Lifetime test of new water hydraulic proportional directional control valve

Franc Majdic,

Jozef Pezdirnik and

Mitjan Kalin

Centre for Tribology, Technical Diagnostics and Hydraulics, Faculty of Mechanical Engineering, University of Ljubljana, Slovenia

ABSTRACT

Besides bio-degradable fluids the tap water is probably the best alternative to protect the environment from destructive pollution. In our Laboratory for power-control hydraulics (LPCH) we have designed, constructed and built up a water hydraulic test rig to investigate the dynamic properties and useful lifetime of the proportional 4/3 water hydraulic directional control valve and of the whole water hydraulic system. Proportional water valve was also newly developed in our laboratory. This proportional valve is spool sliding type of valve. It is constructed that way that we could simply change the material of the spool and the sleeve to investigate tribological and hydraulic properties of the tested material couple in sliding contact. We carried out lifetime test for the first chosen material pair being hardened stainless steel for the spool against hardened stainless steel for the sleeve. The paper shows the change of the leakage flow through time at the duration test and the changes on the sliding surfaces. Duration test was executed with 10 million cycles. The used hydraulic liquid was distilled water; working temperature was in the range from 30 to 35°C, setting pressure of the pressure relief valve was up to 160 bar, the testing frequency was 5 Hz at the spool amplitude of +/- 100 %. The results show that we can be optimistic about usability of the tested proportional control water valve.

NOMENCLATURE

$I_{A,B}$	input signal at the solenoid A, B	%
$p_{A,B,P}$	pressure at the port A, B, P	bar
s_{spool}	movement of the spool	mm
t_i	rising time of the signal for	s
T	temperature	°C
Q_i	(working) fluid flow	m^3/s, lpm

1 INTRODUCTION

Unexpected outflows of problematic hydraulic liquids, for example mineral oils, into the ground and even into the underground drinking water supplies, occur rather frequently. One of today's major challenges to prevent pollution is to use alternative, natural sources of hydraulic fluids to protect our environment. In power-control hydraulics (PCH) there are two ways in which we can mostly or totally protect the environment. The first solution is to use the biodegradable oil /Bar98; Adh04; Kal07; Ver04; Ram07; Kal06; Iga98/ instead of mineral oil. But this is only a partial solution because biodegradable oil, to be useful in PCH, has to contain the necessary additives which are more or less detrimental to the environment. The second and basically surely better solution is the use of tap water as hydraulic fluid. Its application is harmless to the environment but is very disadvantageous in the sense of wide availability of the design solutions /Bac99; Tro96; Kim05; Tan03/. For the designers of water PCH systems the seat type valves are mostly disposable on the market and some relatively simple conventional control valves. Yet without continuously working valves and regulated pumps it is very difficult to design and project a hydraulic system for a machine or production line of a higher technical level. Nowadays the market of the disposable and applicable water-hydraulic components for continuous control is very small. Even if they exist, they are usually very complicated and with a lot of assembly parts.

Despite of rather long years of research work on the field water-hydraulics there is still a lot of insufficient understanding of the tribo-mechanical mechanisms and performances *playing the most important role in the application of components and systems of water PCH. High pressure proportional 4/3 directional spool-sliding control valves are moreover widely used in the oil PCH, but for water PCH they are still almost wholly missing on the market /Kos08/. That was the basic reason for our decision for the researches, investigations and development of the new water 4/3 proportional directional control valve of the spool-sliding type.*

In this work we present results of life time test of a newly developed 4/3 directional continuous control spool-sliding valve for the use water PCH.

2 NEW WATER PROPORTIONAL DIRECTIONAL SPOOL-SLIDING CONTROL VALVE

2.1 Design

We have designed and constructed a proportional 4/3 directional spool-sliding control valve for water as hydraulic fluid. It is used in our water hydraulic test rig for motion control of the water double acting hydraulic cylinder with double-ended rod. With the goal to investigate tribological performances and specific working parameters of the various materials of the elements in sliding contacts inside the valve we needed relative simple, good controlled and easily replaceable testing samples as these elements. Also, their size and shape should enable fast and easy surface analyses. For this purpose, we designed and manufactured functional prototype of water proportional 4/3 directional spool sliding control valve as shown in three-dimensional model in figure 1. Main parts of the functional prototype of a proportional 4/3 directional sliding control valve are: sliding spool (pos. 3), housing sleeve (pos. 2), springs (pos. 7.1 and pos. 7.2), outer housing (pos. 1), adaptors for proportional solenoid, and two proportional solenoids (pos. 4 and 6), one of them (pos. 4) with the inductive transducer (pos. 5). In the main part of our specimen – functional prototype of proportional 4/3 directional control valve sleeve and spool are relative simple in geometry and can thus be indeed easily changed (Fig. 2). We can manufacture these key-parts rather easily and in inexpensive way and thus test different materials .

