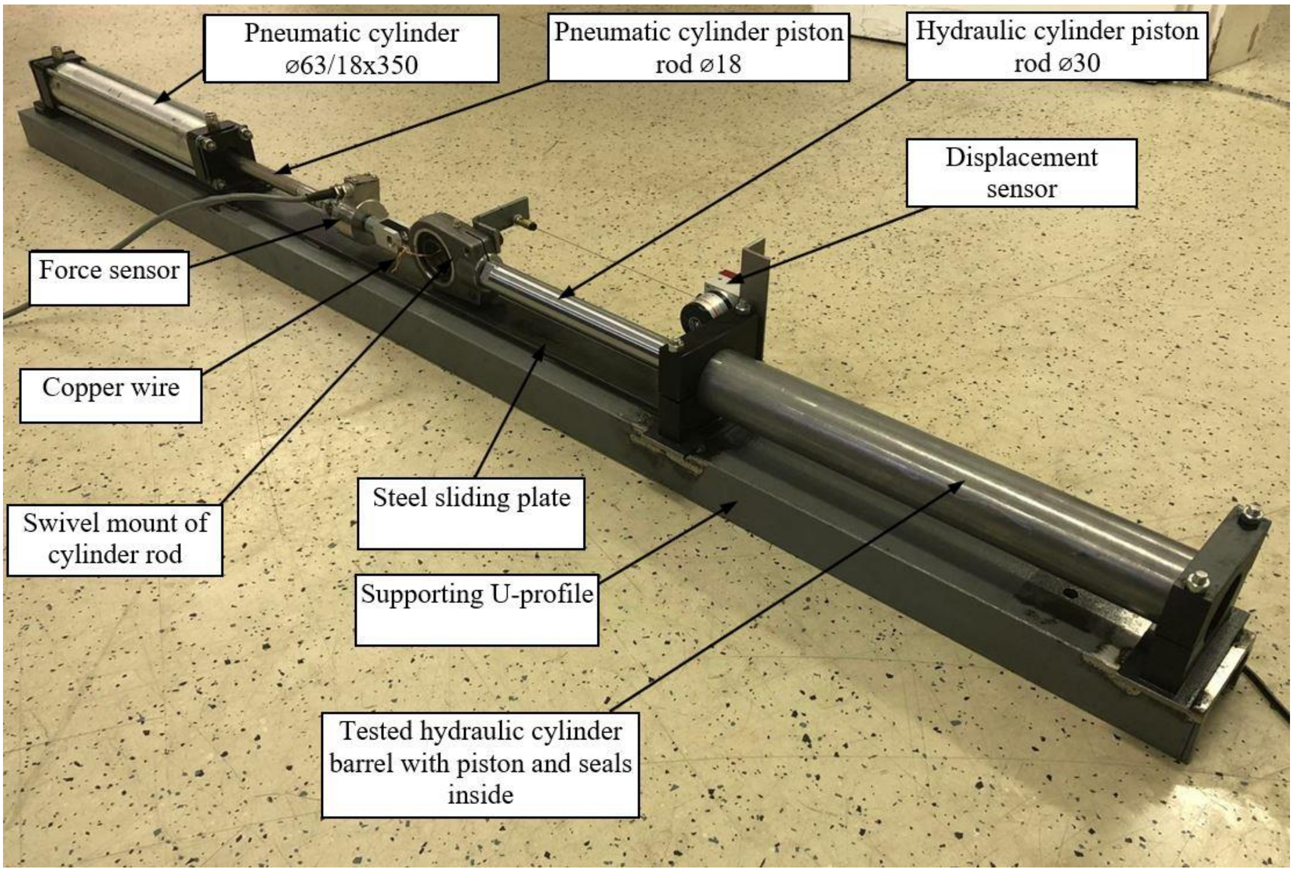


Figure 1: The first, pneumatic-hydraulic test rig - friction force measurements of piston seals (120 mm x 150 mm x 1730 mm)

The pneumatic part of the test rig (Figure 2) consists of a conditioning unit (OZ1), a 5/3-way pneumatic valve (1V1), which controls the direction of the compressed air flow passing through adjustable non-return flow-control valves (1V2 and 1V3), which indirectly control the speed and movements of the piston rod of the pneumatic cylinder (1A). The behaviour characteristics of the seals in water and in oil were measured with a force sensor (U2A) and a wire-type displacement sensor (Figure 1).

