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TRIBOLOGICAL ASPECTS OF WATER HYDRAULICS

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Abstract: *A clean and healthy environment must be an increasing priority. Different kinds of hydraulic fluids are in use nowadays. Unfortunately, the majority of them are harmful. The use of tap water as a hydraulic-pressure medium is one of the possible solutions. This study presents the research and development of different hydraulics components. Every research of a new water-hydraulic component starts with basic tribological investigations of different material pairs and their surfaces. Then follows the design and calculations of the hydraulics characteristics, the production of a prototype and its experimental investigations. The following water-hydraulic components, i.e., proportional control valve, hydraulic cylinder, piston pump, hydraulic accumulator, check valve and hydraulic motor, will be presented.*

Keywords: *water hydraulics, tribological pairs, friction, wear, proportional valve, cylinder, pump, accumulator, hydraulic motor*

1. INTRODUCTION

Fluids are the first and some of the most important components in power-control hydraulics (PCH). The main tasks of the most used traditional hydraulic fluid, mineral hydraulic oil, are: power transmission, lubrication, cooling, elimination of insoluble particles, preventing corrosion, preventing foaming, reducing internal leakage, water extraction, etc. In addition, it is available in large quantities. Unexpected outflows of hydraulic liquids, i.e., mineral oils, into the ground and even into underground drinking-water supplies are a frequent occurrence. One of today's major challenges to prevent harmful consequences for the environment is to use alternative, natural and biodegradable sources of hydraulic fluid. In power-control hydraulics there are two ways in which we can protect the environment. The first solution is to use a biodegradable oil [1-6] instead of a mineral oil, while the second – and better – solution is to use tap water instead of mineral oil. This solution is harmless to the environment, but it is very difficult to realize [7-9]. One reason being that only some relatively simple, conventional control valves exist on the market today. In spite of many years of water-hydraulics research, there is still insufficient understanding of the mechanisms and performance and, consequently, the available component designs. Some of the reasons lie in many of the specifics that water has compared to oil in hydraulic systems, which already affect the research and development phase, and later – in the long term – the performance of the water-hydraulic system. Some of these are described below and some are listed in Table 1. For example, for any research of water hydraulics in real-scale components, home-made components and test rigs are required, because they do not exist on the market. However, this is associated with costs and technical problems.

Table 1. Properties, the main advantages and disadvantages of water

Property	Advantage	Disadvantage
Low viscosity	Lower pressure losses	Higher leakage
High vapour pressure	-	Erosion during the cavitation
High compression modulus / high speed of sound	High / quick responses	Larger "water-hammer effect"
Corrosion protection	-	Poor – special materials are needed
Lubrication, lubrication film	-	Weak, special materials are needed
Thermal conductivity	High – fast heat transmission	-
Relative cost	Low	-
Environmental impact	No negative impact	-
Temperature range	-	Narrow temperature range: 2–50°C
Flash / ignition point	No fire hazard	-

The much lower viscosity of water compared to oil causes a high rate of leakage with clearances typical for oil, while reduced clearances result in excessive wear and high friction. Higher working temperatures, which are still common for oil hydraulics, i.e., around 70 or 80 °C, are hardly acceptable for water in hydraulic systems because of the evaporation at local contact spots [10]. In water, micro-organisms develop with time. This causes several problems with chemical changes to the water and the growth of algae, which results in sediments. The tribological properties of conventional materials (stainless steel) in water are unfavourable, while comparable material selection is poor, and their properties are unknown. For example, a new class of high-potential diamond-like-carbon materials [11-21] that showed excellent properties in a variety of conditions that are in many ways comparable to those in water hydraulics have not been investigated in detail for this application yet. Furthermore, another class of materials that has already confirmed excellent properties suitable also for water [22-29], i.e. ceramics, are probably too brittle for the required dynamic conditions in water hydraulics or are too expensive for precise manufacturing [30], but this has not been investigated either. Corrosion and cavitation are other well-known problems related to tribological performance and the life-time of components. Therefore, research into the chemical and tribological properties that affect the life and performance, as well as the dynamic characteristics, of water hydraulics, are required for the successful development of new components, which is necessary for the wider use of the water in power control hydraulics.

