ENERGY EFFICIENT WATER HYDRAULIC SYSTEMS

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ABSTRACT

Water plays an important role in power transmission systems. The inherent cleanliness of water, combined with its long history as a power source, has pushed water back to the hydraulic forefront. Obviously, economic and environmental forces have had an impact in helping water regain its prominence as a hydraulic fluid. Today, engineers are viewing water hydraulics as an interesting technology that can offer significant advantages to solve power transmission and motion control tasks.

In order to make use of the advantage of water hydraulics the component and system design must be adapted, especially to the physical behaviour of pressurised water. The materials used in the hydraulic components must have high corrosion and cavitation resistance. Poor lubricating properties requires special design of all components with moving parts, such as pumps, motors and valves.

The major aim is to discuss and high light new ideas useful for the design of water hydraulic systems. This paper also will consider the effects on the development of components and systems by using water as a hydraulic fluid. The fluid power technology have promoted advances in operation capabilities, reduced costs, increased reliability and protected the environment.

Key words: Water hydraulics, physical properties, cavitation erosion, hydraulic losses, system efficiency.

INTRODUCTION

The history of water used in hydrostatic systems goes back to the year of 1795. This year Joseph Bramah endorsed water as pressure medium in his new invention, a hydraulic press. Then, water was used as power transmission fluid until the end of the 19th century. In the beginning of the 20th century oil hydraulics was developed as a new technology that resolves the drawbacks of water hydraulics, such as bad lubrication properties, corrosion, cavitation erosion and low efficiency.

Oil hydraulics is still superior to water hydraulics in engineering properties such as system overall efficiency and service life. Due to the specific properties of oil and continuously improved additives, the development of oil hydraulics has been shaped to the present days, see reference [1]. May be a more important factor is that the technological efforts accumulated for water hydraulics are still far less that those for oil hydraulics. To improve water hydraulics the properties of water and compatibility with industrial materials must be considered.

Today, the new water hydraulics is a real frontier of fluid power technology. Production of water hydraulic components is widely spread over the world and new applications are introduced continuously. Some typical applications for water hydraulics are - food processing, nuclear power plants, fire fighting, steel mills, off shore, rock drilling, street sweepers and waste packer lorries.

When asking for a fluid that does not have any negative impact on the environment and does not create fire hazards and safe for life the only fluid to be find is water. The most important requirements for modern industrial processes are safeties and harmless to the environment. Water hydraulics satisfies both of these requirements.

In the development of energy efficient fluid power systems the working principle of the system and thereby the behaviour of the fluid and the losses it will cause in the system is of great importance. When it comes to water hydraulics the physical properties of the fluid, is much more critical then with use of oil.

In fact, water as a pressure medium is beset by certain problems, due to its specific properties. The physical and chemical behaviour of pressurised water requires special materials in the hydraulic components and also a special design to overcome cavitation erosion, corrosion and lubricating problems. However, development and use of water hydraulics is a natural approach to prevent ecological damage in many industrial areas. Today, it is possible to manufacture water hydraulic system with high efficiency and an acceptable service life time. Through advanced of technology it will be possible to increase the application fields of water hydraulics to a wider spectrum than oil hydraulics presently have, [2].

PHYSICAL PROPERTIES OF IMPORTANCE IN SYSTEM DESIGN

The low viscosity and high bulk modulus of water means that applications requiring fast response and energy efficient operation can benefits from using water as pressure medium. Water's lower viscosity means less flow resistance. That leads to low heat generation and reduction in energy losses. High bulk modulus means fast response, which in turn reduces cycle times. However, as will be shown below, low compressibility can also cause problems in form of high-pressure transients and cavitation compared to systems with more compressible fluids, such as mineral oil.

(1) Effects of low viscosity

Viscosity is one of the most important properties of a hydraulic fluid and it has a great influence on the performance of a hydraulic system. Typical viscosity values for oil and water are shown in Fig. 1.