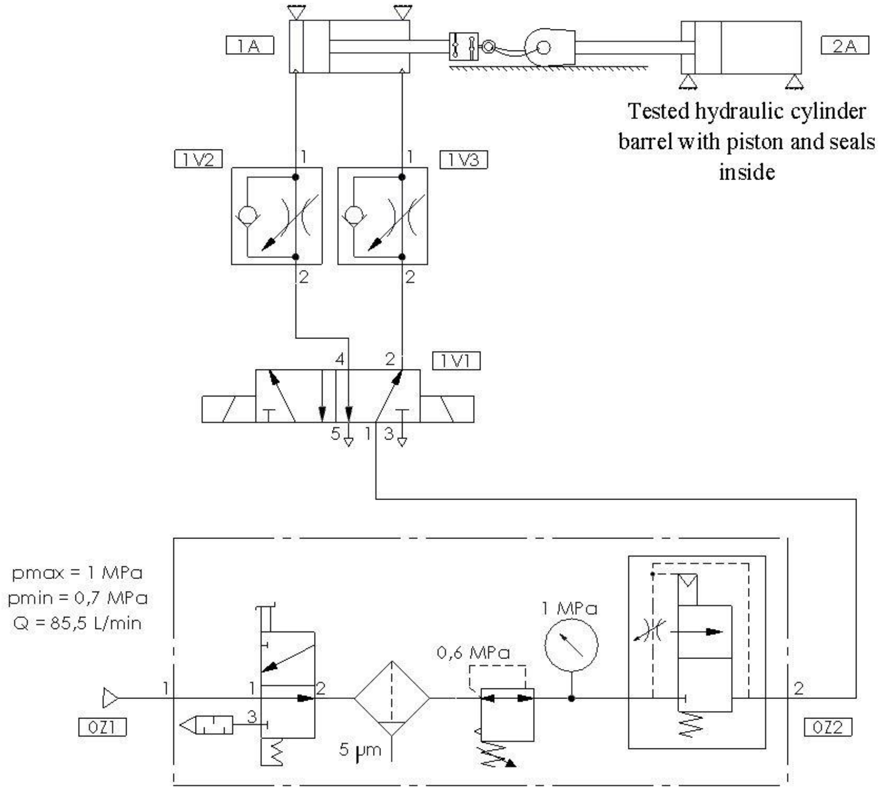


Figure 2: Functional diagram of the pneumatic test rig for measuring the frictional force of the hydraulic-cylinder piston seal

The procedure for measuring the frictional force of piston seals on the pneumatic-hydraulic test rig (Figure 1 and Figure 2 consisted of cleaning and degreasing all of components of the hydraulic test part, mounting the seal, setting the initial conditions and start measuring with Lab View.

2.3. Durability test of piston seals in oil hydraulics

The oil-hydraulic test station (Figure 3 and Figure 4) for piston seal sustainability testing consists of a hydraulic power unit with a 20 kW drive electric motor and a variable displacement axial piston pump with a displacement of 20 cm^3/rev. The pump pushes the hydraulic oil through the pressure line past the pressure relief valve through the 4/3 directional control valve alternately to the tested hydraulic cylinder ⌀50/30x380. The load on the tested cylinder is generated by the brake cylinder ⌀50/30x502. The pressure in the brake cylinder was provided alternately by two pressure valves set at 320 bar. The return line of the brake cylinder was filled with an additional hydraulic pump with a maximum filling pressure of 6 bar. The test rig also has a return line and by-pass filter as well as an oil-air cooler.

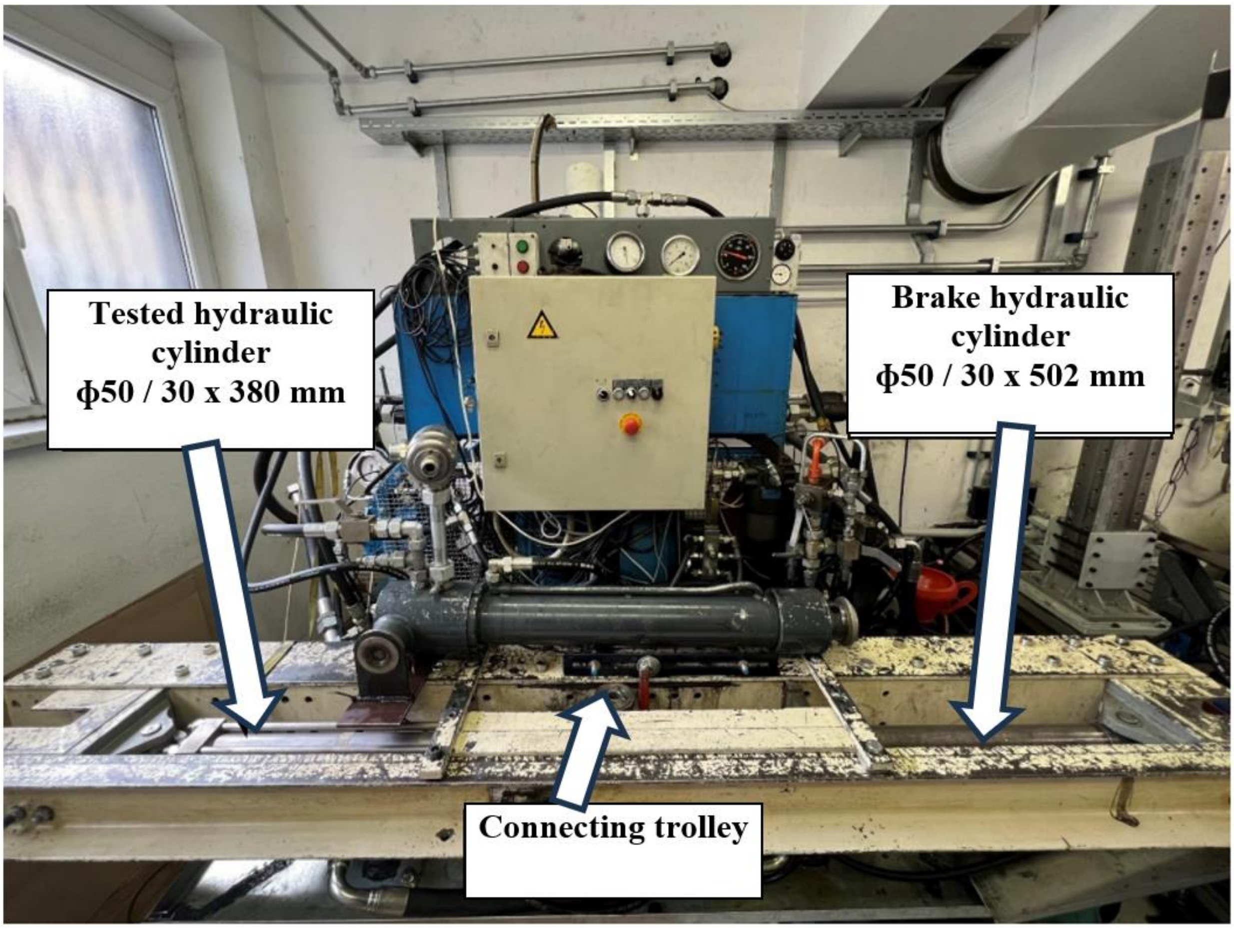


Figure 3: The second hydraulic test rig for long-term tests of cylinder piston seals (185 mm x 160 mm x 2000 mm)

