Ecology trends: Oil vs. Water

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Abstract
A large number of countries are making major efforts to protect their environment. In the past, in Slovenia we have investigated bio-degradable fluids and their application in power-control hydraulics, especially for machines working in environmentally sensitive areas. However, additives must be added to such fluids, and they are not environmentally benign. In contrast, the use of tap water as a hydraulic fluid has no adverse effects on the environment. For this reason we decided to investigate tap water as a hydraulic fluid for power-control hydraulics (PCH).

Using water instead of mineral oil as the pressure medium entails significant changes in the physical parameters. Compared to mineral oil, water differs in terms of the following physical parameters that are important for PCH: an approximately 30-times lower viscosity (at 20 °C) and thus poorer lubrication, a more than 12-million-times higher vapor pressure (at 50 °C), and a 33 to 60 % higher bulk modulus (at 20 °C). Water also provokes corrosion in parts that are not resistant to its effects.

***Key words*:** distilled water, mineral hydraulic oil, biodegradable hydraulic oil, high-pressure water systems, power-control hydraulics, tribological properties

1. Introduction

In recent times there has been a trend in all industries to move in the direction of eco-friendly operations. In the area of power-control hydraulics, mineral oil has one of the biggest impacts on the environment. Unexpected outflows of hydraulic liquids, i.e., mineral oils, into the ground and even into underground drinking-water supplies are a frequent occurrence. Because of this, today's major challenge is to use alternative, natural sources of hydraulic fluid to protect our environment. In power-control hydraulics (PCH) there are two ways in which we can protect the environment. The first solution is to use a bio-degradable oil [1-3] instead of a mineral oil. But this is only a partial solution because biodegradable oil has to contain the necessary additives, which are sometimes detrimental to the environment. The second – and better – solution is to use tap water instead of mineral oil. This solution is environmentally friendly, but it is also very difficult to implement. For water hydraulics a relatively simple conventional control valve already exists on the market; however, the continuous control of water hydraulic systems is needed for almost every hydraulic machine. Nowadays, the market for disposable water-hydraulics components for continuous control is very small. And even if the components can be found, they are normally very complicated and with a lot of parts. Furthermore, despite many years of water-hydraulics research there is still insufficient understanding of the mechanisms and performance.

2. A comparison of hydraulic fluids

Using water instead of mineral oil as the pressure medium entails significant changes in the physical parameters. Compared to mineral oil, water differs in the following physical parameters that are important for PCH: an approximately 30-times lower viscosity (at 20 °C) and thus reduced lubricating qualities, a more than 12-million-times higher vapor pressure (at 50 °C), and a 33 to 60 % higher bulk modulus (at 20 °C). Water also provokes the corrosion of parts that are not resistant to its effects.

The higher energy density of the pressure fluid flow in water hydraulics and the higher vapor pressure of water compared to that of hydraulic mineral oil may cause serious problems in terms of erosion (via cavitation) and abrasion, higher leakage flows and problems with the functioning of valves [4]. A lower viscosity also means a lower lubricating film, which can increase friction and wear, unless we use suitable material pairs [5].

Furthermore, the dynamic behavior of water power-control hydraulic systems (PCHS) differs significantly from that of mineral oil PCHS, especially in terms of pressure amplitudes and oscillating periods in the case of under-damped oscillatory motions. The bulk modulus of water is about 70 % higher than that of mineral oil. The results of a mathematical model suggest about 24 % higher pressure amplitudes in water PCHS, compared to those of mineral oil PCHS, with the other system parameters being the same for both systems.