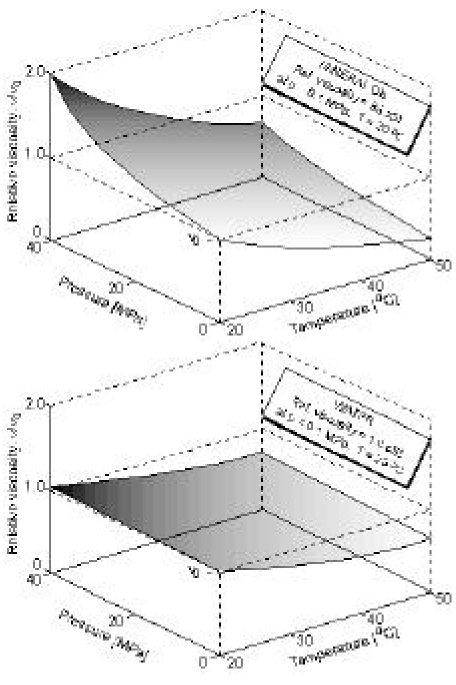

Fig. 1 Comparison between viscosity of mineral oil and water at different pressures and temperatures

Compared to mineral oil, water has a very low viscosity. During working conditions the relation is normally between 1:30 to 1:40. The effect of the low viscosity is that turbulent flow will appear mainly in all components. Not only in flow through valve orifices, also in pipes and in sealing gaps for pumps and motors turbulent flow will be dominant.

Turbulent flow in pipes. Flow in pipes is normally turbulent if water is used. In Fig. 2 can be seen that the flow conditions for water will change from laminar to turbulent at a velocity of about 0,14 m/s (Reynolds no. Re =2300 and the pipe inner diameter is 16 mm). For mineral oil with a kinematic viscosity of 40 cSt the critical velocity occurs at a 40 times higher value, 5,6 m/s.

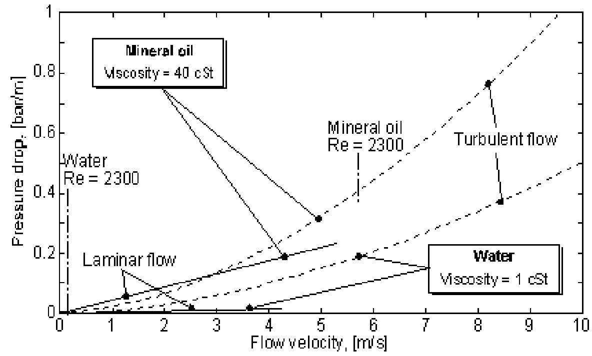

Fig. 2 Pressure drop versus velocity for laminar and turbulent flow in pipes (pipe diameter = 16 mm)

The pipe losses of pressure drop per meter, illustrated in Fig 2 follows the equation,

$$\Delta p_f = l \frac{r \cdot v^2}{2 \cdot d} \qquad (1)$$

where the friction factor for laminar flow is $l_l = 64/\mathrm{Re}$, and for turbulent flow the factor is, $l_t = 0{,}316/\sqrt[4]{\mathrm{Re}}$.

where v - flow velocity, m/s
d - diameter of the pipe, m
r - density of fluid, kg/m^3

From equation (1) it can be seen that, less pipe diameter (d) gives higher velocity for changing from laminar to turbulent flow. But, even with a diameter of 5 mm the critical velocity for water is considerably low. Consequently, during normal conditions, nearly all pipe flows are turbulent in water hydraulic systems.

Leakage flow in sealing gaps will increase due to the low viscosity of water. That means reduced volumetric efficiency for pumps, motors and valves in a hydraulic system. Assuming a gap with the same length, width and pressure difference, the leakage flow ratio between water and oil will be a function of the dynamic viscosity (h) and the height of the gap (h), according to the expression,

$$\frac{q_{l,water}}{q_{l,oil}} = \frac{h_{oil}}{h_{water}} \cdot \frac{h^3_{water}}{h^3_{oil}} \qquad (2)$$

In order to reduce the leakage flow in a water hydraulic component to the same level achieved when mineral oil is used the height of the gap must be reduced to 30 – 35% of the gap in a oil hydraulic component. In the case of the radial gap in a piston pump/motor this can cause difficulties due to thermal expansion induced by friction between solid bodies. Therefore, higher leakage flow have to be accepted in water hydraulic components. In general, water hydraulic equipment has to be produced by lower tolerances, which make the manufacturing more expensive, [3].