The durability test, for the best piston seal from the first test rig, was performed in such a way that the Beckhoff industrial controller switched the 4/3 directional control valve, which directed the hydraulic oil alternately to one side and the other of the tested hydraulic cylinder. The load was generated by the piston rod of the tested cylinder, which was connected to the brake hydraulic cylinder. Both connections were made through two relief valves with bypass valves to the low-pressure pump, cooler and bypass filter.

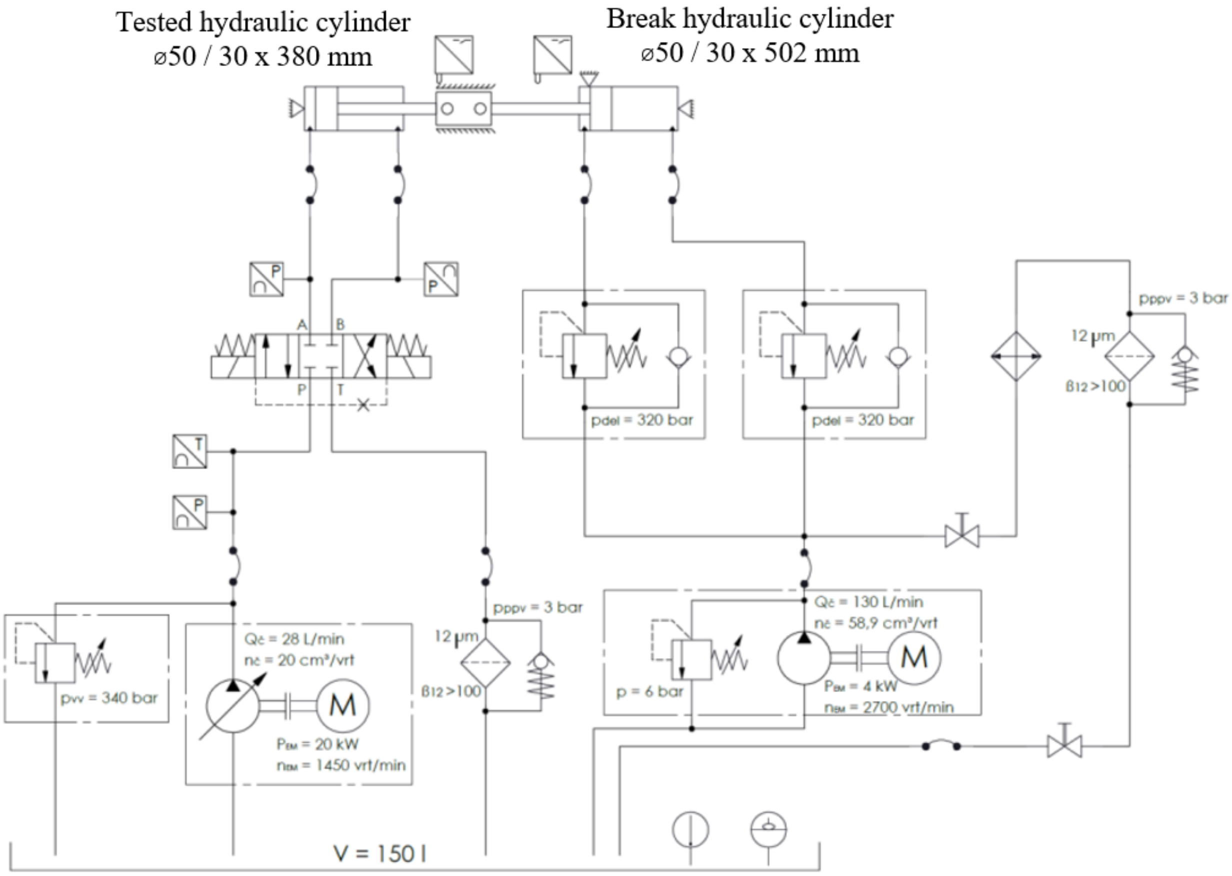


Figure 4: Functional diagram of the hydraulic test rig for long-term test of the hydraulic-cylinder piston seal

To measure the working pressure of the system, which was set to 320 bar with pressure relief valves, we used a measuring device The Parker Service Master Plus and pressure sensors (Figure 5). Then the pressure sensors are connected to both lines of the tested HV, as shown in the hydraulic diagram in Figure 4.

