

# Friction investigations in a water hydraulic cylinder

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## Abstract

Environmental protection regulations are becoming increasingly strict. Using water instead of a hydraulic mineral oil in power-control hydraulic systems we can make a very positive step in complying with these regulations. In this paper we present measurement results of a water hydraulic cylinder on a newly developed water hydraulic test rig. The new water hydraulic cylinder (specimen) was simulated, constructed and tested. This construction was such that we could simply exchange its sealings and/or guiding to investigate the tribological and hydraulic behaviour of the sliding contacts. Combinations of two different types of special, serial produced sealings for the water hydraulics cylinder were first simulated, tested and then compared. Some important results about the dynamic responses of the water hydraulic system at different combinations of sealings, different combinations of the assembled water cylinder, different loads and positions of the hydraulic cylinder rod, different inlet pressures and different inlet flows are presented and compared. The results show significant differences between the different sealings in the water hydraulic cylinder.

KEYWORDS: water hydraulics, hydraulic cylinder, sealings and guidings

## 1. Introduction

When we talk about water hydraulics, we refer to the use of tap water – without any additives – for the hydraulic fluid, rather than the usual oils. Currently, water hydraulics are involved in very few applications, even though such systems have a decidedly low impact on the environment.

Interestingly, it was water that was the first fluid used in industrial power-control hydraulics, more than two hundred years ago /1/. However, in the early years of water hydraulics there were many problems associated with both the durability and the functionality.

During the 19th Century, after the oil industry began to develop /2/, there was no further use of water hydraulics. Oil-based hydraulic machines worked better and for longer than the equivalent water hydraulic machines. The reasons for the replacement of water hydraulics were linked to the low volumetric and mechanical hydraulic efficiencies, corrosion and high wear for the materials known at that time.

However, mineral hydraulic oils are not the best solution. The problem is the risk of pollution to the environment and especially the spoiling of drinking water. One so-called "soft" solution is the use of bio-degradable hydraulic oils /3-8/, but here the problem is with the additives, which tend not to be totally degradable. For this reason, in the early 1990s, many countries /2, 9, and 10/ began with research into the possibilities of using tap water as a hydraulic fluid.

The current situation on the market is that the available water hydraulic components are not persuading customers that they can replace oil-based systems and so lead to a significant increase in use /9/.

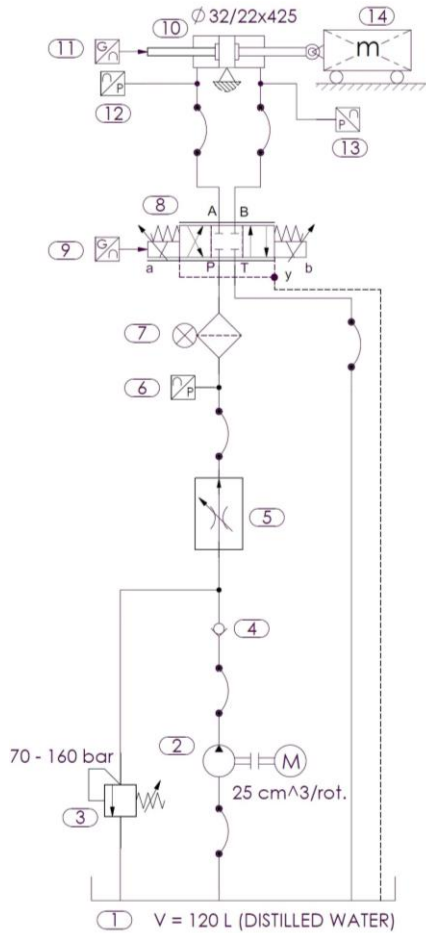
In this paper we would like to show that the design and material of sealing-guiding in a water hydraulic cylinder play a very important role. In order to do this a water hydraulic test rig was designed and constructed /11, 12/. A new water proportional 4/3 directional control valve was designed and long-term tests were conducted /13/. In terms of stationary behavior, the most important functional working characteristics were examined and compared with those of oil hydraulics /14/. Further research on the dynamic and transient characteristics of water power-control hydraulics and a comparison with similar oil hydraulics were made /15, 16/.