3. Properties of water and mineral oil

Kinematic viscosity

The temperature dependence of the kinematic viscosity is important in mineral oils. Therefore, in the process of designing systems, appropriate calculations must be carried out to determine the appropriate mineral oil, which will provide the necessary kinematic viscosity at the operating temperature. It is essential to take into account the temperature of the operating environment of the machine or take appropriate action to "circumvent" it. The most commonly used hydraulic mineral oil is ISO VG 46. For example, the kinematic viscosity of mineral oil ISO VG 46 changes from 3 °C to 50 °C by approximately 15.6 times. In contrast, the viscosity of the water, when changing the temperature, varies significantly less, for example, from 3 °C to 50 °C the kinematic viscosity of water changes by 2.8 times.
We assume that the density of water is 1000 $\frac{kg}{m^3}$ and that the dynamic viscosity of water varies as a function of temperature as shown in figure 1.

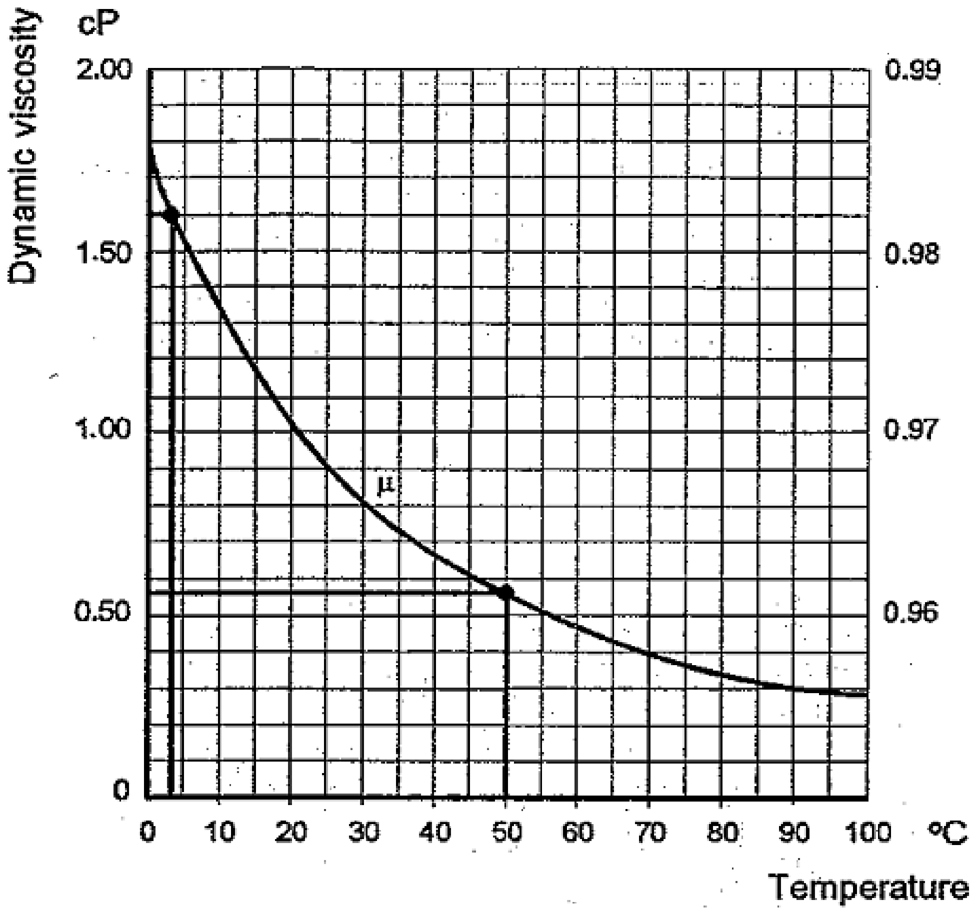

Figure 1: Dynamic viscosity of water as a function of the temperature at air pressure [4]

In our comparison of hydraulic mineral oil with water in the test rig we will take into account an oil temperature of 50 °C and a water temperature of 40 °C. The reason why we used an operating temperature of 50 °C for the hydraulic mineral oil is because it is a generally recommended consideration that the operating temperature of mineral hydraulic oil is at this temperature. We determined that the operating water temperature, acting as a hydraulic liquid, was 40 °C. According to similar research done by other researchers the temperature range should be from 3 to 50 °C. This means that 50 °C is the maximum temperature at which water should be used. The main reason for the upper limit of the water temperature is because of the increased risk of the occurrence of cavitation (low-pressure evaporator).