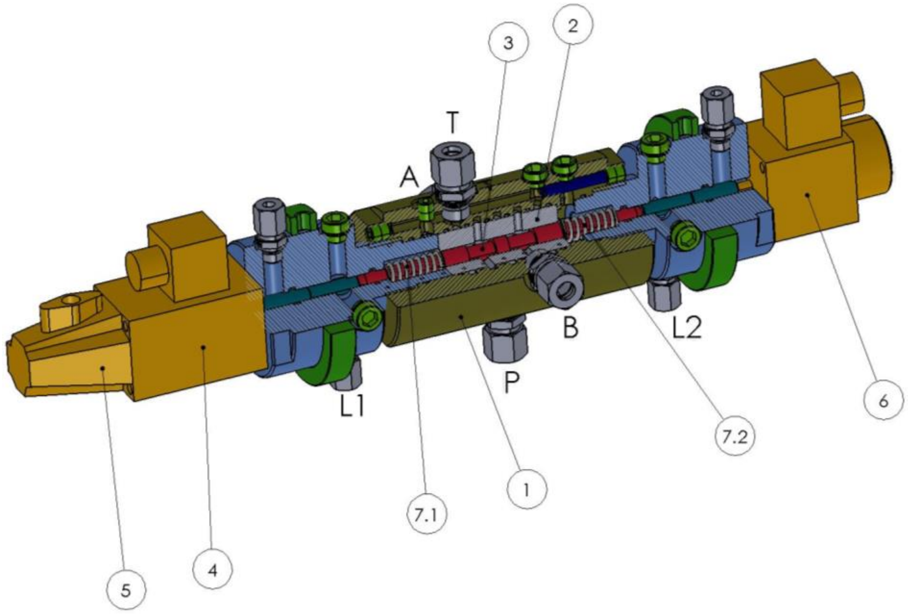


Figure 1: Prototype of water proportional 4/3 directional control valve

2.2 Materials

Martensitic hardened stainless steel (X105CrMo17) was used as our first tested material pair, the same material for the spool and the sleeve. Both elements were hardened on 55 HRC. The liquid inside the system of the water PCH test rig was distilled water, to ensure neutral environment that does not reflect the water type from any particular part of the world.