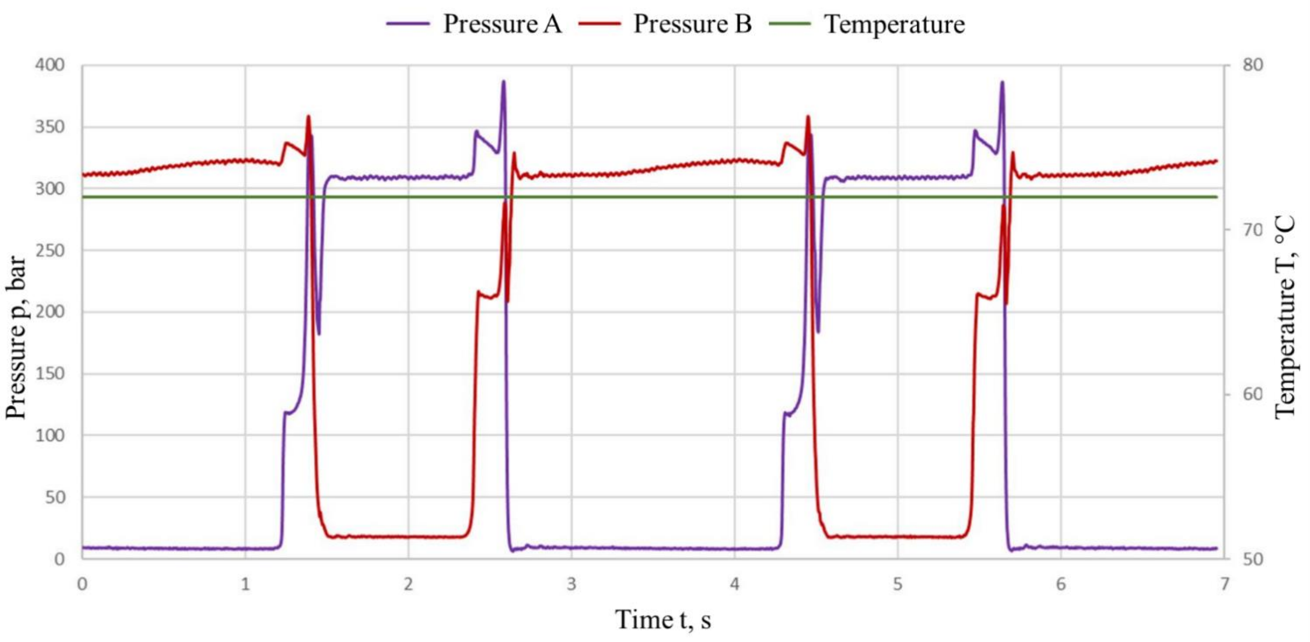


Figure 5: The measured duty cycle of the long-term test - the course of acting pressures and temperatures

3. RESULTS

3.1. Seal friction force in oil and water

The measured frictional force of the first piston seal "KGD 50 34" in mineral oil is shown in Figure 6. The analysis indicates that the highest average frictional force was observed during start-up at a speed of 270 mm/, while the lowest average frictional force occurred at a constant speed of 70 mm/s.

Transitioning to the static starting frictional force of the same piston seal in water, as depicted in Figure 7 the highest average frictional force was noted at a start-up speed of 125 mm/s, whereas the lowest average frictional force was recorded at a speed of 275 mm/s, but a constant sliding speed was not attained.

Figure 8 shows the measured frictional force of the second piston seal "KDA 50 39 9" in mineral oil. The highest average frictional force during start-up was observed at a speed of 125 mm/s, while the lowest average frictional force was measured at a constant speed of 100 mm/s.

The starting friction force and frictional force at constant speed for the second piston seal "KDA 50 39 9" in water is detailed in Figure 9. The highest average frictional force was measured at a speed of 35 mm/s when the piston seal was started up, and the lowest average frictional force occurred at a constant speed of 175 mm/s.

