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POSSIBILITIES AND CHALLENGES ON THE FIELD 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, the design and calculations of the hydraulics characteristics, the production of a prototype and its experimental investigations follow. The following water-hydraulic components were developed, researched and analysed in our laboratory: proportional control valve, hydraulic cylinder, piston pump, hydraulic accumulator, check valve and hydraulic motor.*

Keywords*: Water hydraulics, tribology, components, system*

1. Introduction

Water hydraulics is an old way of technical science, but it is still in beginning of development. Oil hydraulics is phenomen for use of mineral oil as a pressure medium. It is widely in use, more than 80 % of hydraulic system has mineral oil. In 1990's were some researches start to revive environmental friendly water hydraulics [1-3]. The main challenges to use water as a hydraulic pressure medium are right material pairs. A lot of tribological experts worldwide have investigated lubrication and wear properties of different material pairs in water [4-6]. 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. 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 [7]. 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 [8-10] 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 [11-13], i.e. ceramics, are probably too brittle for the required dynamic conditions in water hydraulics or are too expensive for precise manufacturing [14], 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 aspect of sliding contacts lubricated with water

As mentioned, special material pairs should be use in water hydraulics. Before we made prototypes of water hydraulics components, preliminary tribological tests of different material pairs have been done.

2.1 Test rigs

Different tribological test rigs are available. We have used two of them, pin-on-disc and ball-on-flat standard test rig.