2. TRIBOLOGICAL INVSTIGATIONS WITH WATER

Different material pairs

In order to investigate the change in hydraulic parameters, in particular wear resistance and useful life, in selected hydraulic tests for different possible material combinations, model tribological tests were performed to make an initial or preliminary selection. Generally, stainless steel (SS) is the most typical and inexpensive material that is already used in several hydraulic parts and was thus reasonably the first-choice material. Other potential groups of materials include ceramics and polymers. Since ceramic materials are very costly and also have a low fracture toughness, they were not considered as being suitable materials for the real-scale tests with which we would like to compare materials in the later stages of this research. Therefore, they were not included as the "studied" material (disk) in the first screening tribological tests; however, a ceramic was used, at least as a counter-material, i.e. pin, which should also give us some indication of the tribological properties of the selected couples. Different commercially available polymeric materials were also considered. We selected those that can be used in water for a longer time period [14-16] and gave some promising tribological results in the past, and which are also easily commercially available and suggested by world-renowned producers. Thus, we selected two different types of materials from two groups of polymeric materials, i.e., polyetheretherketone (PEEK) and polyimide (PI). A commercially available PEEK (Victrex Europa GmbH, Germany) containing 30 % of carbon (CA30) and 30 % of glass (GL) fibres was used. Polyimides (Vespel) from Dupont™ without any addition (SP1) and containing 15 % of graphite fibres were also tested. The pin materials were SS (X105CrMo17), obtained from Aubert&Duval and hardened to 55 Hrc, and alumina ceramic balls (99.7 % purity, 10 mm diameter) from Hightech Ceram. In total, four types of polymeric materials and stainless steel were selected as the disc materials, while pins were made from the same stainless steel and alumina ceramics.

Figure 2 shows the measurement results for different material pairs lubricated with distilled water at room temperature. Compared to the polymeric materials, significantly higher friction values were measured in the contacts with SS discs, which were in the range 0.6–0.8. Other friction data show friction values between 0.13 and 0.28, which is 2–3 times less than with SS discs. With the exception of the pure polyimide (SP1), with all the other polymer discs, contacts with alumina pins resulted in a lower friction than against SS pins. However, these differences were not very high. Nevertheless, it should be noted that friction in the polyimide SP1/SS contact resulted in the second-lowest friction, i.e., about 0.16. This is important, because the polymeric material contains no additional components and is thus simpler and cheaper. Moreover, the SS pin is also the most preferred counter-material from a practical point of view. The lowest friction in this study was, however, obtained with the PEEK CA30/Al2O3 combination, where the friction was about 0.13.

Different surface properties and hard coatings

Despite the many new materials for highly loaded surfaces, still the most promising materials are stainless steels in combination with hard coatings.

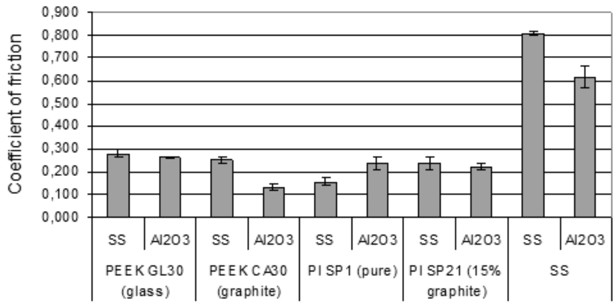

Figure 1. Coefficient of friction for different material pairs (four disc materials against two pin materials)

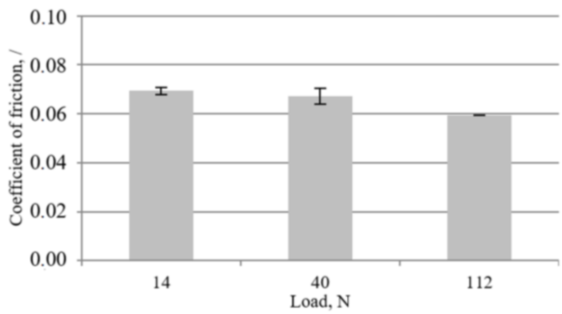

Figure 2. Coefficient of friction for DLC/AISI440 in water at three different loads

Figure 2 shows the COF of the SS/DLC lubricated with water for three different loads. The COF decreased when the load increased. It was also observed that the COF under water-lubricated conditions was slightly lower than the COF under oil-lubricated conditions [31]. As a general observation, the SS/DLC contact clearly provides a significantly lower coefficient of friction (Fig. 2) than the SS/SS contact (see Figs. 1 and 4).