(2) Bulk modulus

The compressibility of the fluid and elasticity of the surrounding for the fluid adds up to a total compressibility, for each separate component in a hydraulic system. The inverse of the compressibility defines the bulk modulus. The effective bulk modulus (b_e) for the fluid and its surroundings can be expressed as,

$$b_e = \frac{b_{fluid} \cdot b_{surrounding}}{b_{fluid} + b_{surrounding}} \qquad (3)$$

From equation (3) it can be seen that b_e will be close to the lowest b-value of the two on the right hand. Even if the hydraulic fluid gives a dominant contribution to the effective bulk modulus, the contribution from other system elements may be of significance as well. This is the case if, for example, hoses are used as pipes in the hydraulic system.

Both b_{fluid} and $b_{surrounding}$ have a strong connection to the pressure level. There is also an influence from temperature, but not so strong as from the pressure. If the fluid is a mixture of liquid and air bubbles (or other gas bubbles), the fluid bulk modulus (b_{fluid}) will be drastically reduced by the volumetric amount of bubbles. The influence is strongest at low pressure levels, let say below 50 bar.

From theory it is possible to calculate the effective bulk modulus analytically, but this is rather complex to carry out, which has been discussed above. In practice, thumb rules based on experiences (measurements) is used to estimate a value or a function for the effective bulk modulus, see Fig. 3.

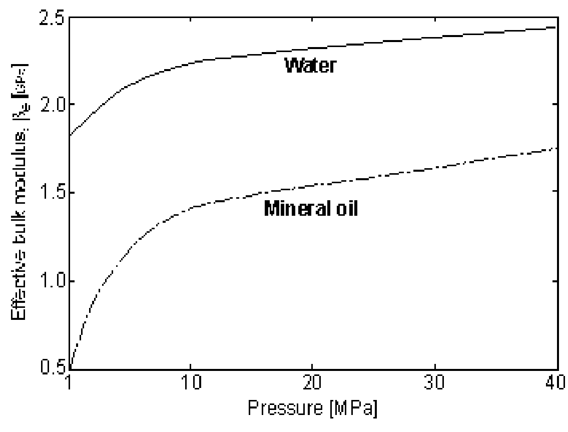

Fig. 3 Typical values for effective bulk modulus with water and mineral oil as fluid

(3) Heat capacity and heat transfer

Heat capacity is an other property, which has influence on cavitation, especially in water hydraulic system because of the low boiling temperature. In a hydraulic system all pressure losses in pumps, pipes, valves and other components results in an increased fluid temperature. This temperature increase is mainly dependent on the specific heat capacity of the fluid, c_p. The thermal process can be assumed as isentropic and the temperature difference, *DT* is a function of the pressure drop, *Dp*, following the relation,

$$\Delta T = \left(1 - a_p \overline{T}\right) \frac{\Delta p}{\overline{r} \cdot \overline{c}_p} \qquad (4)$$

where a_p - fluid thermal expansion coefficient, -
r - density of fluid, kg/m^3

Due to the difference in specific heat capacity, c_{pwater} = 4180 J/kgK and c_{poil} = 1890 J/kgK (at a temp. of 40^{o}C), the temperature increase versus pressure drop for water is about 50% of that for mineral oil. There is also a difference in the thermal expansion coefficients α_{pwater}=.0002 1/K, α_{poil}=.0007 1/K respectively.

In practice that implies that it is easier to control the fluid temperature in a water hydraulic system than in an oil system. In order to avoid vaporisation occurring in the pump inlet, of a water hydraulic system it is important to hold the temperature of water in the tank below 45^{o}C.

Under the condition of turbulent flow in a pipe, it is also notable that water will have a much higher heat transfer coefficient than oil. Therefore, heat transfer by water can be more that 20 times higher of that by oil. This is also an important contribution to the low temperature rise in water hydraulic systems.

(4) Friction

Due to the poor lubricating properties of water, special materials and designs of all components with moving parts, such as pumps, motors and valves are required. The main wear in component seals and bearings can be related to friction. When using water as lubricating fluid the selection of materials and design features that reduces the contact forces and thereby the friction between sliding parts are of highest importance.