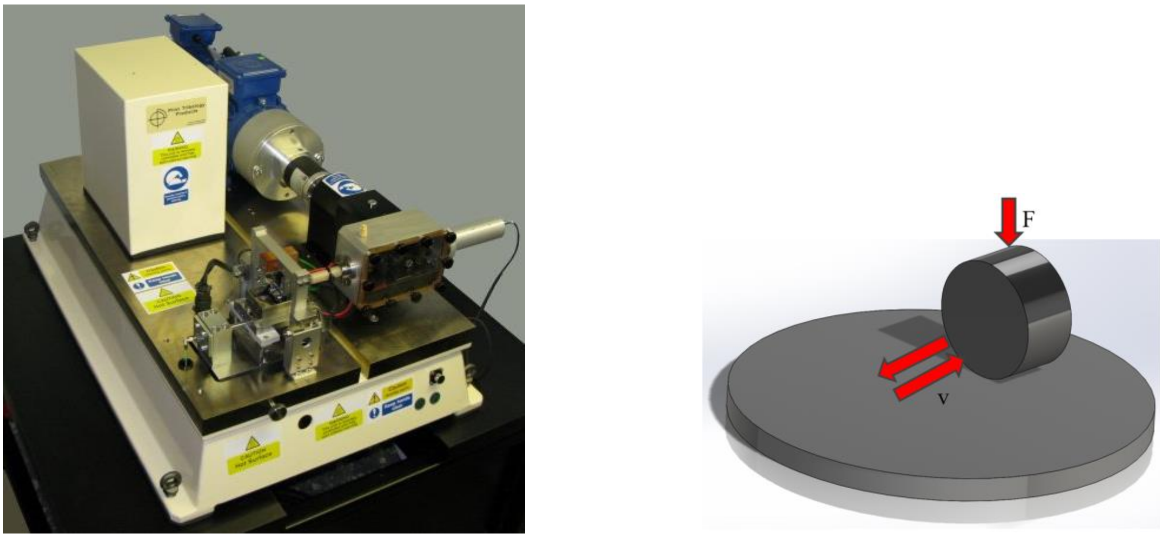
Pin-on-disc

First tests were performed in a pin-on-disc apparatus (CSEM, Switzerland) with uni-directional sliding between the disc and the pin, see Figure 1.a. The relative sliding velocity was 0.1 m/s and a load of 1 N was applied (Fig. 1.b), which corresponded to 40-70 MPa of initial contact pressure, depending on the material pair. In the open literature [4-5], data are available for some selected polymeric materials at lower pressures, but our goal was to investigate the higher-end load-region of those materials. Tests were run for 370 m of total sliding distance. All the tests were performed in a cup with distilled water at around 21ºC, i.e. at room temperature conditions. These conditions correspond to a boundary lubrication regime, where hydrodynamic effects are negligible and the tribological performance depends primarily on surface and interface phenomena. Friction was monitored during the test and wear loss of the disc materials was subsequently calculated. The first empirical friction and wear results are presented in Figure 5 respectively. At present, detailed surface analyses, which would allow determination of wear and friction mechanisms and confident interpretation of the results, are still in progress.

a. b.

Fig. 1. a) CSEM pin-on-disc, b) testing principle

The next tribological tests were performed using the ball-on-flat testing geometry in a commercially available reciprocating sliding device (Cameron Plint TE77, Figure 2). Loads of 14 N, 40 N and 112 N, simulating those in a hydraulic motor, were applied through a stationary loading system, and this resulted in about 614 MPa, 868 MPa and 1227 MPa of initial maximum Hertzian contact pressure. The stroke was 10 mm and the frequency 5 Hz, which provided 0.1 m/s of relative contact velocity. Prior to the test, the disc was submerged in oil or water before the ball was brought into contact. The calculated Tallian's lambda value [15] suggested boundary lubrication. Every experiment lasted for 180 minutes. The total sliding distance in each experiment was 1080 m. Every test was repeated three times in a room at ambient temperature. Results of measurement is shown in Figure 6.b.



a. b.

Fig. 2. a) Cameron Plint TE77 ball-on-flat, b) testing principle

2.2 Polymer materials

Polymer materials are widely used in mechanical engineering. A wide range of different polymers are available on the market. Advantages of composite polymers are: wear resistance, self-lubrication, low coefficient of friction (COF), good chemical stability, low weight, an easy way to make, etc. Disadvantages of composite polymers are: water absorption, residual tension, less rigidity, higher temperature sensitivity, etc. In combination with steel materials, composites with different inclusions are used to enhance the properties of the base material. Carbon fiber composites are the most commonly used for industrial applications. Carbon based materials have a wide range of mechanical, thermal, electrical and tribological properties suitable for many different applications. Of these, carbon nanotubes, carbon fibers and graphite are the most widely used thermoplastic composites.

Potentially tribological useful polymer/composite materials for water hydraulics are: POM-C, PA66+GF30, PEEK, PEEK+CF30, PEEK+GF30, PTFE, PRFE+CF30, PI, etc. Figure 3 shows differences between water absorption for POM and PA 66 [16]. In this case, POM is much more useful for water hydraulics than PA 66.

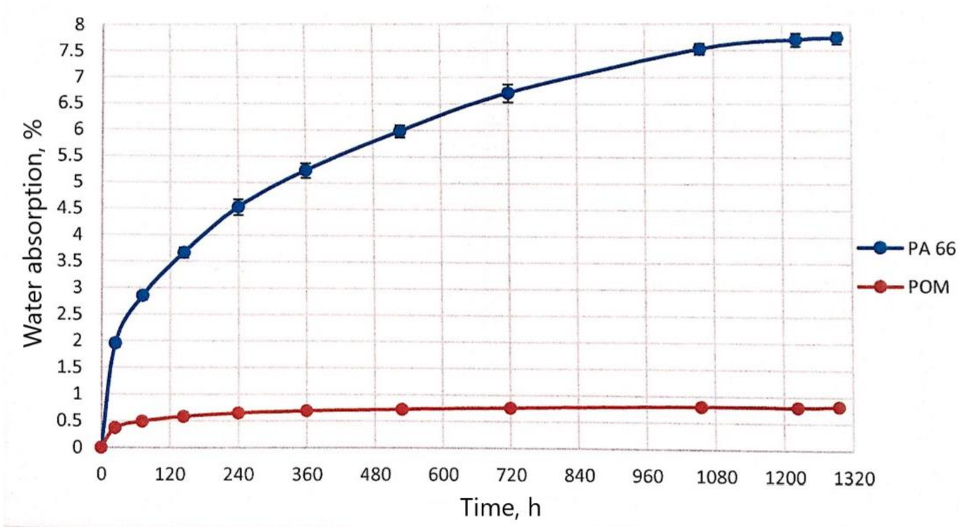


Fig. 3. Water absorption for POM and PA 66 [16]