3. NEW WATER-HYDRAULIC COMPONENTS

Through research in the Laboratory for Fluid Power and Control at the Faculty of Mechanical Engineering, University of

Ljubljana, some new water-hydraulic components were developed.

3.1 Proportional directional control valve

Despite the many years of research work in water hydraulics, there is still an insufficient understanding of the tribo-mechanical mechanisms and performances playing the most important roles in the application of components and systems for 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 from the market [32]. That was the basic reason for our decision for the research, investigations and development of the new water 4/3 proportional directional control valve (Fig. 3) of the spool-sliding type [33].

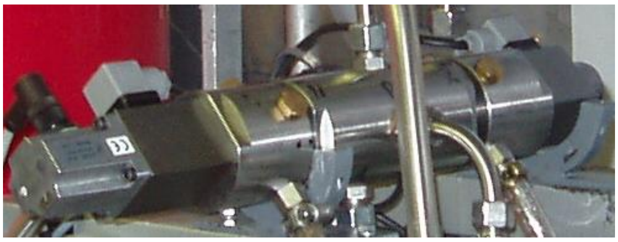

Figure 3. Prototype of proportional directional control valve for water hydraulics

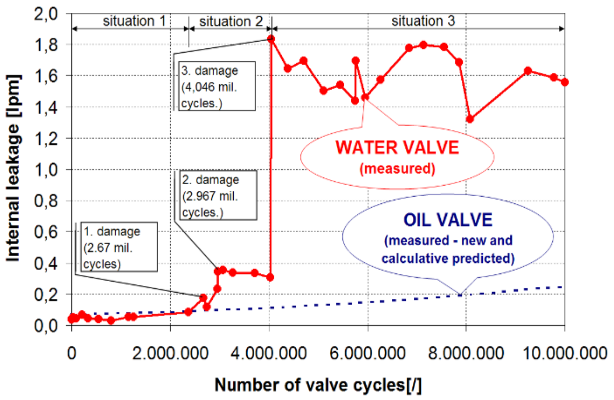

Figure 4. Measured values of the internal leakage of the water directional 4/3 proportional control valve during the whole lifetime test, depending on the number of switching cycles and the quality of the water filtering

Figure 4 shows the results of a long-term lifetime test of a proportional directional valve for water hydraulics. The situations were as follows: 1- single, by-pass filtering, 2 – without filtering, 3 – improved, double filtering (by-pass and pressure filter, both were 1 μm), the pressure was 160 bar, the flow was 20 l/min, the frequency was 5 Hz and the water temperature was 40°C. The leakage measured during the lifetime test of the water 4/3 proportional directional control valve oscillated, probably owing to the 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 to 1.55 lpm. The calculated, predicted internal leakage of a similar, oil 4/3 proportional directional control valve should be 0.24 lpm after 10 million cycles.

3.2 Hydraulic accumulator, piston type

The new water-hydraulic accumulator (Figure 5) was designed, manufactured and tested by the Laboratory for Power-Control Hydraulics. This water accumulator was constructed in such a manner that we could easily exchange its seals and/or study the tribological and hydraulic behaviour of the sliding contacts. The hydraulic accumulator with a 4-litres volume allowed a maximum working pressure of 390 bar. A prototype was manufactured and a certificate was acquired from the European Pressure Directive PED 97/23/EC. The piston type of water-hydraulic accumulator consists of the following parts (Fig. 1): piston with special seals and guides for gas and water, tube, piston rod, two end-covers, two pressure and two temperature sensors and a displacement sensor for the detection of the piston's position. The necessary additional equipment is a pre-set pressure-relief valve and two manually operated ball valves [33].