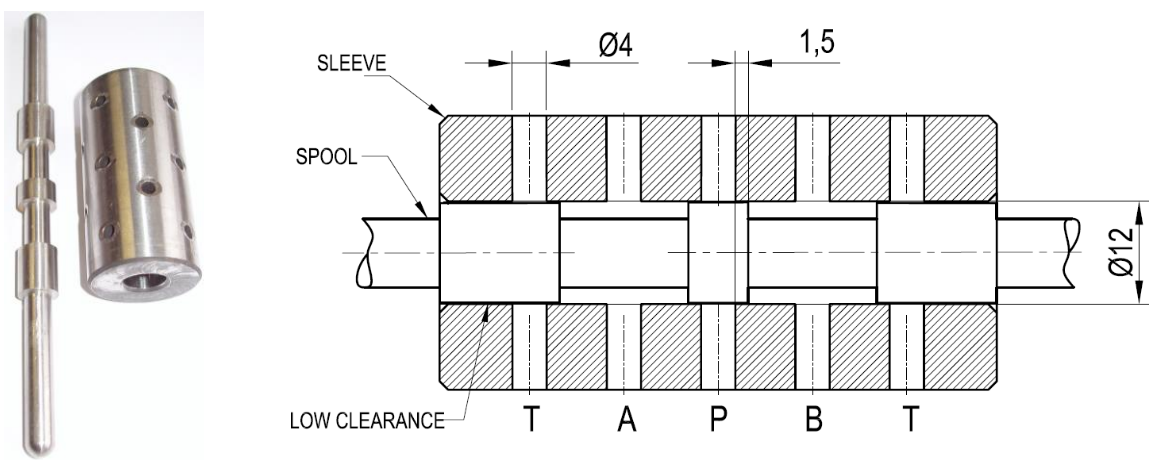


Figure 2: The main parts – spool and sleeve

3 TESTING

3.1 Test rig

The double test rig, realized as twin test rig, one part of it intended to investigate water power-control hydraulics (PCH) and the second part to investigate comparatively oil PCH, was built and put to work /Maj07/. This twin test rig has been used also to test and investigate the water and, comparatively, also the oil valve, both being proportional 4/3 directional spool-sliding control valves. The test rig has been used to carry out the comparative dynamic-transient and static-long-term life-time tests under the same, or at least, analogue working conditions. Figure 3 shows the hydraulic circuit of the water part of the test rig. It contains standard Danfoss axial piston pump, type PAH 25 (Fig. 3, pos. 2.0), with the flow 35 lpm /Maj07/ at 1450 r/min at the volumetric efficiency 97%. This pump delivers water through the pressure-compensated flow control valve (Fig. 3, pos. 6), which ensures constant flow of 30 lpm through the specimen – the proportional directional control valve (Fig. 3, pos. 8). Pressure-line water filter with rating of 1 μm (Fig. 3, pos. 7) was installed on the P line – close to water proportional directional control valve. This valve was controlled from the PC in closed loop. On the connection port A of the proportional valve, we have had connected stainless steel tube to which further the pressure transmitter (Fig. 3, pos. 10.1) and fixed orifice with diameter of 1.5 mm (Fig. 3, pos. 9.1) on the end were connected. Fixed orifices were used to simulate the load at the ports A and B of the specimen (water proportional valve). The second branch on the connection B has been equal to the first just described. The water relief valve (Fig. 3, pos. 5) was set to 160 bar. Centrifugal water pump (Fig. 3, pos. 13) was used to maintain constant temperature (air cooler – Fig. 3, pos. 14) and to enable an off-line filtering (Fig. 3, pos. 15).

Pressures on the P and T connection ports of water proportional valve were measured during test using two pressure transmitters (Fig. 3, pos. 11 and 12). Control of the proportional magnets (Fig. 3, pos. 8), data acquisition and control of the electro-motors were provided and automated through a PC.

The oil part of the hydraulic test rig is equal to the water test rig, concerning function, but it is assembled using standard on-market-disposable components.