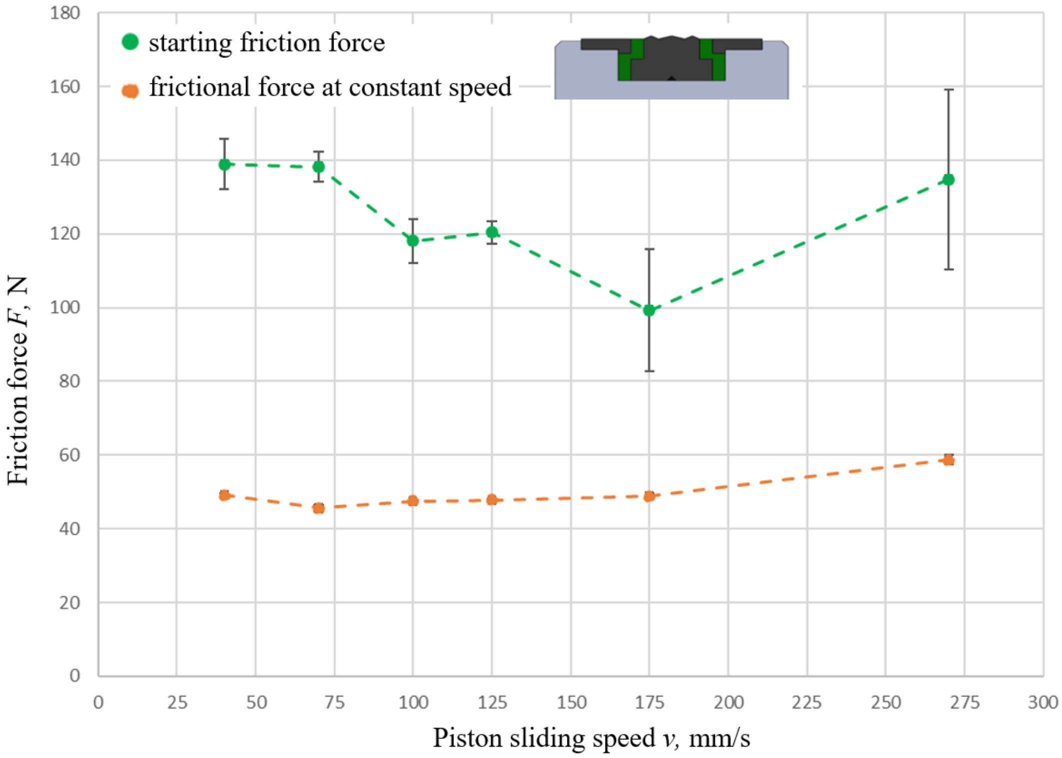


Figure 6: Measured friction force of piston seal "KGD 50 34" in mineral oil

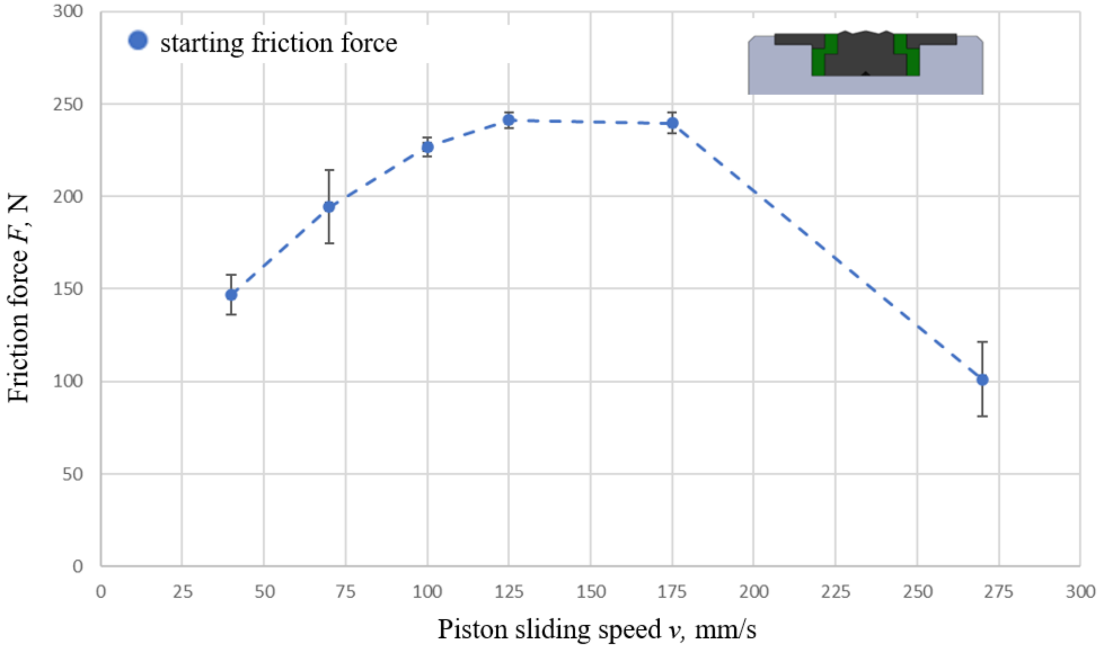


Figure 7: Measured friction force of piston seal "KGD 50 34" in water

The starting friction force and frictional force at constant speed, measured with the third piston seal "YB 50 39 4.2" in mineral oil is shown in Figure 10. The highest average frictional force was measured at a speed of 270 mm/s when the piston seal was started up, and the lowest average frictional force was measured at a constant speed of 35 mm/s.

Figure 11 shows the measured frictional force of the third piston seal " YB 50 39 4.2" in water. The highest average frictional force was measured at a speed of 270 mm/s when the piston seal was started up, and the lowest average frictional force was measured at a constant speed of 35 mm/s.