In order to reduce the wear on a surface, materials with low friction coefficient must be used. For many materials the steady state friction coefficient follow the Stribeck curve, [2]. The friction of seal materials for a pump at constant speed may be explained by this curve. However, unsteady motion shows friction characteristics deviating from the Stribeck curve. For example, the static friction is time dependent due to the squeeze effect between the surfaces, and this is not shown in a Stribeck curve. It is hard to expect this squeeze film effect for water, since its viscosity is very low.

To reduce the friction and thereby the fatigue wear a suitable combination of polymers and metals or ceramics have been found to be a good solution. A relatively new polymer, PEEK (polyeter-eterketon) shows a very low friction coefficient, about 0,02, in contact to steel with a water film. This friction coefficient is comparable with 0,05-0,07 for steel to steel with mineral oil. Today, PEEK, has turn to be commonly used for sliding parts in water hydraulic pumps and motors, [4].

(5) Cavitation – cavitation erosion

Cavitation is a common phenomenon in fluid power systems. It will cause effects like noise, vibrations, reduced efficiency and erosion, see [5]. Cavitation comes from gas bubble formation due to pressure drop induced by the fluid flow. If cavitation occurs near a material surface and is violent enough, rapid wear of the component will take place. Besides, lubricating properties and corrosion, cavitation erosion is the major problem in water hydraulic systems.

The main initiator for cavitation is the vapour pressure. Since cavitation remains from implosion of gas bubbles in the fluid, its vapor pressure is an important initiator for cavitation. At a temperature of 50°C the vapor pressure for water is about 0,12 bar and for mineral oil is the vapor pressure considerably lower, approximately $1{,}0 \cdot 10^{-8}$ bar. In other words, the risk for cavitation is much higher in water than in oil.

The amount of air in the fluid will create different stages for the initiation of cavitation. In mineral oil, cavitation is mainly due to vaporisation of dissolved air (gas cavitation), whereas cavitation observed in water mainly comes from boiling of water itself (vapor cavitation). The reason is that the air solubility is about five times higher for mineral oil (about 10 volume % at atmospheric pressure) then for water.

During normal conditions, cavitation (cavitation choking) downstream a valve orifice will take place when the downstream pressure is becomes lower than about 50% of the upstream pressure. The erosion effect from the jet increases exponentially with the upstream pressure and can be 100 times higher for water then for mineral oil. The amount of material removed by cavitation is lower the harder the material is. Metallic material hardness is the most important variable in this case. This is the reason why high quality steel alloys (Cr, Ni, Mo, Mg), heat treated steels and ceramics are particularly resistant to cavitation erosion, [5].

The implication on valve design is that the maximum pressure drop over one separate resistor must be reduced to, let say less than 70 bar. For higher pressure differences a multi-resistor valve is the most effective solution, but also more expensive. Fig. 4 shows different designs of pressure valves with two resistors, [5].

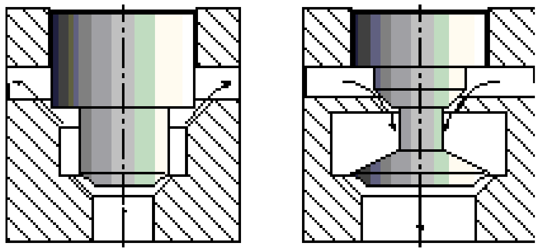

Fig. 4 Examples of two-resistor pressure valves, [5]

In this case, the greater part of the pressure difference is decompressed within the first resistor. With a sufficiently high pressure after the first resistor an absorption of the vapour bubbles will take place, which eliminate cavitation erosion. At the second resistor, the cavitation erosion is much less severe due to the low pressure difference.

(6) Pressure transients

Pressure transients can be observed in pipes and other components all the times when the velocity of flow is changed. High-pressure peeks in a pipe can typically be caused by rapidly closing valves. The pressure amplitude Δp [Pa] caused by a rapid change in flow Δq [m^3/s] will follow Joukowskis equation, which is

$$\Delta p = Z_c \cdot \Delta q = \frac{1}{A}\sqrt{b_e \cdot r} \cdot \Delta q \qquad (5)$$

where Z_c - characteristic impedance of pipe, Ns/m^5
A - cross sectional area of the pipe, m^2

In systems with the same pipe diameter and the same flow disturbances, the ratio of pressure amplitudes between water and oil is $Dp_{water}/Dp_{oil} \approx 1.5$, which is shown in Fig. 5.