Some important results on the dynamic responses of a water hydraulic system for different combinations of sealings (two different types), different combinations of assembled water cylinder (differential hydraulic cylinder and hydraulic cylinder with double rod), different loads and positions of the hydraulic cylinder rod (without load and with a load of 163 kg in the horizontal position), different inlet pressures (70, 110 and 150 bar) and different inlet flows (1, 11 and 22 lpm) are presented and compared. They show the important working parameters for each variation of use of a water hydraulic cylinder. The used hydraulic liquid was demineralised water; the working temperature was in the range from 30 to 35°C, the setting pressure of the pressure relief valve was up to 160 bar.

## 2. Experimental

### 2.1. Test rig

The water hydraulic test rig intended to investigate the water power-control hydraulics (PCH) (Fig. 1.a and 1.b.) was constructed and used for the experimental investigations /11, 12/. This water hydraulic test rig was also used to test the water valves, with the valve being of the proportional 4/3 directional spool-sliding control type. The same test rig was used to carry out comparative stationary /14/, dynamic-transient /15/ and static-long-term life-time tests /12, 13/ under the same, or at least analogous, working conditions. Figure 1 shows a simplified hydraulic circuit of the water (**Fig. 1**) test rig. The water hydraulic test rig uses a standard axial piston pump, type PAH 25 (**Fig. 1**, pos. 2), with a displacement of 25 cm<sup>3</sup>/rev. This pump delivers water through a pressure-compensated flow-control valve (**Fig. 1**, pos. 5), which ensures a constant flow (in these series of experiments, 1, 11 or 22 lpm) through the newly designed water proportional directional control valve [11, 12] (**Fig. 1**, pos. 8). A pressure-line water filter with a rating of 1 µm (**Fig. 1**, pos. 7) was installed on the P line, close to the water proportional directional control valve. This valve was controlled from a PC in a closed loop. To the connection port A of the proportional valve we connected a stainless-steel tube, to which a pressure transmitter (**Fig. 1**, pos. 12) and a double-acting hydraulic cylinder (**Fig. 1**, pos. 10) were connected at the end. The second branch on the connection B was the same. A roller-guided load-mass of 163 kg (**Fig. 1**, pos. 14) was connected to the rod of the hydraulic cylinder. The water relief valve (**Fig. 1**, pos. 3) was set to different pressures (70, 110 and 150 bar). A centrifugal water pump, a temperature transmitter and an additional 1-µm by-pass filter were used to maintain a constant temperature and to ensure high-quality off-line filtering. The pressure on the P connection port of the water proportional valve was measured during the test using a pressure transmitter (**Fig. 1**, pos. 6). The control of the proportional magnets (**Fig. 1**, pos. 9), the data acquisition and the electro-motors was automated with a PC. The water hydraulic test rig (**Fig. 1.a**) is assembled from standard, commercially available, water hydraulic components, except for the proportional directional 4/3 control valve and the hydraulic cylinder. These two components were designed in our LPCH. The tubes for the water and oil hydraulic cylinders were made from stainless steel and the rod was made from hard-chromium-plated steel. A photograph of the water hydraulic test rig is shown in **Fig. 1.b**.



a.

b.

**Figure 1:** a. Simplified hydraulic circuit for the water hydraulic test rig, b. Photo of water hydraulic test rig

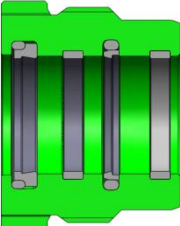
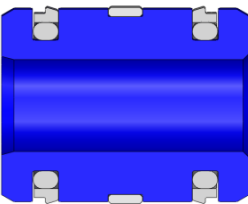
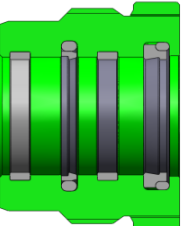
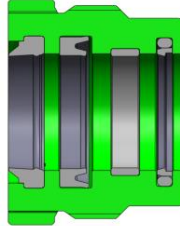
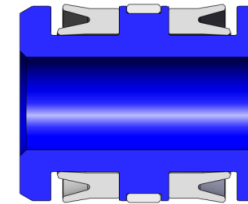
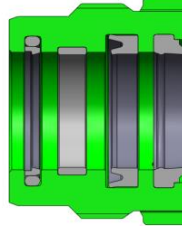
## 2.2. Specimen and sealing combinations

A double-acting, double rod hydraulic cylinder (**Fig. 2**) for using water as a hydraulic fluid was designed with the goal of investigating the static and dynamic performance of the hydraulic cylinder related to the specific working parameters and studying the tribological behaviour of various sealings and guidings (**Tab. 1**). Water hydraulic cylinder has a modular design that has easy exchange of one type of the sealing and guiding with another.