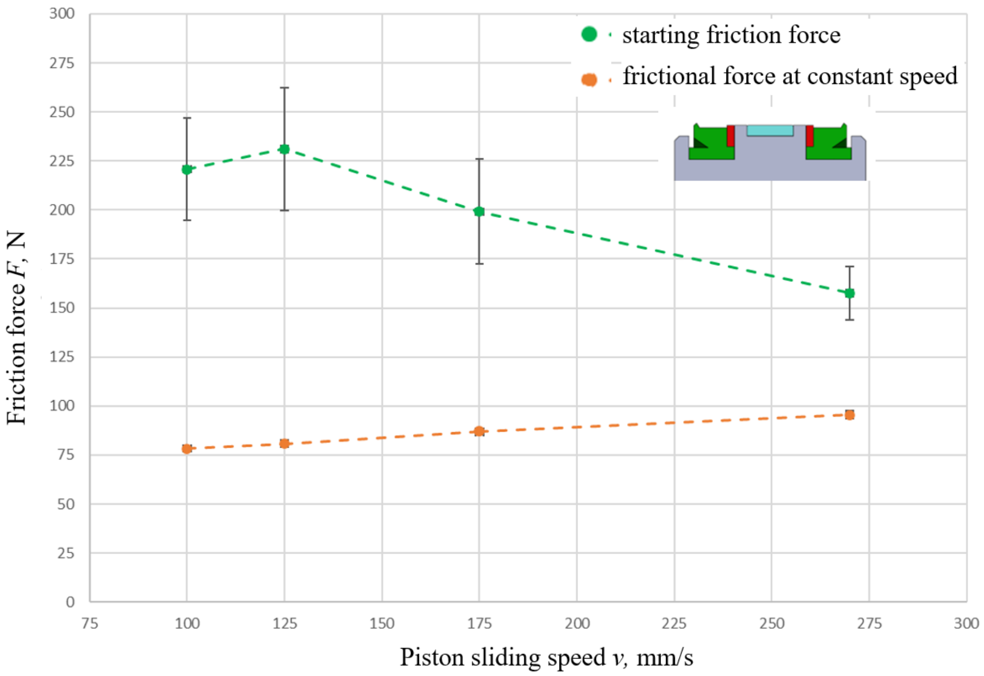


Figure 8: Measured friction force of piston seal "KDA 50 39 9" in mineral oil

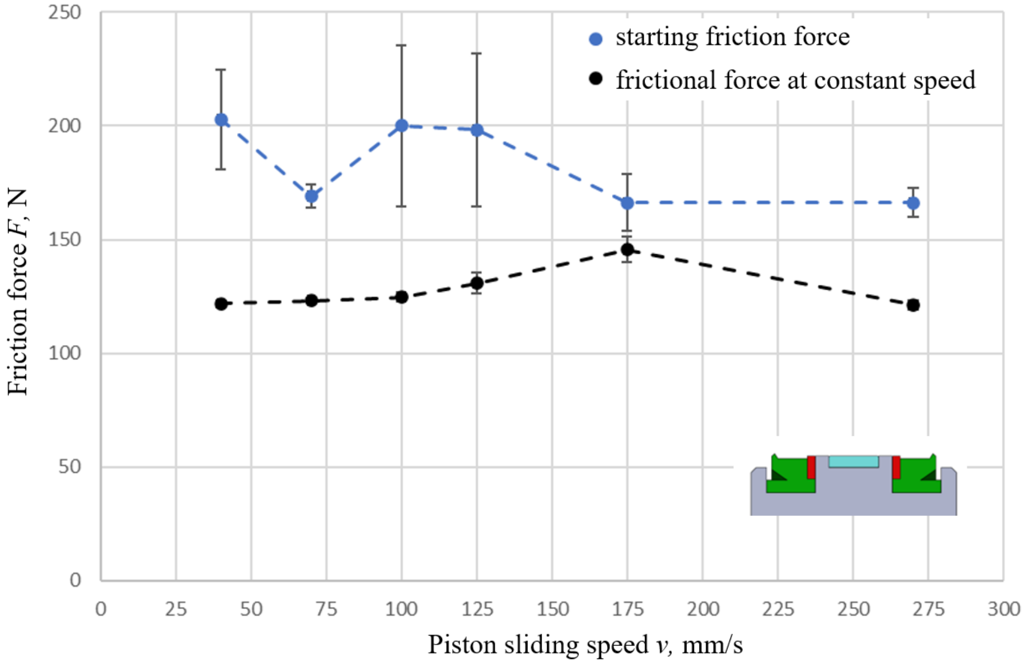


Figure 9: Measured friction force of piston seal "KDA 50 39 9" in water

With seal KDA 50 39 9, the frictional force in mineral oil is 60% of the force generated by the same type of seal in water. The seal type YB 50 39 4.2 generates in mineral oil 80% of the force generated by the same type of seal in water. However, with the KGD 50 34 water seal, the frictional force does not stabilize at a lower value because the speed does not reach a constant value. The reason for this is a greater frictional force and thus greater damping, which means that the piston sealing unit does not reach a constant speed until the piston rod is pulled out of the tube. Therefore, we have not calculated the friction ratio in mineral oil versus water for the KGD 50 34 seal type, since we have only specified the maximum value of the force. It is clear that the holding force in mineral oil is often greater than in water (seal type KPD 50 39 4.2) or the holding forces in both hydraulic fluids are the same (seal type YB 50 39 4.2). At speeds above 175 mm/s, the adhesive forces either reach equal values (KPD 50 39 4.2) or the adhesive force in water exceeds the force in mineral oil (YB 50 39 4.2). Extremal values of starting friction force and friction force at constant speed in mineral oil and water are represented in Table 2 and Table 3.