The kinematic viscosity of the most commonly used mineral oil, i.e., ISO VG 46, is 30 $\frac{mm^2}{s}$ at the optimal operating temperature of 50 °C. In the case of water, the kinematic viscosity at the optimum working temperature of 40 °C is 0.67 $\frac{mm^2}{s}$, which is approximately 48 times less than for the oil. It follows that the preheating of the water in the initial start-up in a cold environment is not necessary, as is the rule for mineral oil.

Modulus of compressibility

The compressibility modulus is an important parameter that describes by how much each liquid compresses at a given pressure and temperature. The modulus of compressibility in power-control hydraulics has a significant effect on the pressure-surge effect. The lower the modulus of compressibility, the more the liquid compresses and subsequently leads to a smaller pressure increase. In slow “dynamic” changes we must consider the isothermal compressibility module. In hydraulics we consider slow changes to be those that last longer than 3 minutes. The isothermal compressibility module β_S for a mineral hydraulic oil is in the range from 1.33 to 1.54 · 10^4 bar, while for water it is a constant 2.1 · 10^4 bar. The average isothermal compressibility modulus of mineral oil is therefore 1.44 · 10^4 bar. If we take a look at the ratio of these two modules for the same compressibility changes in pressure and volume, we find that the compressibility of the mineral oil is 46% higher. This information is very important because it shows that the water compresses much less, in comparison with the mineral hydraulic oil. In quick "dynamic" changes we must consider the adiabatic compressibility modulus; quick changes in hydraulics generally represent changes that take place in under 1 minute. The adiabatic compression module β_S is in the range 1.0–1.6 · 10^4 bar for mineral hydraulic oil, whereas for water (without air bubbles) it is a constant 2.4 · 10^4 bar. For the field of engineering it is normal to use an isentropic/adiabatic compressibility module.

Arrangement of the molecules in the gap

The form of the water molecules is closest to a circle having a diameter of about 0.3 nm, while an oil molecule is oval with a length of about 2 nm. Figure 2 shows the distribution of oil and water molecules in a gap of 0.01 μm (10 nm). The real heights of the gap in the oil proportional valves are up to 3 μm, while they are lower in the water proportional valve due to the significantly lower viscosity than in the oil. The molecules of oil are up to 2.3 times wider than the water molecules [4].