The available results of wear and friction coefficients are difficult to compare because the authors use different measurement methods. Measurements are influenced by different measurement times, different loads, different applied loads, different temperatures, different sample shapes, different methods of sample preparation, different methods of manufacturing the materials themselves, and different ways of supplying water during the measurements. Figure 4 shows the coefficients of friction (COF) for the polymer materials presented as a function of velocity at different loads. The lowest COF 0,045 were authors [17] found out with composite PEEK450-FC30 against stainless steel AISI630 at 1,66 MPa contact pressure. The highest COF 0,33 were authors [18] found out with composite PPS in contact to Inconel 625 at 5 MPa contact pressure.

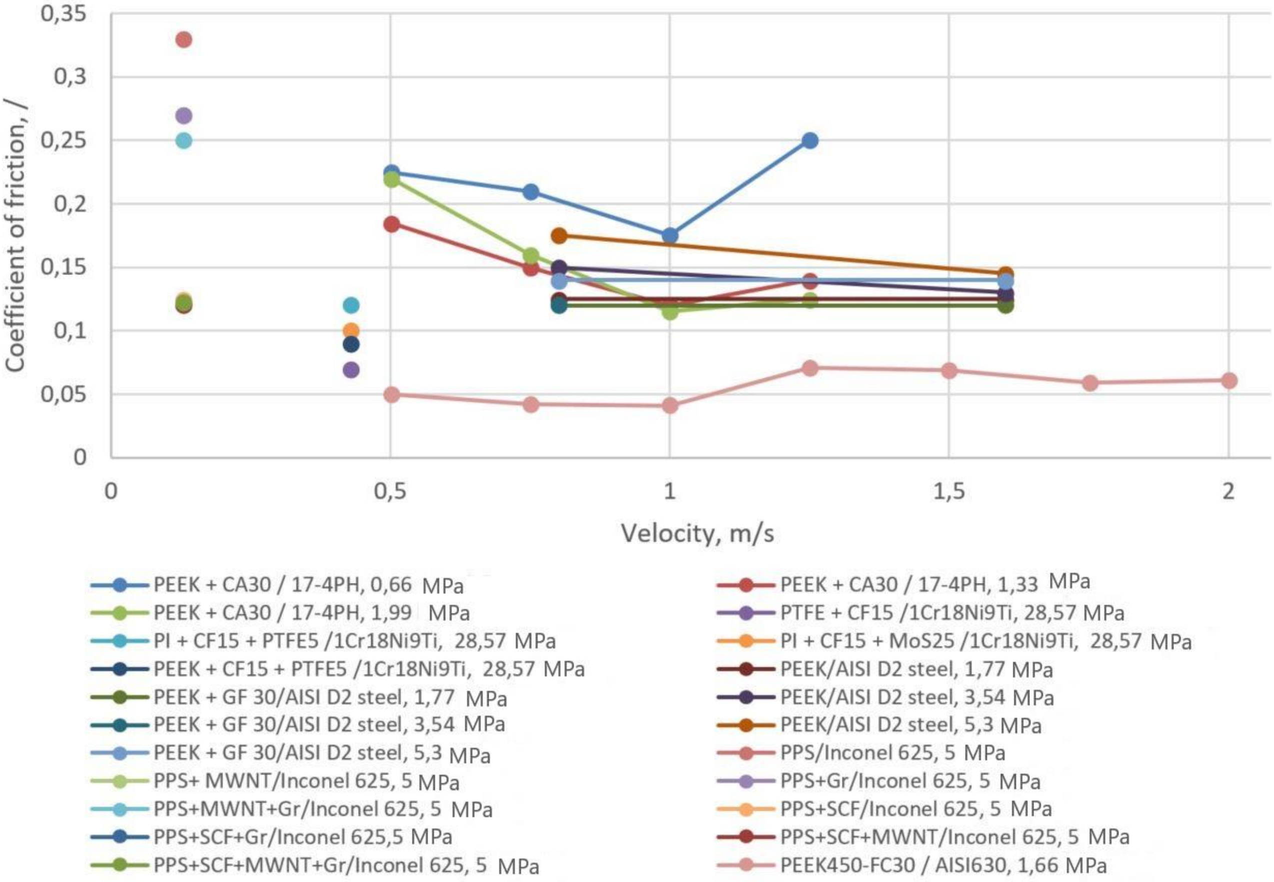


Fig. 4. An overview of tribological results for different polymers in water [17-21]

Our first preliminary results of COF in water on pin-on disc test rig are shown of figure 5. Compared to polymeric materials, significantly higher friction values were measured in contacts with stainless (SS) discs, which were in the range of 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 pure polyimide (SP1), with all other polymer discs, contacts with alumina pins resulted in lower friction than