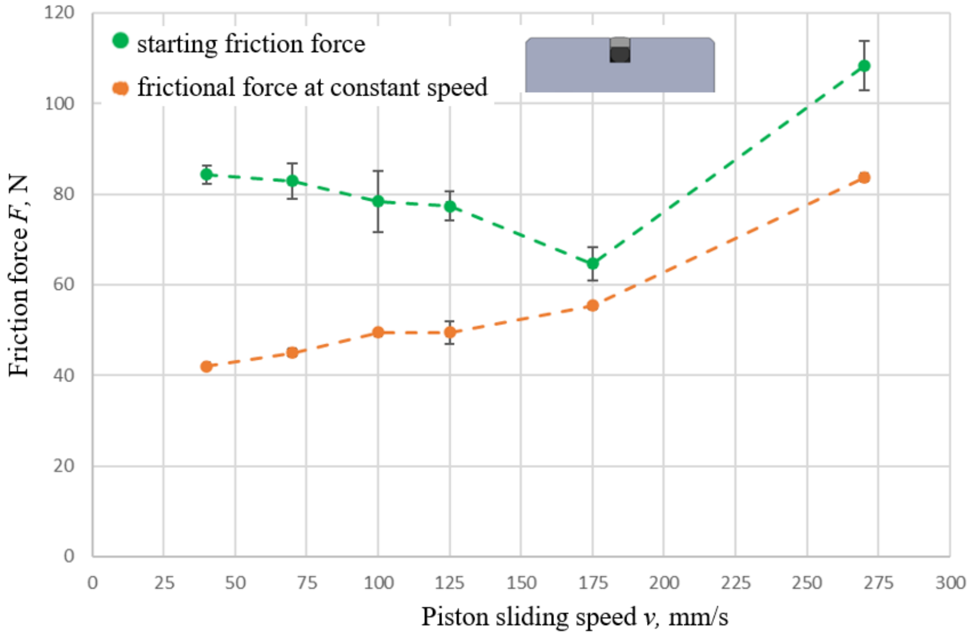


Figure 10: Measured friction force of piston seal "YB 50 39 4.2" in mineral oil

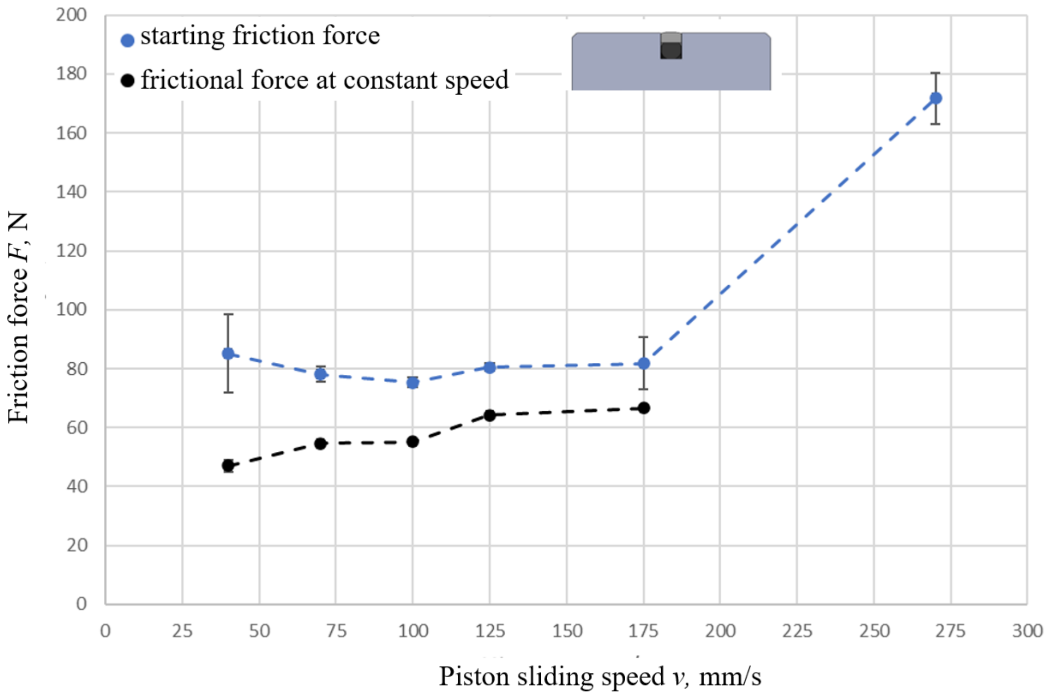


Figure 11: Measured friction force of piston seal "YB 50 39 4.2" in water

Table 2: Measured starting friction force in mineral oil and in water

Seal type	Mineral hydraulic oil				Water			
	F_{min}	v (F_{min})	F_{max}	v (F_{max})	F_{min}	v (F_{min})	F_{max}	v (F_{max})
	N	mm/s	N	mm/s	N	mm/s	N	mm/s
KGD 50 34	100	175	137	270	100	270	246	125
KDA 50 39 9	160	270	230	125	165	270	205	35
YB 50 39 4.2	67	175	110	270	75	100	172	270

Table 3: Measured friction force at constant speed in mineral oil and in water

Seal type	Mineral hydraulic oil				Water			
	$F_{\min}$	v ($F_{\min}$)	$F_{\max}$	v ($F_{\max}$)	$F_{\min}$	v ($F_{\min}$)	$F_{\max}$	v ($F_{\max}$)
	N	mm/s	N	mm/s	N	mm/s	N	mm/s
KGD 50 34	45	70	58	270	-	-	-	-
KDA 50 39 9	77	100	95	270	145	175	145	175
YB 50 39 4.2	42	35	84	270	47	35	63	125

For sealings there are a few new alternatives due to impact on health and the environment for PTFE and other PFAS materials such as he hydrolysis-resistant high-performance polyurethane [14]. Mentioned new polyurethane material will also be included in our next researching activities.

3.2. Piston seal durability test in mineral hydraulic oil

The best tested seal from the first test (YB 50 39 4.2) was then subjected to sustained testing on the oil hydraulic test rig. Figure 12 shows the average increase in leakage of the "YB 50 39 4.2" piston seal over the duration of the endurance test. The internal leakage increased from an initial 0.0011 ml/s to an average of 0.009 ml/s after the seal had been run for 100 km. After 100 km, the worn seal is still inside of acceptable limits, according to visual inspection, as shown in Figure 13. At 30x surface magnification, a slight wear of the seal edge can be seen, but it is still below the critical limit.