Figure 5. Prototype of a piston-type water-hydraulic accumulator

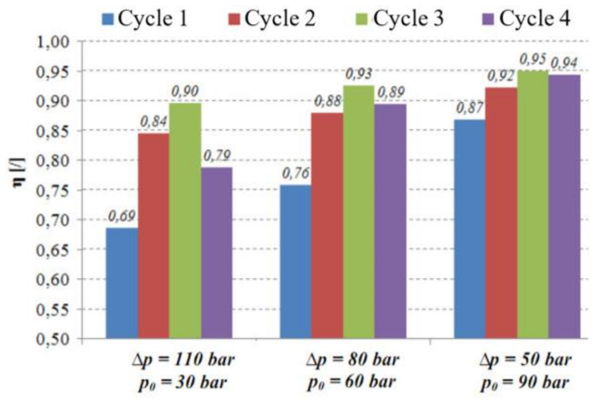

Figure 6. Influences of different nitrogen pre-filling pressures for all four cycles on the water-hydraulic accumulator efficiency

Figure 6 shows the pre-filling pressure effect of nitrogen on the efficiency of the accumulator measured in the water-hydraulic system. As can be seen, in all four cycles (different compression and expansion times) the efficiency rises with an increase of the nitrogen pre-filling pressure.

3.3 Modular hydraulic cylinder

A double-acting, double-rod hydraulic cylinder (Fig. 7) 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 [34]. The water-hydraulic cylinder has a modular design that has the easy exchange of one type of sealing and guiding with another.

Figure 7. A prototype of the double-acting, double-rod, water-hydraulic cylinder

Figure 8 shows the influence of 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 PTFE material 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 was also when moving the cylinder rod with a constant velocity, 12.1 bar at a flow of 22 lpm and an inlet pressure of 150 bar. The PTFE material used for sealing/guiding is very promising for water hydraulics [35].

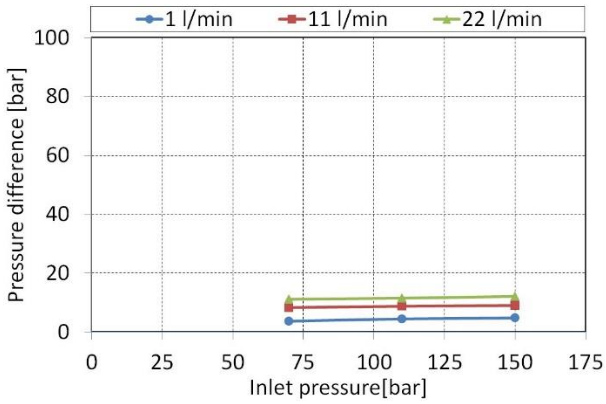

Figure 8. Friction due the pressure difference between the A and B ports of the water cylinder at the moment of moving the cylinder rod with a constant velocity for the hydraulic cylinder with a load of 163 kg in the horizontal position for different inlet pressures and different flows with sealing/guiding PTFE materials

3.4 Check valve

The check valve was designed (Fig. 9) in such a way that it can be simply and quickly disassembled [36]. Check valves consist of a housing made from two pieces, seat, closing element, guidance element and spring. The design of the valve allows researchers to experiment with different closing elements (ball, different conical elements, etc.) and different numbers of flow channels (from 1 to 6). Figure 10 shows the results for the fully-open slot.

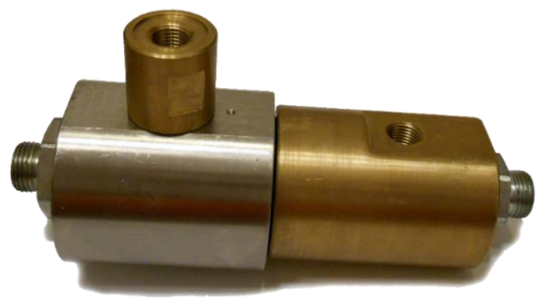

Figure 9. A prototype of the water-hydraulic check valve

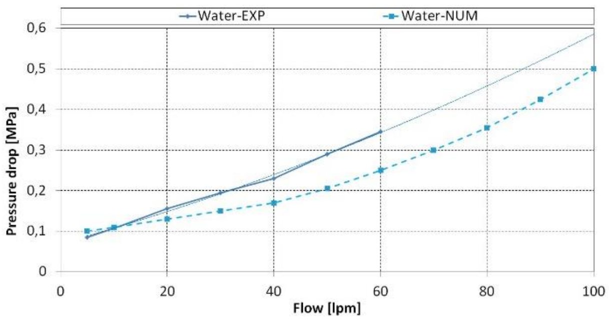

Figure 10. Comparison between experimental measurement (EXP) and numerical (NUM) simulations for the water check valve