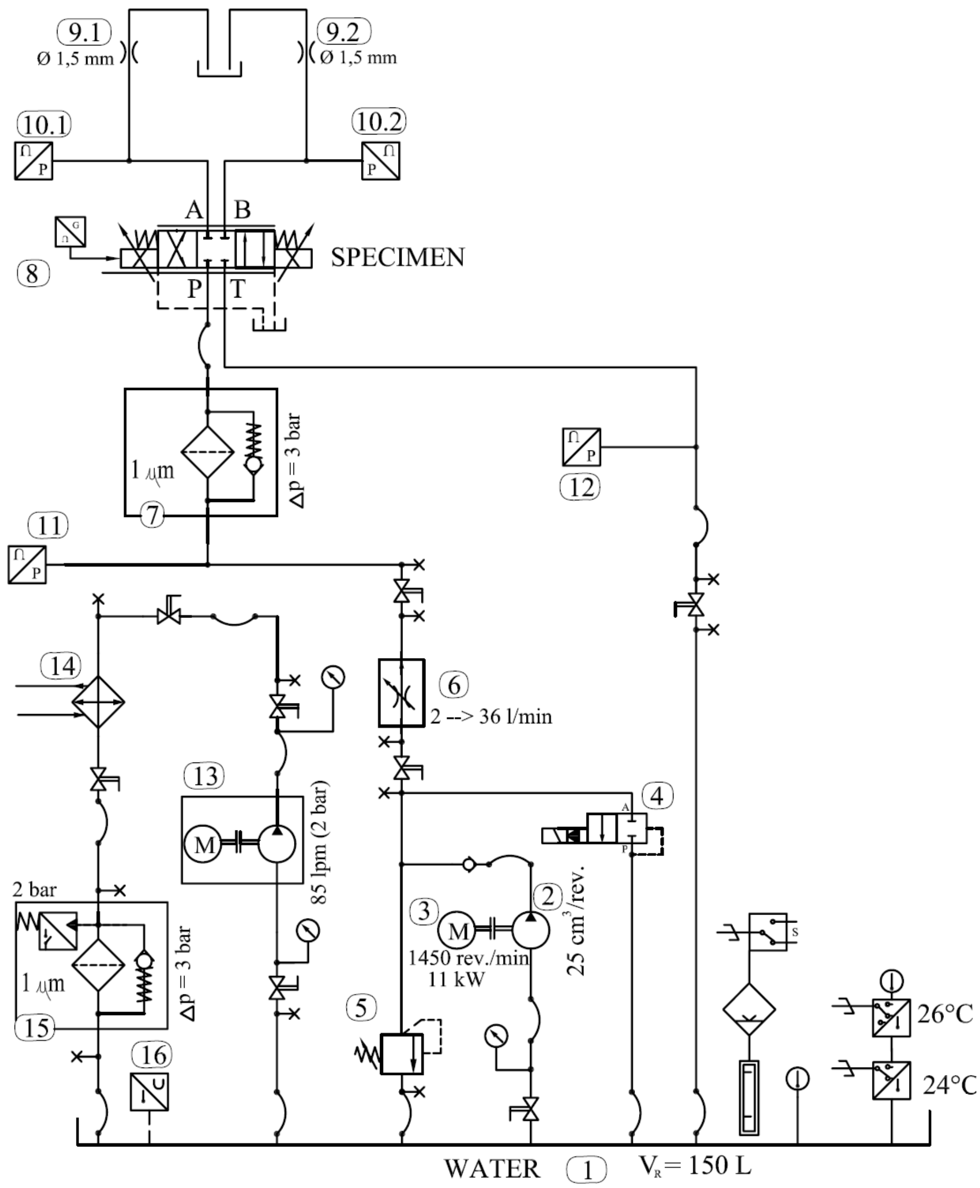


Figure 3: Hydraulic circuit of the water of hydraulic double test rig

3.2 Procedure and testing parameters

One of our goals carrying out presented testing was preliminary determination of filtering importance in water hydraulics. Ten millions cycles long lifetime test of our new water proportional 4/3 directional control valve was carried out at three different testing regimes (Fig. 4). First regime, from start to 2.5 millions of cycles, was done with single – by-pass filtering (Fig. 3, pos. 15, filter rating: 5 µm) – without pressure filter (Fig. 3, pos.

7). Second regime, from 2.5 to 4 millions of cycles, was executed without filtering. In that regime troubles were expected and they occurred too; blocking of spool and wear. In the last, third regime, from 4 to 10 millions of cycles, improved, double filtering (Fig. 3, pos. 7 and 15) with filtering rate of 1 μm was used.

One testing cycle means switching the water proportional 4/3 directional control valve from zero (middle or neutral position) to cross-shaped position considering the symbol of the valve (port P connected to port B and port A connected to port T) and further after that switching it through zero into parallel position (port P connected to port A and port B connected to port T). One cycle of lifetime testing then ends with disconnection from parallel to zero position of the testing valve.

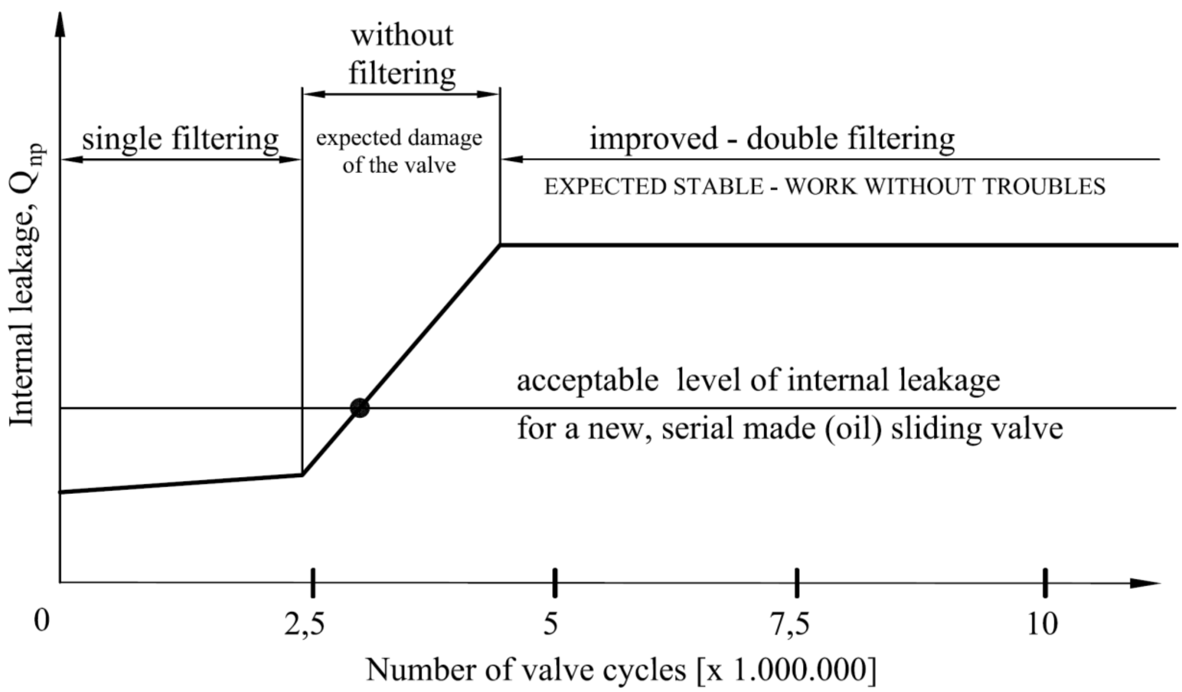


Figure 4: Three different regimes of water proportional directional control lifetime test