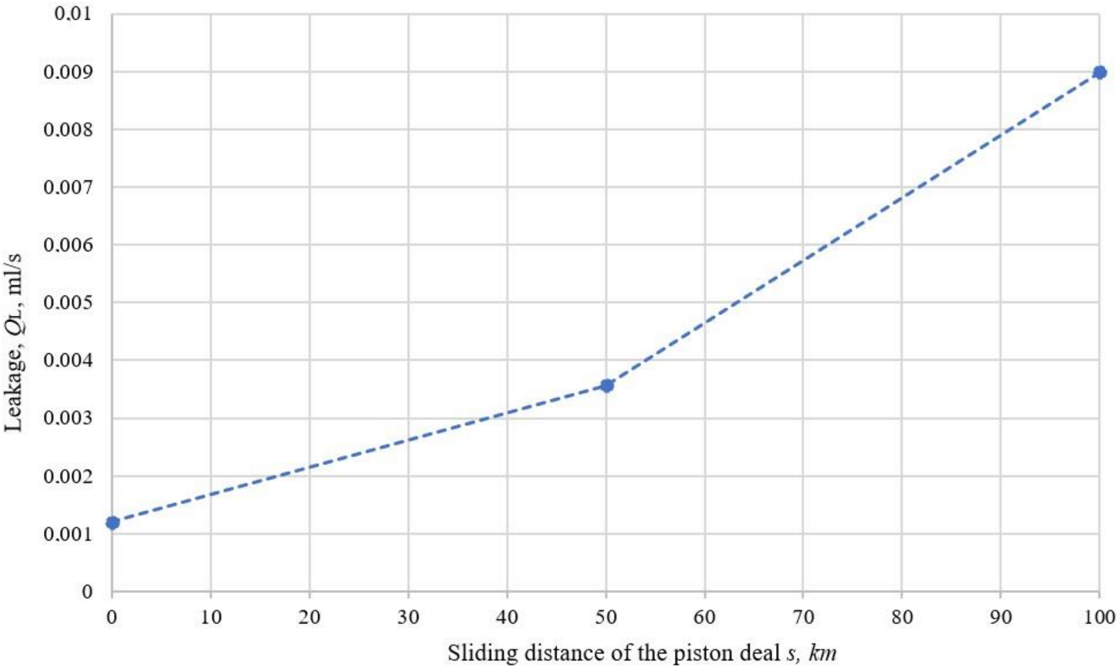
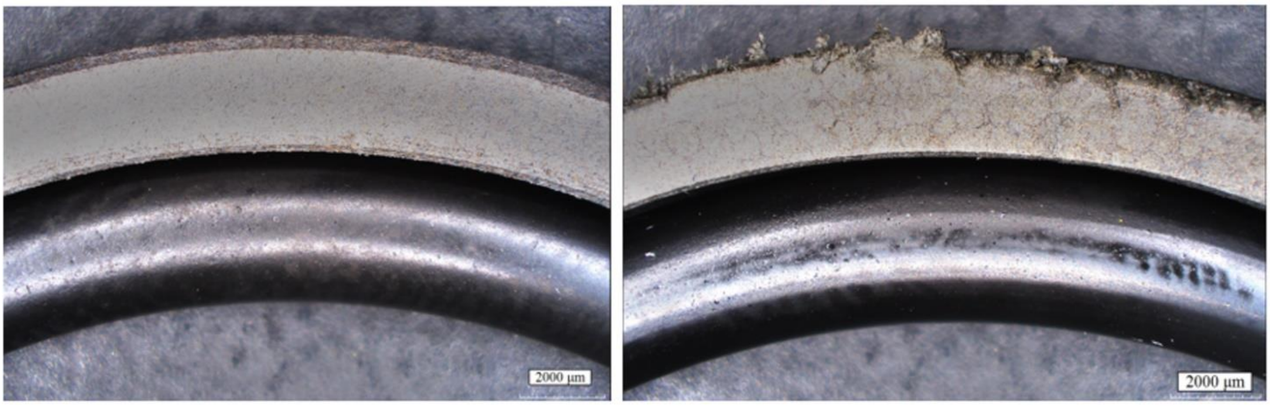


Figure 12: Leakage of the seal "YB 50 39 4.2" on the durability test with mineral hydraulic oil



a b

Figure 13: Surface of tested seal "YB 50 39 4.2"; a) before and b) after 100 km of durability test

4. CONCLUSION AND OUTLOOK

Frictional force was measured at six different speeds for pulling the piston rod out of the cylinder tube in mineral oil and water at the first test rig. The measurements were performed with three different piston seals. An endurance test was performed for the "YB 50 39 4.2" seal type and the leakage of the piston seal assembly was measured in three different piston positions of the tested cylinder. It was found that the seal leakage increased during the durability test. After 100 km of travel, the leakage increased by 7.5 times at the working pressure of 320 bar. Despite the multiple increase, the seal is still usable for most applications with an average final leakage of 0.009 ml per second. It would be advisable to make further research on the influence of working pressure and temperature on the wea rate of the seal and consequently, leakage. We have shown that the amplitude of the frictional force is larger in tap water than in mineral oil. The fraction of frictional force in mineral oil is 60% to 85% of the frictional force generated by the same piston seal unit in water. Lower friction of seals in mineral oil compared to water is mainly due to the significantly thinner lubricating film of water compared to the thickness of the lubricating film of mineral hydraulic oil. In the present study, we have investigated the influence of two hydraulic fluids (mineral oil and water) on the frictional force. We found that the frictional force of piston seals is greater in water than in mineral oil. Considering the ratio of the frictional force in mineral oil and water, we chose the "YB 50 39 4.2" PTFE seal for use in water and oil hydraulics, since the frictional force values in water and mineral oil differ by only 15%. In our future study promising materials such as PFAS (new polyurethane material) will be investigated along with well-established NBR and TPU materials.

ACKNOWLEDGEMENT

The authors would like to thank the company MAPRO, which donated the tested seals and hydraulic cylinder.

NOMENCLATURE

F	Friction force	N
FKM	Fluoroelastomers or fluoro rubber due to American standard (ASTM)	
HNBR	Hydrogenated Nitrile Butadiene Rubber	
ISO VG 46	Mineral hydraulic oil	

KD	A sealing material that assures a good reaction against shock pressure peaks and low friction in the low pressure range (Aston Seals)	
KDA	A sealing material mainly used with high pressure and the backup ring offsets large gaps or structural deflections (Aston Seals).	
KGD	A sealing rubber element with low permanent deformation which assures good sealing performance (Aston Seals).	
NBR	Nitrile Butadiene Rubber	
$n_{č}$	Rotational speed of the pump shaft	Rpm
p	Pressure	Pa, bar
p_{del}	Working pressure	Pa, bar
p_{EM}	Power of driven electromotor	Pa, bar
p_{pdv}	Pressure of filter by-pass valve	Pa, bar
p_{vv}	Pressure setting of the main pressure relief valve	Pa, bar
PTFE	Polytetrafluoroethylene, a thermoplastic polymer	
PTU	Thermoplastic polyurethane	
v	Sliding velocity	m/s, mm/s
V	Volume	m^3, L
YB	A dynamic seal element which assures exceptional low friction and high speed performance (Aston Seals).	

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