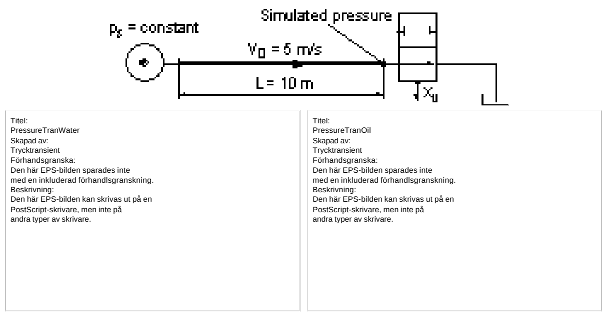

Fig. 5 Simulated pressure transients in water (the left diagram) and oil respectively

As can be seen from the figure, the simulated system consists of a constant pressure source, a 10 metre long line and a valve with a return connection to tank. The plots in Fig. 5 shows pressure transients caused when the valve is closed instantaneously. The flow velocity before valve closing is 5 m/s for both simulations. The results shows that pressure transients are more severe in water than in oil hydraulic system, because of their higher amplitude and a higher frequency. The amplitude of pressure transients will be reduced by decreasing the initial flow velocity and/or by increasing the valve switching time.

ENERGY EFFICIENT SYSTEM DESIGN

(1) Pump efficiency

The viscosity, bulk modulus and friction forces have implications on the pump overall efficiency. High leakage flow caused by low viscosity of water means that the overall efficiency will be low, especially in the low speed range. The higher bulk modulus of water will reduce the compression losses, but they are not so dominant at a pressure level of 15 MPa. In the high speed range the friction losses will be more and more dominant. However, due to low viscosity the friction forces will be reduced, which means higher efficiency. The pump overall efficiency calculated from an efficiency model developed in [6] is shown in Fig. 6.

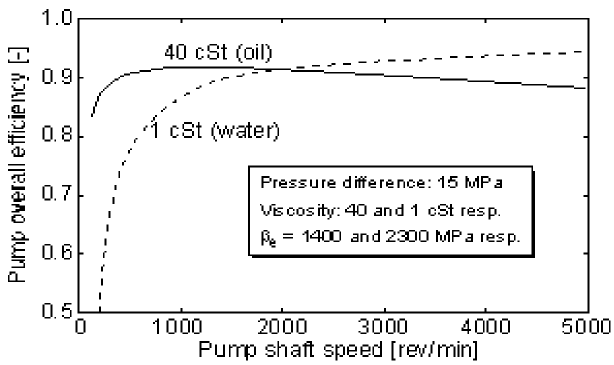

Fig. 6 Pump overall efficiency versus shaft speed for oil and water respectively

(2) System efficiency

The most promising idea in the design of high efficient water hydraulic system is to adapt both pressure and flow, as good as possible, to the actual load requirements. In practice that means minimization of the hydraulic losses in the system.

As shown in Fig. 7, this can be realized by speed control of the pump or by displacement control. The losses in the hydraulic systems, depicted in the figure, are highly dependent on the application and the loading cycle. The main question is whether the losses of the system will stay inside a reasonable range during operation, without damaging the system.