4 RESULTS

Figures 5 and 6 show the results of interval measurement during lifetime test of water 4/3 directional control valve. Figure 5 shows measured movement of the spool and pressure on the P connection and figure 6 pressures on A and B connections.

Frequency of the spool was 5 Hz and its control signal +/- 100 %. Pressure on the P connection was 160 bar, maximum pressures on A and B connections depended on flow through orifices (Fig. 3, pos. 9.1 and 9.2) and were approximately 120 bar. Working flow through orifices was approximately 20 lpm.

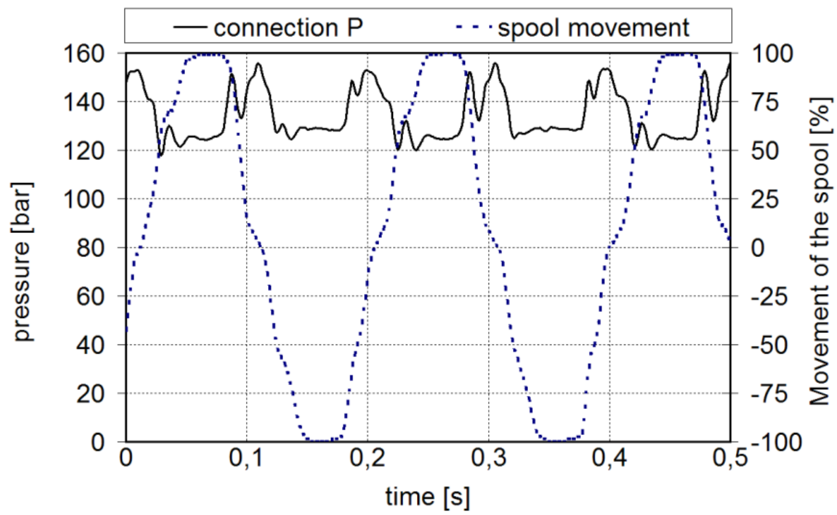


Figure 5: Example of measuring of spool position and pressure on the connection P depending on time during lifetime test of water 4/3 directional control valve (pressure = 160 bar, flow = aprox. 20 lpm, frequency = 5 Hz)

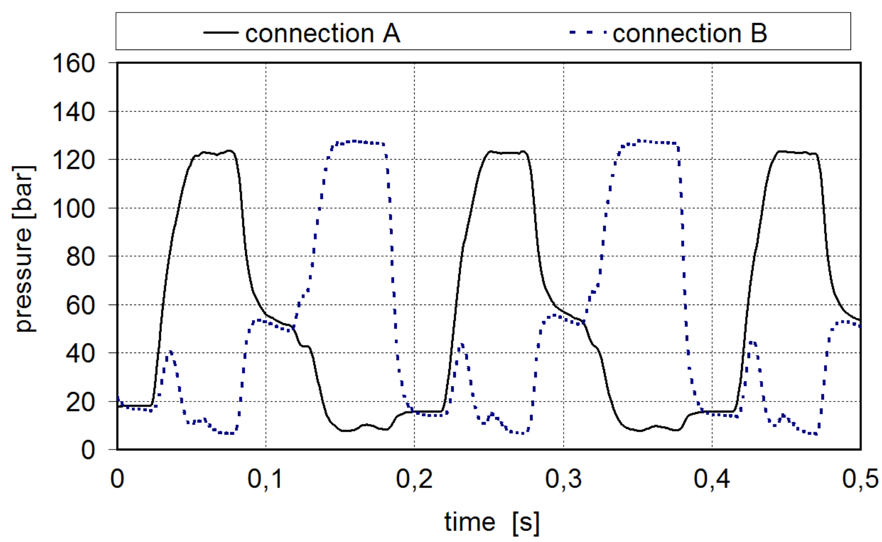


Figure 6: Example of pressure measuring on the A and B connections depending on time during lifetime test of water 4/3 directional control valve (pressure = 160 bar, flow = approx. 20 lpm, frequency = 5 Hz)