**Figure 2:** Specimen, a new water double-acting, double rod hydraulic cylinder

In this investigation we used two types of standard sealings and guidings, both suitable for mineral oil and water as the hydraulic fluid. The first combination of sealings and guidings (**Tab. 1**, combination A) was based on Polytetrafluoroethylene (PTFE) with a bronze compound (PTFE B602). The allowed maximum sliding velocity for this material is 5 m/s and a temperature range from 5 to 100°C. In the second combination of sealings and guidings (**Tab. 1**, combination B) we used Polyurethane with a hardness of 94 Sh (94 AU 925) for the material of sealings and Polytetrafluoroethylene (PTFE B500) for the guidings. The allowed maximum sliding velocity for Polyurethane is 0.5 m/s and a temperature range from 40 to 105°C.

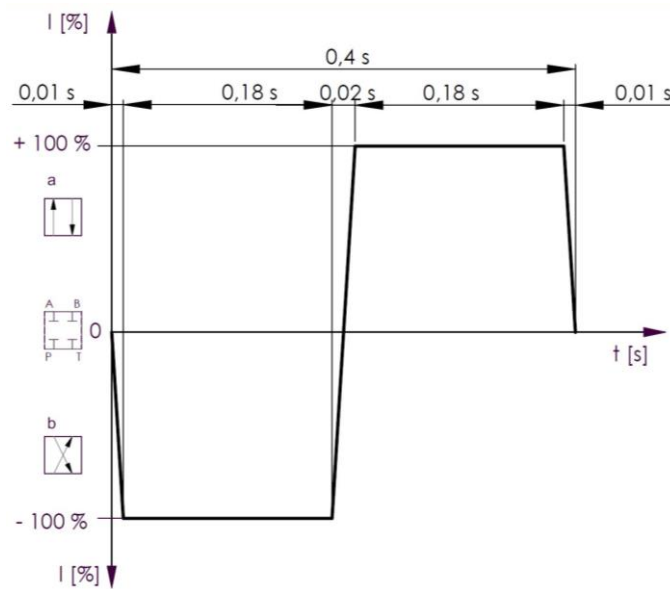
Combination A		+		+	
Combination B		+		+	

**Table 1:** Different sealing/guiding combinations for the double rod water hydraulic cylinder

### 2.3. Experimental procedure and testing parameters

The whole testing procedure was fully automated with PC software /12/. All the presented results were recorded with the same procedure, using the same controlling signal (**Fig. 3**) for the water proportional 4/3 directional control valve. After the start of an individual measurement the proportional valve was switched from the zero position (**Fig. 3**) to the cross-shaped position (solenoid a energized). As a consequence of this the piston rod of the cylinder starts to move forward. The electrical controlling signal increases from 0 to 100% in 0.01 seconds. The electrical signal then stays at the same level for 0.18 seconds and holds the spool in the valve in the cross-shaped position. After 0.01 seconds the solenoid A is de-energized and the solenoid B is energized at the same time, so that the spool in the valve moves from the cross-shaped to the parallel position in approximately 0.02 seconds and the cylinder rod starts to move backwards. Between switching from the cross-shaped to the parallel position of the

directional valve, the cylinder rod stops moving for a brief moment. The electrical input signal for the parallel-shaped position remains at 100 % for 0.18 seconds. In the final phase the input signal decreases from 100 % to zero in 0.01 seconds and the cylinder rod stops moving. The total time needed for the measurement of one cycle was 0.4 seconds.



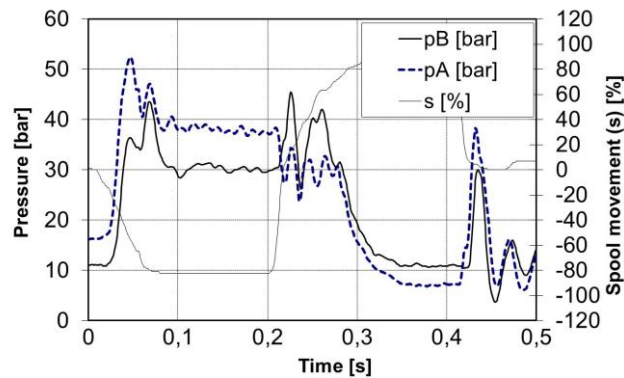
**Figure 3:** Shape of the step-controlling signal for control of the water proportional 4/3 directional control valves (**Fig. 1.a**, pos.9)

The measurements were performed with and without the load mass of 163 kg. The water hydraulic cylinder and the load mass were in all the presented measurements positioned in the horizontal direction. The tests were made with three different flows (1, 11 and 22 lpm) and three different pressures (70, 110 and 150 bar). In the water hydraulic test rig we used distilled water, the working temperature in the water test rig was maintained through cooling at 40 °C +/- 2°C. All of the presented measurements were repeated at least three times.