against SS pins. However, these differences were not very high. Nevertheless, it is to be noticed that friction in the polyimide SP1 / SS contact resulted in the second lowest friction – about 0.16. This is important, because the polymeric material contain 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 friction was about 0.13.

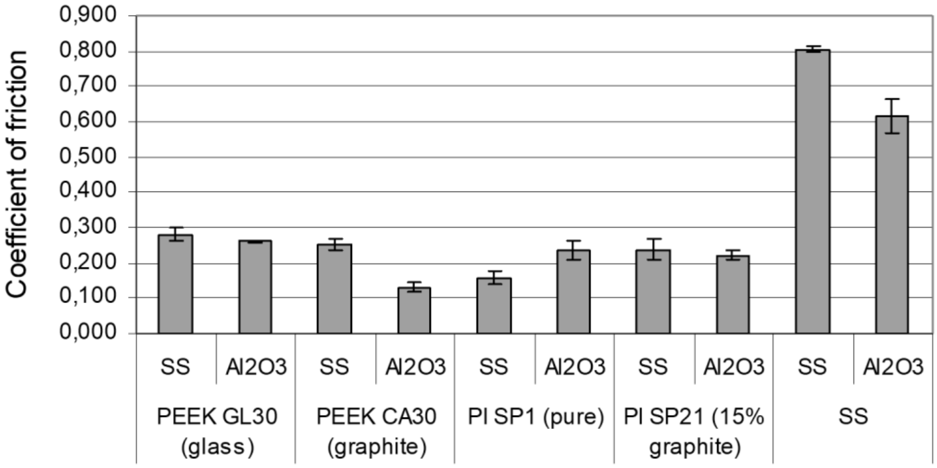


Fig. 5. Coefficient of friction for selected material pairs (SS and Al2O3 pins against four different disc materials is shown)

2.3 Metal materials and coatings

Polymers and even composite materials are not useful for higher loads. With this reasons we made tribological tests on TE77 standardised test rig (Figure 2) with metal materials in contact lubricated with pure water. Figure 6.a shows coefficient of friction (COF) for two similar stainless steels AISI 440C in contact at three different normal forces (14 N, 40 N and 112 N), two different roughness (0,05 µm an 0,2 µm) at hardness of 60 HRc of both materials in contact. The highest COF 0,47 was at load 112 N and roughness 0,05 µm, the lowest COF 0,32 obtained at the same load (112 N) and at roughness of 0,2 µm. Figure 6.b shows the obvious advantage of diamond like carbon coatings (DLC) lubricated with water. The lowest COF 0,058 obtained at maximum load 112 N. It is more than 5-times lower than in contact of AISI440C / AISI440C.