4.1 Internal leakage

The measured internal leakage of water 4/3 proportional directional control valve has been the main result of the lifetime test. Increasing value of leakage, when there was single – by-pass filtering used, from start to approximately 2,5 millions of testing cycles is shown in Figure 7. Each point – dot in diagram shows the mean value of at least three measurements of internal leakage at 40° and pressure 160 bar. There are three curves in the diagram, the first one (the main) represents the measured values for the water valve. It shows how internal leakage increased from initial 0.036 lpm up to 0.0843 lpm at the same conditions. Possible reason for oscillating the mean values of internal leakage during lifetime test lies in different positions of spool in the time of leakage measuring process. The less or more excentric position of the spool inside the bore of the sleeve is considered that way. The second line (the thin line) shows the predicted, calculated value for the internal leakage for water proportional valve. It is extrapolated from the initial measured values taking into account normal working parameters. The third – dashed line shows the predicted, calculated value for the internal leakage for the oil proportional directional control valve. This curve too is extrapolated from the initial measured values taking into account normal working parameters for such oil hydraulic systems working at 50°C and 160 bar.

We did not carry out the lifetime test for the equivalent oil proportional valve, so we calculative predicted an average increasing of gap between the spool and the bore of the sleeve of the oil sliding type of valve for 3 μm in 10 millions cycles period. After 2.5 million cycles the internal leakage of water valve was lower as the predicted internal leakage of oil valve.

We changed the testing regime after 2.5 millions of testing cycles (Fig. 4). Namely no filtration of water was executed in the water test rig in the period from 2.5 to 4 millions testing cycles. In this period the three considerable damages occurred on the sliding surfaces between the spool and the bore of the sleeve (Fig. 7). It came to the blockages of the spool inside the sleeve. The reason for that lies in enough large hard contaminant particles in water; they occurred to come between the spool and the sleeve and consequently blocked the spool interrupting its movement. After each blockage, the couple spool - sleeve was disassembled and damaged surfaces carefully polished. Owing additional polishing of sliding surfaces, the leakage increased.