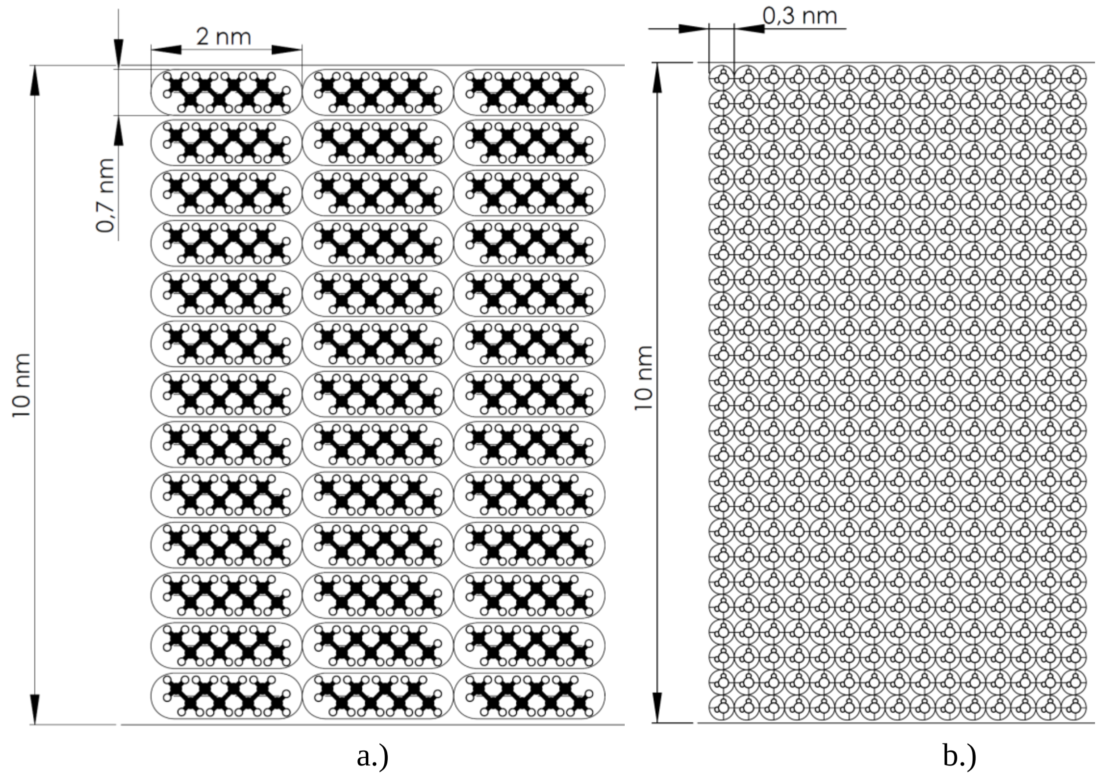

Figure 2: Comparison of the arrangement: a) oil [4] and b) water molecules [4] of the end slot, magnification about 10,000,000 ×

Comparison of water and other hydraulic liquids

Table 1: Important characteristics of water compared to other hydraulic liquids [4]

Hydraulic Fluid / Properties	Mineral oil **HLP***	Oil-Water emulsion **HFA***	Water-polymer emulsion **HFC***	Liquid with high ignition point - without water content **HFD***	Vegetable oil (rapeseed) **HTG***	**WATER**
Kinematic viscosity at 50 °C [mm^2/s]	15–70	≈ 1	20–70	15–70	32–46	**0.55**
Density at 15 °C [g/cm^3]	0.87–0.9	≈ 1	≈ 1.05	≈ 1.05	0.93	**1**
Vapor pressure at 50 °C [bar]	$1.0 \cdot 10^{-8}$	0.1	0.1–0.15	$< 10^{-5}$	not available	**0.12**
Compression modulus $ß_s$ [N/m^2]	$1.0–1.6 \cdot 10^9$	$2.5 \cdot 10^9$	$3.5 \cdot 10^9$	$2.3–2.8 \cdot 10^9$	$1.6 \cdot 10^9$	**$2.4 \cdot 10^9$**
Speed of sound at 20 °C [m/s]	1300	not available	not available	not available	not available	**1480**
Thermal conductivity at 20 °C [W/(m · °C)]	0.11–0.14	0.598	≈ 0.3	≈ 0.13	0.15–0.18	**0.598**
Specific heat at 20 °C and constant press. [kJ/(kg·°C)]	1.89	–	–	–	–	**4.18**
Max. working temp. range [°C]	–20 → 90	5 → 50	–30 → 65	0 → 150	–20 → 80	**≈ 3 → 50**
Flash point [°C]	210	–	–	245	250–330	**–**
Ignition point [°C]	320–360	–	–	505	350–500	**–**
Corrosion protection	good	satisfactory	good	good	good	**poor**
Environmental impact	large	large	large	large	small	**without**
Relative costs for liquid [%]	100	10–15	150–200	200–400	150–300	**≈ 0.02**
Usage [%]	85	4	6	2	3	**≈ 0 (so far)**

NOTE: Symbols used for hydraulic fluids marked with * are in accordance with the Standard ISO 6743.

4. Other properties of water

The global trend in the development of water hydraulic systems is driven in the direction of using drinking water (“tap water”) as the hydraulic fluid - drinking water should be familiar with those features that are relevant for the hydraulics. Some of the features mentioned in this paragraph were detected during the measurements, but because of the size of the task we will not analyze them in detail. Due to the formation of algae we had to prematurely (compared to the oil test rig) replace the filter cartridges.