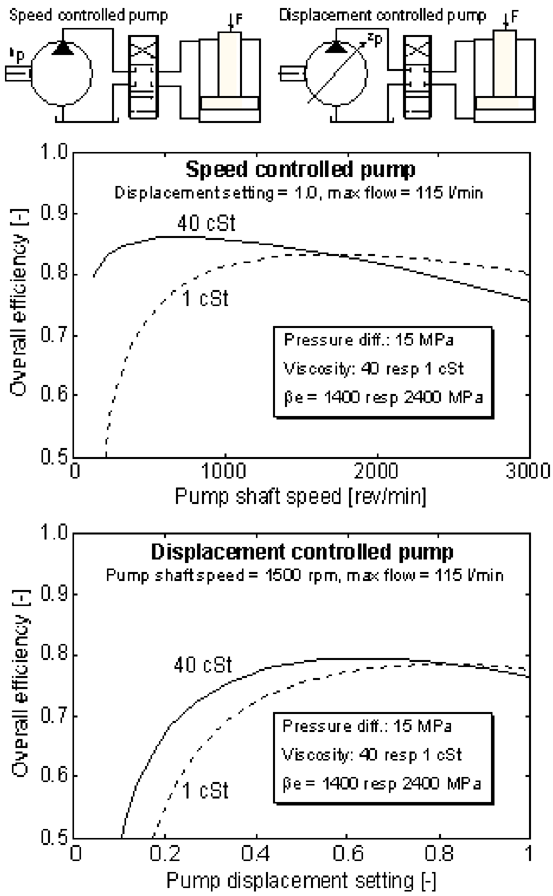

Fig. 7 System overall efficiency with speed and displacement controlled pump respectively and different fluids

Fig 7 shows clearly that the speed controlled pump gives higher efficiency, especially in the low flow range. When the pump speed is controlled, water (1 cSt) will shown a higher efficiency at maximum power. However, this depends mainly on the higher pump speed (3000 rpm) instead of 1500 rpm for displacement controlled pump.

(3) Pump pulsations

A specific problem related to hydraulic pumps is the flow pulsations (flow ripple) due to periodic variations in displacement volume and compression effects in the fluid. When the flow ripple interacts with the impedance of the system connected to the pump, pressure pulsations will be created. If the impedance of the system changes, part of the energy in the propagating waves will be reflected and standing waves occur. If a frequency in the pump pulsations is the same as a resonance frequency of the pipe connected to the pump the pulsation amplitude can be very large. The incoming amplitude can be gained up to 1000 times. Especially in the low frequency range the pulsations can generate critical vibrations in the hole system because of interaction with different mechanical resonance frequencies.

In Fig. 8 the source flow from an axial piston pump (in-line pump with 7 pistons) is shown at two different speeds, 300 and 3000 rpm and for two different fluids, water and oil. From the flow curves it can be seen that the maximum pulsation amplitude is approximately 50% higher for mineral oil than for water. The amplitude is dominated by the compression effects and the bulk modulus in the simulation models is just two times higher for water than for mineral oil (β_{water}=2,0 GPa, β_{oil}=1,0 GPa). Therefore, the flow needed to increase the cylinder pressure to the system pressure level with oil as a fluid will be about twice of water. In the actual pump the leakage flow has some influence on the pulsation amplitude, but much less than the compressibility of the fluid.

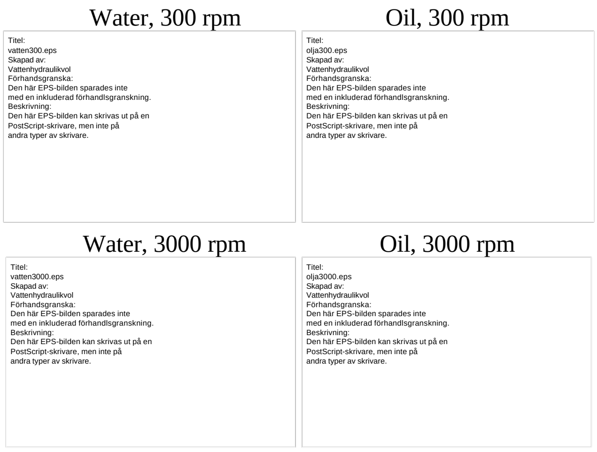

Fig. 8 Pump source flow for water and oil at different shaft speeds

The results confirm that the pressure pulsations in a given pipe connected to a given pump will be nearly the same for water and mineral oil ($\Delta p_{oil} \approx \Delta p_{water} = Z_c \Delta q$) as long as the pump ripple amplitude is dominated by compression effects and no resonance "collisions" in the pipe occur.

In fact, the pulsation amplitude is very sensitive to pump and system design and the operating condition. However, the main problem related to pump speed control is that the pump pulsation frequencies are proportional to the shaft speed. For some speed interaction between pump pulsation and pipe resonance frequencies can occur and give large pressure amplitudes. In such applications a promising idea is to use some form of fluid power attenuators, [7]. Thus can be considered as an analogue of a band pass filter. The attenuator will reduce the pressure amplitudes in a certain frequency range.