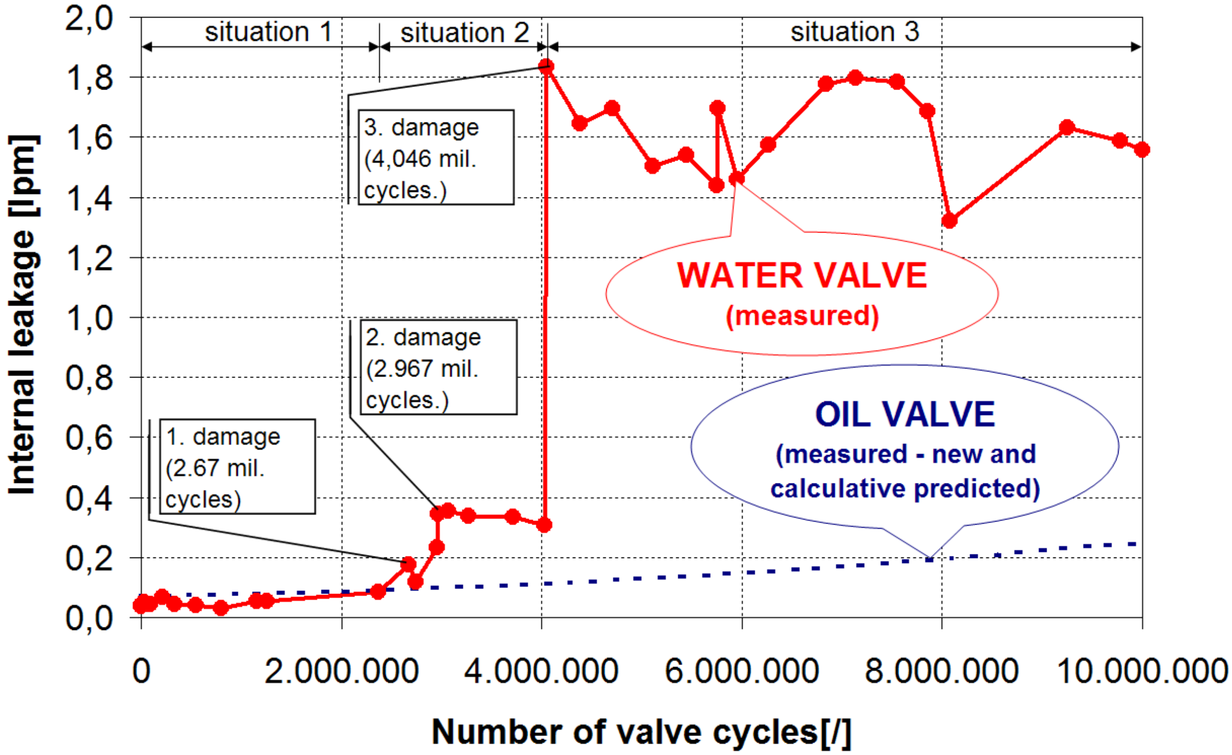


Figure 7: Measured values of internal leakage of water and oil directional 4/3 proportional control valve during the whole lifetime test, depend on number of switching cycles and quality of water filtering.
Situations were: 1- single, by-pass filtering, 2 – without filtering, 3 – improved, double filtering (by-pass and pressure filter, both were 1 μm)
(pressure = 160 bar, flow = approx. 20 l/min, frequency = 5 Hz, T_{water} = 40°C, T_{oil} =50°C)

Through the next and the last period of testing, from 4 up to 10 millions testing cycles, the improved double filtering was included into the water hydraulic system of the test rig. Both, by-pass and additional pressure, filters have been applied with filtration rate of 1 μm. During this testing period no problems concerning blocking or retaining the valve spool appeared, its movements were normal.

The leakage measured during lifetime test of the water 4/3 proportional directional control valve oscillated probably owning to different positions of the spool (centric /

eccentric, turned at different angles inside the sleeve). The measured leakage at the end of the testing procedure amounted 1,55 lpm. Calculative predicted internal leakage of the similar, oil 4/3 proportional directional control valve should be 0,24 lpm after 10 millions of cycles.

4.2 Wear

Sliding surfaces of the spool of the water 4/3 directional control valve have been observed occasionally by electronic microscope (SEM) during lifetime test. Figure 8 shows the location of the sliding surface area investigated and presented in this paper. One of the most important sliding and to the bore of the sleeve sealing surface sections of the spool is indicated in Figure 8.

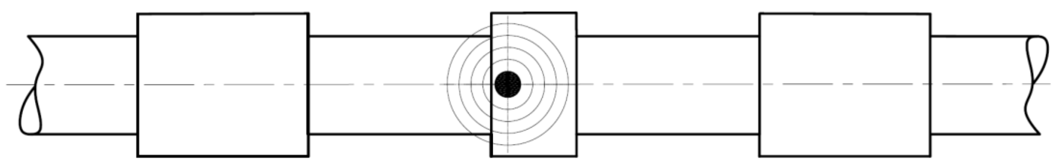
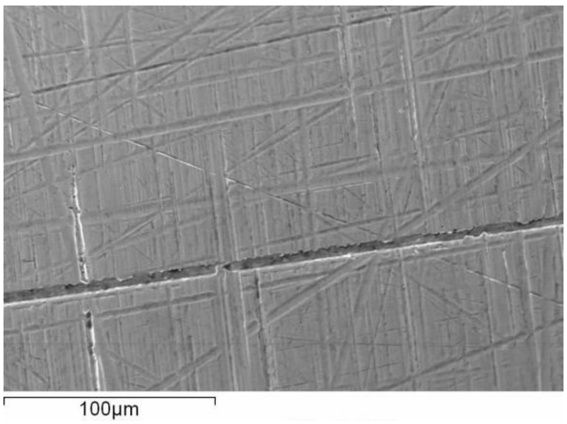


Figure 8: Observed and by an electronic microscope (SEM) investigated spool sliding surface

Photos of the Fig. 9 show the changes on one part of the sliding surface of the spool during lifetime test. The damage is obviously caused first of all as the result of two and three body abrasion wear. The first picture (Fig. 9.a) shows the surface before the test started. Vertical scratches probably resulted from manufacturing during rotational grinding and polishing. All other scratches presumably result from unsuitable handling with spool. Horizontally oriented scratches directly increase internal leakage as they lay in the direction of the spool movement. The second picture (Fig. 9.b) shows the appearance of the spool surface after 95000 testing cycles. On the rather smooth surface two rather large damages are obvious at the edge of the spool. These defects presumably result from manufacturing process. The largest initial scratches result from self polishing during first 95000 testing cycles. A lot of fine horizontal scratches are obvious from the picture; horizontal line is the direction of spool movements. They probably proceed from abrasive wear.

The third picture (Fig. 9. c) shows a lot of clearly visible horizontal scratches after 2.67 millions of testing cycles. That picture was recorded after the first damage occurred (spool blocking) in the water valve. These horizontal scratches are probably resulting from numerous non-filtered hard particles in water. They appeared between the sliding spool and the bore of the sleeve and damaged both surfaces. Those scratches and later necessary treatment (polishing of sliding surfaces) caused almost double increase of internal leakage.