Properties of drinking water

Although "pure" water is present almost everywhere on the globe, the quality of it depends on the geographical location. In general, water is pumped from boreholes, wells, lakes and rivers. To ensure that the water is drinkable, a process of chlorination must be applied for the destruction of bacteria and other microorganisms [6]. Significant progress towards improving the quality of drinking water has been made by European standards adopted in 1980 ("European Union 80/778/EEC Direction"). These directives have set allowable levels of undesirable substances in drinking water (microbiological requirements for drinking water, etc.). Below we will summarize the requirements from the European Directives for drinking water that are important with respect to the use of water as a hydraulic liquid (to ensure the functioning of the hydraulic system).

The **hydrogen ion concentration** is expressed as the pH value of the water. The EU directive defines the allowed range of pH for drinking water to be between 6.5 and 8.5, which is generally useful for hydraulic components [6]. Lower pH values lead to a greater risk of corrosion.

The **chloride content of ions (Cl-1):** EU directives prescribe a maximum content of 25 $\frac{mg}{l}$. However, this content is mostly greater. Values above 200 $\frac{mg}{l}$ can cause corrosion cracks, even on stainless steel. Free chlorine (Cl2) must not be present in drinking water. With respect to hydraulics, free chlorine also increases the possibility of corrosion.

Water hardness is determined by data on the presence of magnesium (Mg) and calcium (Ca) in the water. However, the EU directive does not give any maximum permissible values of magnesium and calcium. In the experience of researchers in the field of water hydraulics, a water hardness of between 5 and 10 °d (the °d unit is German hardness degree) makes it suitable for use in hydraulic fluids. A higher hardness increases the possibility of the formation of lime deposits and possibly “lumpy” formations, which can then travel through the hydraulic hoses and the hydraulic components. When the flow through the components in the hydraulic system is sufficient, the limestone is removed and carried away by the water to the filter. If the water contains too much limestone, it must be removed from the water with a carbon oxide.

When using drinking water as a hydraulic liquid we have to limit the corrosion by choosing the proper materials and by maintaining the quality of the water. It is important to know that water is electrically conductive and may act as an electrolyte, where the presence of impurities (such as, e.g., detergents) or when specified additions ("additives") are added. In such cases there is an increase in electrolytic corrosion. Therefore, the materials that are used in combination with water as a hydraulic fluid must correspond to the specified electrochemical properties. For this reason, materials such as aluminum or zinc must not be used, while the use of copper alloys and nickel-chromium steel is appropriate.

The **bacteria** in water used as a hydraulic liquid often cause problems. Typical plant bacteria, fungus, and other soil microorganisms cause clogging of the filter (frequent change of filter cartridges) and odors. In a hydraulic system that uses water as a hydraulic fluid, the amount of bacteria and fungus increases and adversely affects these devices in two ways:

- bacteria and fungus can contaminate the environment through the external leakage of the hydraulic liquid,
- the organic coatings that accumulate over time on the internal walls of the hydraulic components can be increased and subsequently cause corrosion.

5. Summary of the advantages and disadvantages of water

Table 2 shows the basic advantages and disadvantages of water when used as a hydraulic liquid. Below are listed the main advantages, such as a low pressure loss due to the low viscosity, a rapid response to control signals, efficient heat transfer, relatively low cost, no pollution and an absence of flammability. The main disadvantages of water as a hydraulic liquid are the higher internal leakage, the occurrence of cavitation erosion, the higher pressure increase in hydraulic hammer, the poor corrosion resistance, the poor lubrication (a thin lubricating film) and the possibility of freezing.