Figure 10 shows the results of the experimental and numerical investigations of the water-hydraulic check valve for fully-opened slots. At a water flow of 60 lpm, 0.35 MPa of pressure drop was measured. The results of the numerical investigations show lower valves.

Hydraulic motor

A low-speed, high-torque, orbital hydraulic motor that converts the energy of a fluid under high pressure into the motion of a shaft of the hydraulic motor was developed. The important mechanical parts of the hydraulic motor are (1) the inner rotor, (2) the floating outer ring, and (3) the gerotor housing, as presented in Figure 11.

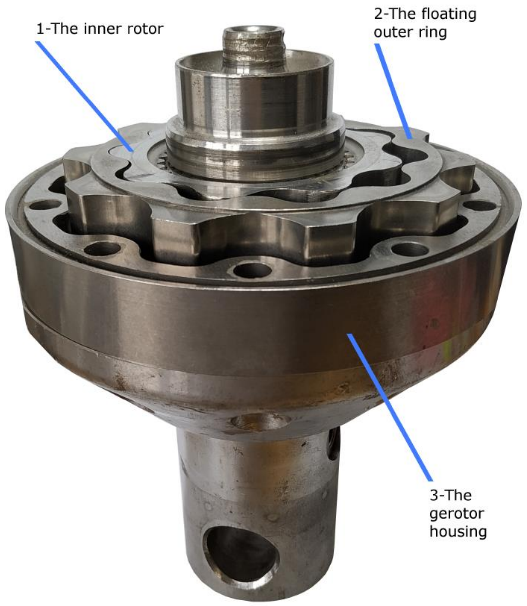

Figure 11. A prototype of a low-speed water-hydraulic motor

The modified hydraulic motor (steel/DLC contacts) satisfactorily operated for a few hours. The relatively high average total efficiency (up to 12.1%-green field) was observed at the higher rotational speeds, as shown in Figure 12, where one circle represents the average total efficiency at a specific operating point regarding the rotational speed and the pressure difference. The measurement included four physical quantities (p, pressure; n, rotational speed; M, torque; Q, flow rate), which are needed to calculate the total efficiency of the orbital hydraulic motor [37].

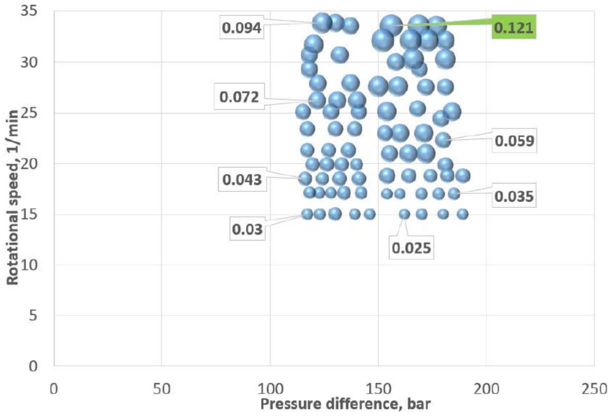

Figure 12. Total efficiency (value in label) of the modified hydraulic motor for water

4. CONCLUSION

The paper deals with the tribological aspects of water hydraulics. The key results can be summarized as follows:

- the material pair PEEK CA30/AL23 had the lowest coefficient of friction among the tested samples. The coefficient of friction in water was close to 0.1;
- the diamond-like-carbon coating reduced the coefficient of friction in water significantly;
- in-depth research and understanding of the tribological behaviour in different contacts leads to the development of new components in hydraulics (e.g., proportional directional control valve, accumulator, cylinder, check valve, hydraulic motor)

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