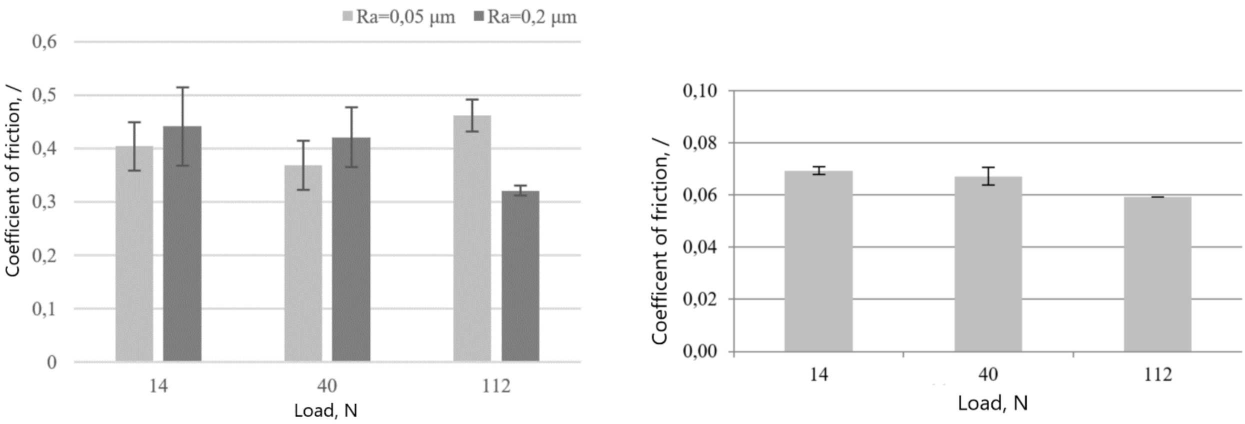


Fig. 6. Coefficient of friction in water a) AISI 440C/AISI440 , b) coating DLC / AISI 440C

3. Water hydraulics components

Laboratory for fluid power and controls from Faculty of Mechanical Engineering University of Ljubljana was start with researches and development on the field of water hydraulic in 2006. Since then, a lot of research and developed several prototypes of water-hydraulic components have been done. Some of them are presented below.

3.1 Directional proportional control valve

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 [22]. 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. 7) of the spool-sliding type.

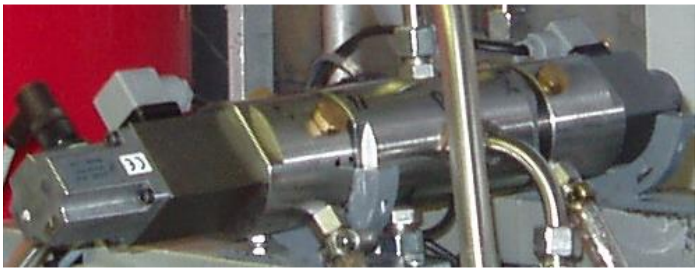


Fig. 7. Prototype of proportional directional control valve for water hydraulics

Fig. 8 shows the results of a long-term lifetime test of a proportional directional valve for water hydraulics. The situations were as follows: single, by-pass filtering, 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 first testing procedure amounted to 0,0825 lpm. The calculated, predicted internal leakage of a similar, oil 4/3 proportional directional control valve should be 0.085 lpm after 2,5 million cycles.