Table 2**:** Properties and the main advantages and disadvantages of water as a hydraulic fluid

Properties	***Advantages***	***Disadvantages***
Low viscosity	A small pressure loss	Higher internal leakage
High evaporation pressure	–	The occurrence of cavitation erosion
High compression modulus / high speed of sound	Fast responses	The largest increase in pressure in the pressure surge effect
Corrosion protection	–	Bad - required special materials
Lubrication and lubrication film	–	Low - required special materials
Thermal conductivity	Good - rapid heat transfer	–
Relative price	Low	–
Impact on the environment	There are no negative impacts	–
Temperature range	–	Narrow temperature range: 2–50 ° C
Fire hazard	No danger	–

6. Test Rig

The test rig that we used to perform the measurements is shown in Figure 3. On the left-hand side of the figure is the water test rig and on the right-hand side is in the function-comparable oil hydraulic test rig [7].

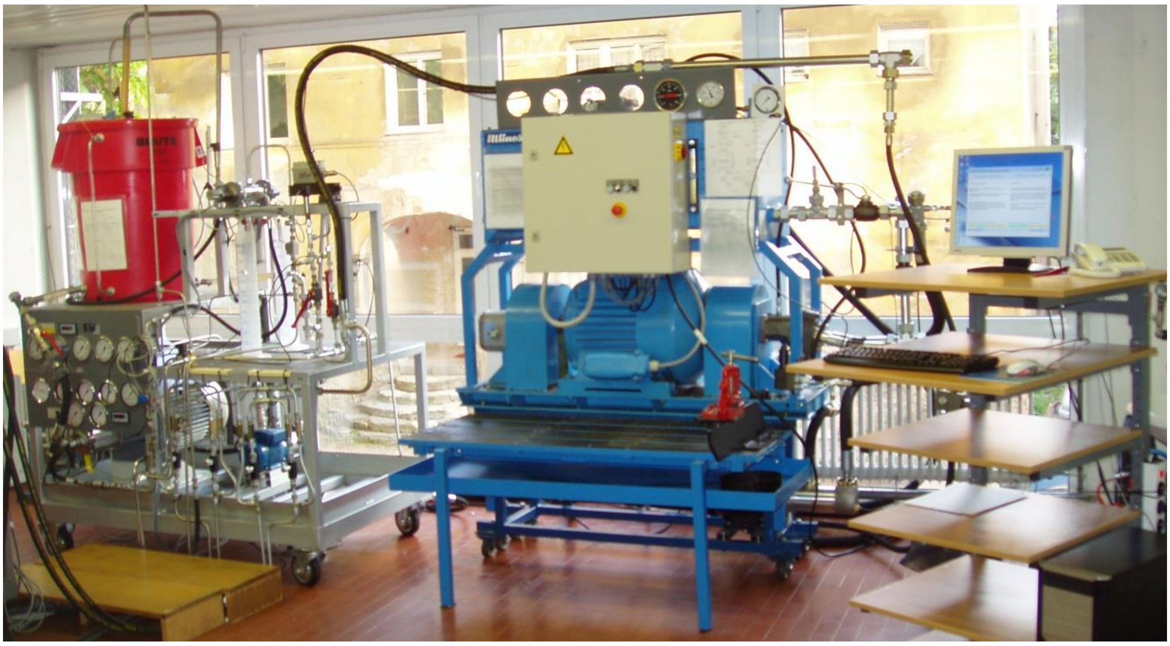

Figure 3: Water hydraulic test rig on the left-hand side and the oil hydraulic test rig on the right-hand side [7]

7. Conclusion

Water as a hydraulic liquid has great potential in future research and later also for industrial applications. However, there is still a requirement for a series of measurements and the need to find materials that would be appropriate (corrosion resistant, low wear and low friction) and of course affordable for mass production. It will be necessary to achieve a high level of reliability, which is currently unachievable. The use of tap water as a hydraulic fluid in everyday life is currently difficult to imagine, but in the future there will be more and more companies attempting to employ such systems.

Water has great potential mainly due to its very low purchase price, compared with mineral hydraulic oil, its low kinematic and dynamic viscosity, its lack of flammability, its availability and also because of its lack of impact on the environment (no pollution).

8. References

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