APPLICATIONS

Water hydraulic components and systems are more expensive than oil hydraulics, due to the requirement of special materials and designs. Because of the high level of monitoring required the operating cost is not much lower than for oil hydraulics. However, in all industrial application areas where safeties, cleanliness and environmental harmless are important requirements, water hydraulics can be a real competitor to oil hydraulics. Today, most of the components available for oil hydraulics have also entered the market for water hydraulics. Even sophisticated components, such as servo valves are available, see [8], [9], [10] and [11].

In order to increase the overall efficiency of a hydraulic system variable displacement pumps and motors for oil are commonly used. However, there are no variable pump or motor for water hydraulics offered yet. In the pump case the problem can be solved, by controlling the pump shaft speed. In this paper it has been shown that speed control is more efficient than displacement control, especially at partial loading of the system. However, it is important that the pulsation problem is considered.

Some typical applications for water hydraulics are - food processing, chemical industries, paper industries, steel mills, nuclear power plants, fire fighting, off shore technology, rock drilling, street sweepers and waste packer lorries.

Due to environmental protection the mobile applications are of special importance. These applications are mainly in vehicles, which are to be used in environmental sensitive surroundings, such as cities, coastal waters, parks etc. In Sweden there are two interesting mobile applications operated with water hydraulics. The first one is a waste packer lorry and the second a street sweeper. These vehicles are, owned by the waste handling company ***Renova***, the City Council of Gothenburg.

The waste packer lorry is a daily operated vehicle and the hydraulic system must be designed for outdoor temperatures of –10 to +40 ^{o}C. Therefore, the tap water is frost protected by 35% food grade propylene glycol. This fluid is classified as a non-hazardous to humans and the environment.

The application mentioned above makes clear that water hydraulics is no longer restricted to stationary applications. Good use can also be carried out in many mobile machines. Among the characteristics offered by water hydraulics are excellent functionality and reliability, energy saving design and, last but not least, a very environment-friendly pressure medium.

This is just the brief conclusion from the European Eureka-project "Water-hydraulic lifting systems with variable speed" in which Danfoss, in cooperation with the "Institut für Fluidtechnik" at the Dresden University of Technology, converted an ordinary electrically driven forklift truck for operation with a water-hydraulic lifting and tilting system, [12]. In this project it has been proved that solely from the point of view of function, water-hydraulic systems lend themselves incredibly well to mobile machines, even though units such as forklift trucks do impose high demands on water hydraulics.

CONCLUSIONS

From being a technology for enthusiastic engineers and pioneers, the water hydraulic technology has become more commercial and considered as a competitive alternative to oil hydraulics. The advantages of water hydraulics as clean and environmental friendly techniques have been utilised. At present, pure water hydraulics has a market share of less than 5% of the total market for hydraulic equipment, [3]. However, modern water hydraulic technology is still new and a lot of problems must be solved to make the technique more widely available for power transmission.

It is quite clear that at present, oil hydraulics is still superior to water hydraulics in engineering properties such as lubrication, power density and service life time. The causes of superiority are the physical and chemical properties of oil. However, when the drawbacks are solved through advances of technology the new water hydraulics will be used in a number of new applications areas. To recognise what needs to be done to improve water hydraulics, physical and chemical properties of water and its compatibility to industrial materials must be put into focus.

Now there is an increasing demand for water hydraulics equipment. In part, the demand is environmentally driven but, in many cases, there is both a clear technical and an economic motive. Also, the ability of the water hydraulics industry to deliver the components needed depends primarily on the materials available to make them. New materials suitable for water hydraulic components are being offered to the engineer almost daily.

At present, purchasing a water hydraulic system can be a more expensive proposition than buying a comparable oil system, based simply on the purchase price. But the number of applications where this premium is worth paying and where the medium term cost is actually in favor of water continues to improve. So, in the future, many more hydraulic systems will use water-based fluids, raw or tap water, or possibly even sea-water. More manufacturers of components for oil hydraulic systems will enter this market as it now moves into a maturing process, bringing the benefit of wider product ranges and greater market understanding. Specifying water hydraulics for the correct application, in a cost-effective and reliable manner, will become ever easier.

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