### 3. Results

**Figure 4** shows an example of measurements on the water hydraulic test rig with a water hydraulic cylinder (specimen). The first curve is for the movement of the controlling spool in the proportional 4/3 directional control valve (s [%]), the second and the third are for the working pressures on both ports of the water hydraulic cylinder for a known signal (**Fig. 3**), an inlet-system pressure of 110 bar, flow 22 lpm, without load, cylinder horizontally positioned. The pressure difference between the A and B ports of

the water cylinder was, just to start moving the cylinder rod, 15.4 bar, and 7.6 bar to move the cylinder rod with a constant velocity.

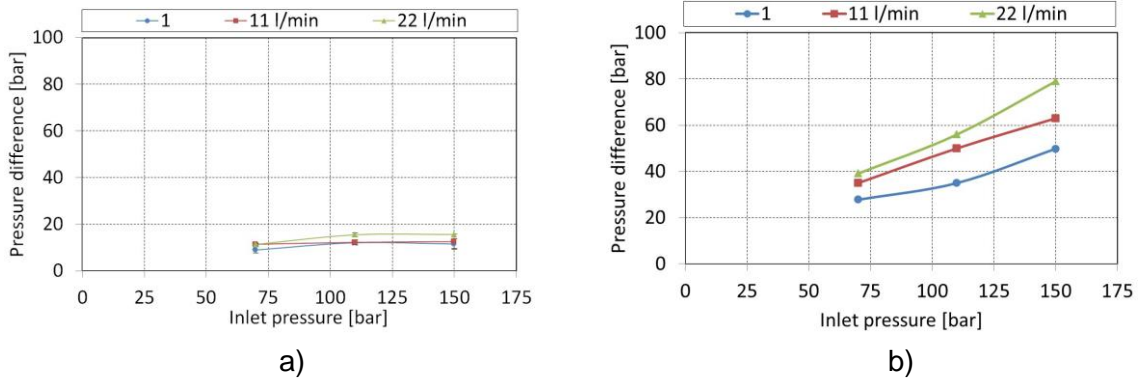


**Figure 4:** Example of measurement results on water hydraulic cylinder with A type of sealing at inlet pressure 110 bar, inlet flow 22 lpm, without load, cylinder in the horizontal position

### 3.1. Hydraulic cylinder without load in horizontal position

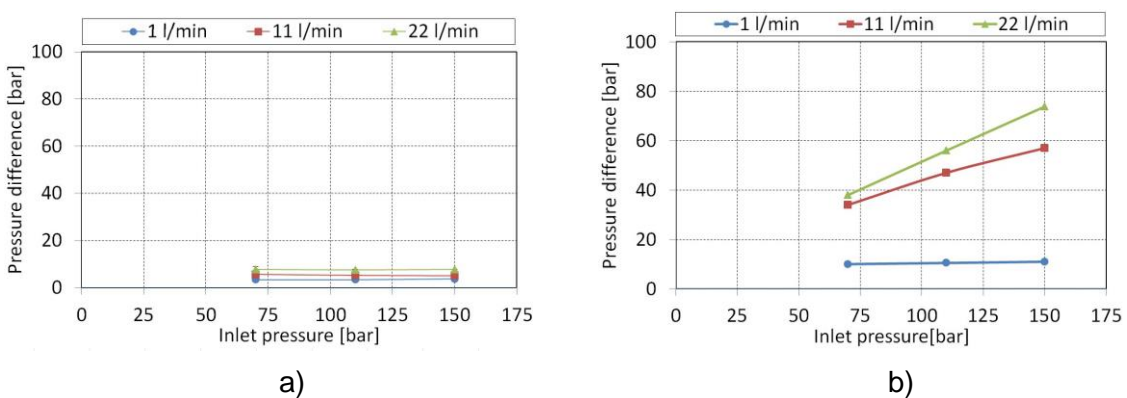
**Figure 5.a** and **5.b** show the influence on the pressure difference between the A and B ports during instantaneous starting of the water hydraulic cylinder rod for three different inlet pressures (70, 110 and 150 bar) and three different inlet flows (1, 11 and 22 lpm) to the water cylinder in the horizontal position without load. **Figure 5.a** shows the measured pressure difference for the water hydraulic cylinder with sealing/guiding combination A (**Tab. 1**) and **Figure 5.b** measured results at the same hydraulic parameters for the sealing/guiding combination B (**Tab. 1**).