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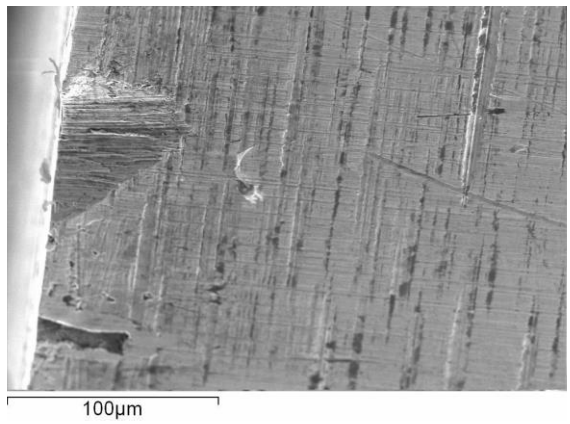
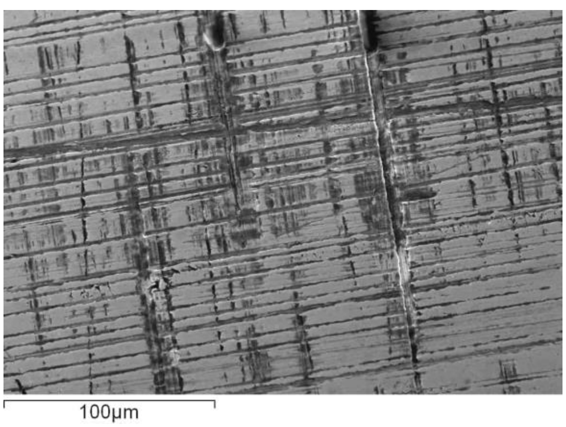
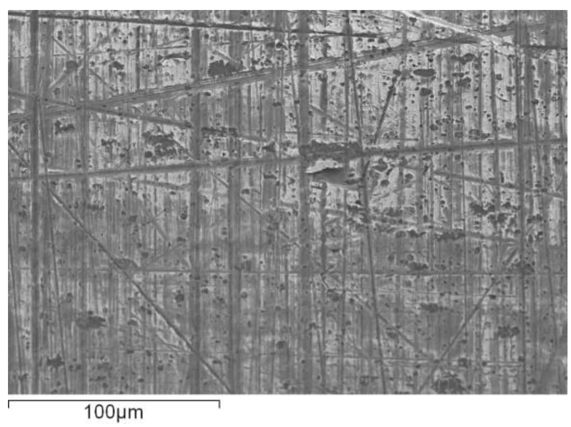


b.



c.



d.

Figure 9: ‘’Average’’ state of sliding surfaces of the spool during lifetime test: a) before test, b) after about 95000 cycles, c) after 2.67 millions of cycles, d) after 10 million cycles.

The fourth picture (Fig. 9.d) shows the surface after 10 millions of cycles at lifetime test.

In this Figure, besides abrasive damages, the damages caused by cavitation are obvious. Dimples caused by cavitation are mostly relatively small and shallow. We presume that they did not have significant influence on the internal leakage. Sliding surface (Fig. 11.d) is relatively smooth owning to the improved – double filtering in the last testing regime (from 4 to 10 millions of testing cycles).

CONCLUSION

Lifetime test of the new water proportional 4/3 directional control valve was carried out. Three different regimes were tested through 10 million cycles with 5 Hz switching frequency of the tested water valve at +/- 100 % of control signal, pressure 120 bar and flow 20 lpm through valve. Results show an important role of filtering quality of water. The new, tested water proportional 4/3 directional spool-sliding control valve has acceptable level of internal leakage after lifetime test. Leakage looses represent approximate power of 0.4 kW at pressure 160 bar and water temperature of 40°C. It is clearly evident that an appropriate filtering could keep working characteristic of water hydraulic components near the initial level for some millions of working cycles.

ACKNOWLEDGEMENT

The authors want to acknowledge the Slovenian Research Agency ARRS (Proj. Nr.: L2-9407 from 2006) for partial funding of the work. The authors are sincerely grateful to the company Tajfun Planina d.o.o. (Planina pri Sevnici, Slovenia), for financial and technical support. The majority of the components of the oil test rig were donated by the Kladivar Žiri d.d. (Žiri, Slovenia) and flexible hoses by the HIB Kranj. The authors are sincerely very grateful for this support.

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