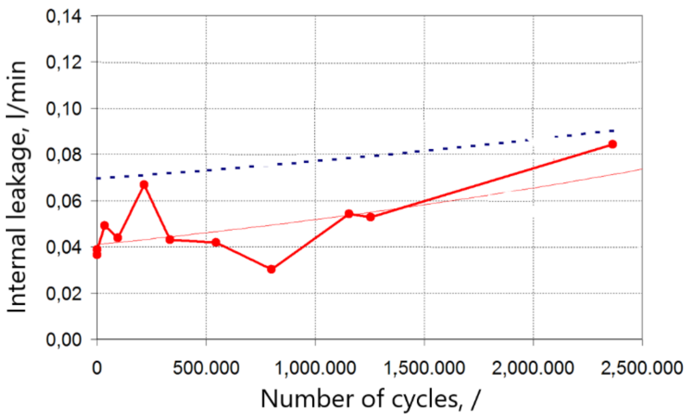
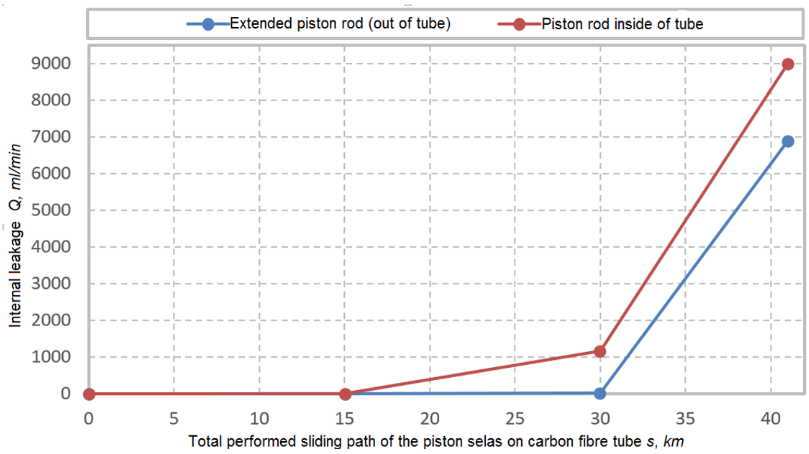


Fig. 8. Results of leakage during long-term tests of proportional water directional control valve

3.2 Light-weight hydraulic cylinder

The purpose of presented research was to find out the wear on the seals installed in a carbon water hydraulic cylinder tube, later referred as a specimen. It contains the results of measurements of the internal leakage (Figure 9.a) through the piston seals of the specimen and the pressures on both sides of the piston. After 30 km of sliding path first signs of wear – internal leakage was found (Fig. 9.a). After 40 km of sliding distance, cylinder was destroyed (Fig. 9.b).

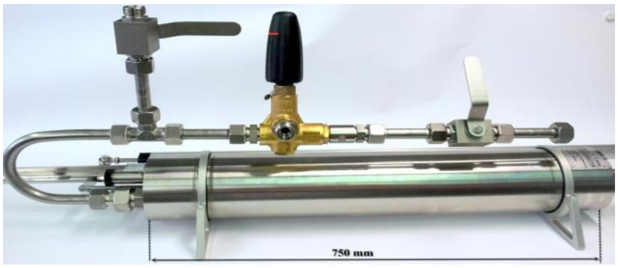


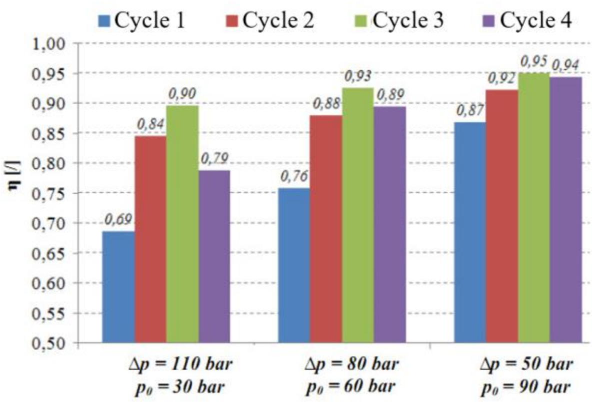
a. b.