The lowest pressure difference between the A and B port of the water cylinder with sealing/guiding combination A (**Fig. 5.a**) was, just to start moving the cylinder rod, 8.9 bar occurred at 1 lpm and an inlet pressure of 70 bar. The highest pressure difference for sealing/guiding combination A (**Fig. 5.a**) was also, just to start moving the cylinder rod, 15.6 bar at a flow of 22 lpm and an inlet pressure of 150 bar. For sealing/guiding combination B (**Tab. 1**) the lowest pressure difference (**Fig. 5.b**) was at the moment when the cylinder rod started to move, 27.7 bar at 1 lpm and inlet pressure 70 bar and the highest, 79 bar at inlet flow 22 lpm and inlet pressure 150 bar.



**Figure 5:** Pressure difference at the moment to start moving the cylinder rod between the A and B ports of the water cylinder in the horizontal position without load for different inlet pressures and different flows: a) with sealing/guiding combination A and b) with sealing/guiding combination B

**Figure 6.a** and **6.b** shows the influence on the pressure difference between the A and B ports during moving of the water hydraulic cylinder rod with constant velocity for three different inlet pressures and three different inlet flows at the water cylinder in horizontal position without load. The lowest pressure difference between the A and B ports of the water cylinder with the sealing/guiding combination A (**Fig. 6.a**) was when moving the cylinder rod with a constant velocity, 3.4 bar occurred at 1 lpm and an inlet pressure of 70 bar. The highest pressure difference for the sealing/guiding combination A (**Fig. 6.a**) was also when moving the cylinder rod with a constant velocity, 7.8 bar at flow of 22 lpm and an inlet pressure of 150 bar. For sealing/guiding combination B (**Tab. 1**) was the lowest pressure difference when moving the cylinder rod with a constant velocity (**Fig. 6.b**), 10 bar at 1 lpm and inlet pressure 70 bar and the highest, 73.8 bar at inlet flow 22 lpm and inlet pressure 150 bar.



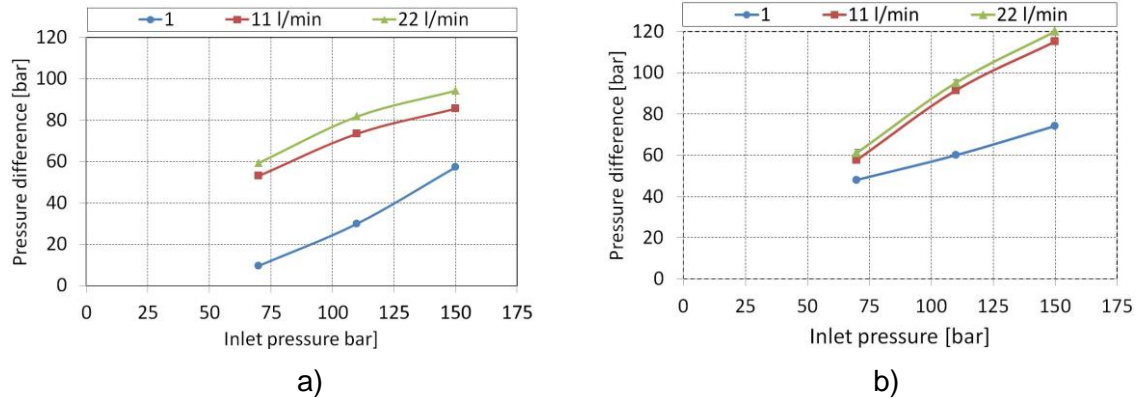
**Figure 6:** Pressure difference between the A and B ports of the water cylinder at the moment of moving the cylinder rod with constant velocity for the hydraulic cylinder in the horizontal position without load for different inlet pressures and different flows: a) with sealing/guiding combination A and b) with sealing/guiding combination B



### 3.2. Hydraulic cylinder with load in horizontal position

**Figure 7.a** and **7.b** shows the influence on the pressure difference between the A and B port during instantaneous starting of the water hydraulic cylinder rod for three different inlet pressures (70, 110 and 150 bar) and three different inlet flows (1, 11 and 22 lpm) to the water cylinder with a load of 163 kg in the horizontal position. **Figure 7.a** shows the measured pressure differences for a water hydraulic cylinder with sealing/guiding combination A (**Tab. 1**) and **Figure 7.b** measured results at the same hydraulic parameters for sealing/guiding combination B (**Tab. 1**).

The lowest pressure difference between the A and B ports of the water cylinder with sealing/guiding combination A (**Fig. 7.a**) was, just to start moving the cylinder rod with the load in the horizontal position, 9.6 bar occurred at 1 lpm and an inlet pressure of 70 bar. The highest pressure difference for sealing/guiding combination A (**Fig. 7.a**) was also, just to start moving the cylinder rod, 94.3 bar at a flow of 22 lpm and an inlet pressure of 150 bar. For sealing/guiding combination B (**Tab. 1**) the lowest pressure difference (**Fig. 7.b**) was at the moment to start moving the cylinder rod with the load in the horizontal position 48 bar at 1 lpm and inlet pressure 70 bar and the highest, 120 bar at inlet flow 22 lpm and inlet pressure 150 bar.

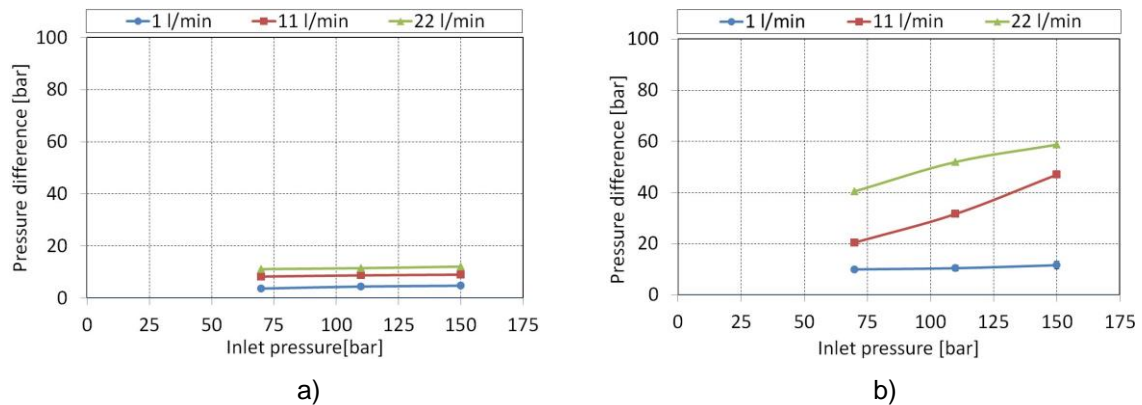


**Figure 7:** Pressure difference at the moment to start moving the cylinder rod between the A and B ports of the water cylinder in the horizontal position with a load of 163 kg for different inlet pressures and different flows a) with sealing/guiding combination A and b) with sealing/guiding combination B

**Figure 8.a** and **8.b** shows the influence on the pressure difference between the A and B ports during the moving of the water hydraulic cylinder rod with a constant velocity for three different inlet pressures and three different inlet flows for the water cylinder with a load of 163 kg in the horizontal position.

The lowest pressure difference between the A and B ports of the water cylinder with the sealing/guiding combination A (**Fig. 8.a**) was when moving the cylinder rod with a

constant velocity, 3.7 bar occurred at 1 lpm and an inlet pressure of 70 bar. The highest pressure difference for the sealing/guiding combination A (**Fig. 8.a**) was also when moving the cylinder rod with a constant velocity, 12.1 bar at flow of 22 lpm and an inlet pressure of 150 bar. For sealing/guiding combination B (**Tab. 1**) was the lowest pressure difference when moving the cylinder rod with constant velocity (**Fig. 8.b**), 10 bar at 1 lpm and inlet pressure 70 bar and the highest, 58.7 bar at inlet flow 22 lpm and inlet pressure 150 bar.



**Figure 8:** Pressure difference between the A and B ports of the water cylinder at the moment of moving the cylinder rod with a constant velocity for the hydraulic cylinder with a load of 163 kg in the horizontal position for different inlet pressures and different flows: a) with sealing/guiding combination A and b) with sealing/guiding combination B

#### 4. Conclusion

A friction investigation with two different water hydraulic cylinder sealing/guiding combination "packets" was carried out.