Fig. 9. Results of long-term tests of carbon-fibre hydraulic cyl. tube, a. internal leakage, b) wear

3.3 Hydraulic accumulator

The new water-hydraulic accumulator (Figure 10.a) 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: 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 [23]. Figure 10.b 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.



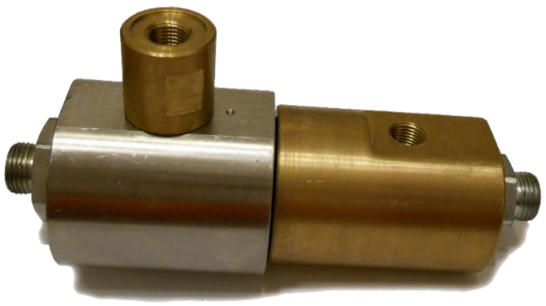


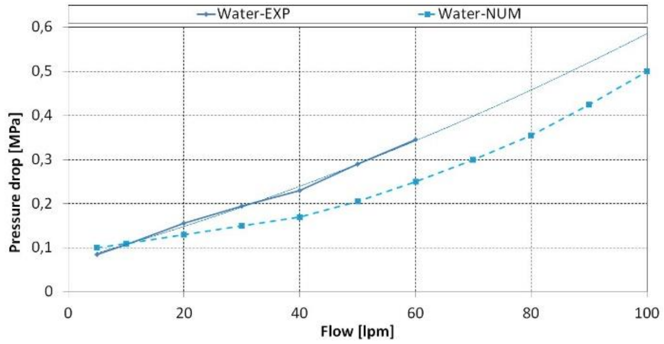
a. b.

Fig. 10. a) Prototype of a piston-type water-hydraulic accumulator, b) Influences of different nitrogen pre-filling pressures for all four cycles on the water-hydraulic accumulator efficiency

3.5 Check valve

The check valve was designed (Fig. 11.a) in such a way that it can be simply and quickly disassembled [24]. 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 11.b 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.



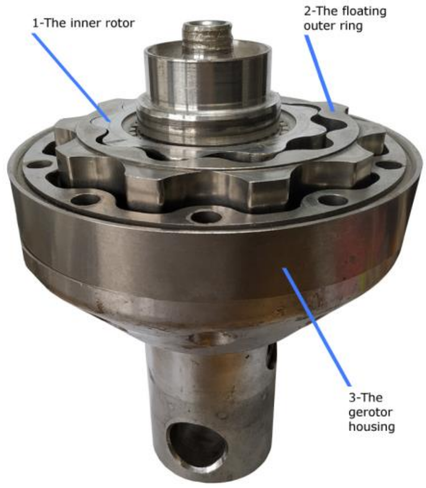


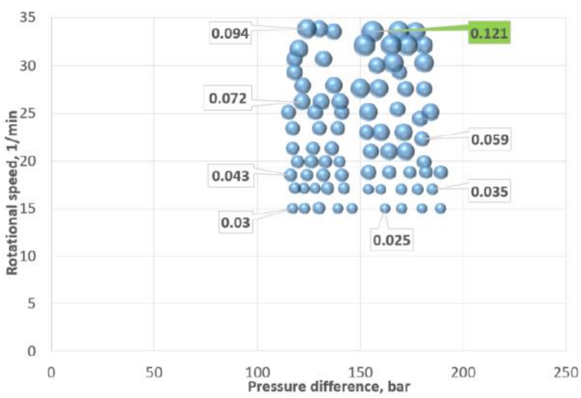
a. b.

Fig. 11. a) A prototype of the water-hydraulic check valve, b) Comparison between experimental measurement (EXP) and numerical (NUM) simulations for the water check valve

3.6 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 12.a. 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.b, 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 [25].





a. b.

Fig. 12. a) A prototype of a low-speed water-hydraulic motor b) Total efficiency (value in label) of the modified hydraulic motor for water

4. Conclusions

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).

Presented results show that water hydraulics has a lot of possibilities for the further researches and development.

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