A large difference between the friction behavior of these two sealing/guiding combinations was observed.

The most promising sealing/guiding material for the water hydraulic cylinder seems to be Polytetrafluoroethylene with a bronze compound (PTFE B...). It has an approximately 6 to 63 bar lower pressure difference in the unloaded condition and between 6 and 46 bar lower pressure difference in loaded condition, in comparison to the most commonly used material, i.e., Polyurethane.

## 5. Bibliographical References

- /1/ J. Bramah. The Hydraulic Press, U K Patent Nr.. 2045, 1795.
- /2/ E. Trostmann. Water Hydraulics Control Technology, Lyngby,1996, Technical University of Denmark, ISBN: 0-8247-9680-2.
- /3/ M. Kalin, F. Majdič, J. Vižintin, J. Pezdirnik & I. Velkavrh. Analyses of the Long-Term Performance And Tribological Behaviour of an Axial Piston Pump Using Dimond-like-Carbon-Coated piston Shoes and Biodegradable Oil, Journal of Tribology, 2008, vol. 130.
- /4/ M. Kalin, F. Majdič, J. Vižintin & J. Pezdirnik. Performance of axial piston pump using DLC-coated piston shoes and biodegradable oil. In, The 12th Nordic Symposium on Tribology, Helsingor, Denmark, June 7-9, 2006. Nordtrib 2006, 10 Pgs.
- /5/ M. Kalin & J. Vižintin. A comparison of the tribological behaviour of steel/steel, steel/DLC and DLC/DLC contact when lubricated with mineral and biodegradable oils, Wear 261, [1], 2006
- /6/ J. Barriga, M. Kalin, K. Van Acker, K. Vercammen, A. Ortega & L. Leiaristi. Tribological performance of titanium doped and pure DLC coatings combined with a synthetic bio-lubricant. Wear 261, 2006, pp. 9-14.
- /7/ M. Kalin, J. Vižintin, K. Vercammen, A. Arnšek, J. Barriga & K. Van Acker. Tribological performance of lubricated DLC coatings using biodegradable oils. The coatings in Manufacturing Engineering 2004, pp. 457-465.
- /8/ J. Barriga, M. Kalin, K. Van Acker, K. Vercammen, A. Ortega, L. Leiaristi. Tribological characterisation and validation of carbon based coatings combined with bio-lubricants. Proceedings of the 11th Nordic Symposium on Tribology. Norway, June 2004. Pg. 508-517.
- /9/ K. Koskinen, T. Leino & H. Riipinen. Sustainable development with water hydraulics – possibilities and challenges, Proceedings of the 7th JFPS International Symposium in Fluid Power, 2008, Toyama, Japan, Vol. 1, pp. 11 – 18.
- /10/ F. Majdic, J. Pezdirnik & M. Kalin. Comparative tribological investigations of continuous control valves for water hydraulics, The Tenth Scandinavian International Conference on Fluid Power, SICFP 2007, Tampere, Finland.

- /11/ F. Majdic & J. Pezdirnik. Advances in Water Power-Control Hydraulics Experimental Research, Journal of Mechanical Engineering 54 12, 2008, pp. 841-849.
- /12/ F. Majdic, J. Pezdirnik & M. Kalin. Experimental validation of the life-time performance of a proportional 4/3 hydraulic valve operating in water, Tribology International 44, 2011, pp. 2013-2021.
- /13/ F. Majdic, J. Pezdirnik & M. Kalin. Lifetime test of new water hydraulic proportional directional control valve, The Seventh International Conference on Fluid Power, 7th IFK 2010, Aachen, Germany.
- /14/ F. Majdic, J. Pezdirnik & M. Kalin. Characteristics of stationary behaviour of water- and oil-based power-control hydraulics, In submission: ASME-Journal of Applied Mechanics, 2012.
- /15/ F. Majdic, J. Pezdirnik & M. Kalin. Test Rig and Comparison of Pressure Changes at Transient Phenomena in Water- and Oil-based Power-Control Hydraulics, In submission: Strojarstvo, 2012.
- /16/ F. Majdic & J. Pezdirnik. Oscillations of Cylinder Piston Rod – Comparison of Amplitudes and Frequencies Resulting the Transient Phenomena in Tap Water- and Oil-based PCHS, In submission: Journal of Vibroengineering , 2012.