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Experimental validation of the lifetime performance of a proportional 4/3 hydraulic valve operating in water

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ABSTRACT

One of the alternative hydraulic fluid is water, which is environmentally acceptable, low-cost and non-flammable. We have designed a new hydraulic test rig and a new water proportional control valve to investigate the tribological and hydraulic behaviour of such water-based systems under pressures of up to 16 MPa and flows of up to 30 lpm. In this work, we present the lifetime performance of all-stainless-steel valve with distilled water being used as the hydraulic fluid. The results show that the water-based valve can operate for more than 10 million cycles under industrial relevant conditions if the water cleanness is appropriately maintained.

1. Introduction

With technological progress and global industrialisation, ecology is becoming more and more important for sustainable development world-wide. Power-control hydraulics is an important area of mechanical engineering [1–3], where large quantities of harmful substances (i.e., hydraulic fluids) threaten the environment with potential pollution resulting from accidents and occasional spillages [4]. It is well known that some outflows in terms of noxious hydraulic fluids occur during everyday operations, even with regular maintenance [5]. There are two possible solutions to improve this situation: the first one is to use biodegradable oils [6–10]; the second one is to use tap water as the hydraulic fluid [11,12]. The second one is much more effective and environmentally neutral, but it is more difficult to achieve. The employment of tap water in hydraulic systems implies a completely different environment for all the mechanical and hydraulic components, different dynamic and lubricating conditions, and this requires a completely or partially modified selection of materials and the design of the hydraulic system [13].

In today's industrial-scale-components market we find mainly simple, water-based components and systems, while more complex components that would enable the use of a larger amount and variety of water-based hydraulic systems instead of oil based systems are still to a large extent missing. Accordingly, there is a clear need to develop new and more advanced water-hydraulic components. In particular, continuous-control hydraulic systems are of great interest since they are required in almost every advanced hydraulic system, but to our knowledge, the development of these water-based components has not yet taken place [14].

These reasons motivated us to develop a new proportional 4/3 directional control valve suitable for water-hydraulic applications. Several specific requirements are associated with this kind of valve when the spool and the sleeve are sliding in water. Namely, the low viscosity of water suggests that the gap between the spool and the sleeve should be very low in order to maintain a low internal leakage and a high volumetric efficiency. On the other hand, this further implies the need for very accurate manufacturing with close design tolerances (circumference and cylinder) and a low roughness. Moreover, a small gap combined with a relatively poor lubricant (i.e., water) also suggests the danger of there being high friction and wear for the contacting surfaces. For this reason, filtering will probably also play an important role in any successful operation. With these constraints identified, the materials should be properly selected, on the basis of tribological and corrosion performance, as well as taking into account machinability and costs.

It is clear that steel is not the best material for water-lubricated applications for reasons of corrosion, wear and friction. Certain types of ceramics, which are known to provide relatively low wear and friction under water lubrication [18–22] and which are actually widely used in several water-based applications, might be more appropriate. Another potential class of materials are polymers, due to their low adhesion, low specific weight and their excellent corrosion resistance. However, polymers are

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Nomenclature

$Q_{L,max}$	maximal internal leakage flow of the valve [m^3/s]
Q_{np}	measured internal leakage flow [m^3/s]
n_{ip}	number of the leaving cross-sections
Δp	pressure difference in the gap [Pa]
D_m	middle diameter [m]
S	gap between spool and sleeve, when spool is in the centric position [m]
f_{ecc}	factor of eccentricity
ρ	density [kg/m^2]
υ	kinematic viscosity [m^2/s]
L	axial overlap between spool and the sleeve in the neutral position of the spool [m]

sometimes very difficult to manufacture to appropriate tolerances and experience dimensional instability, while ceramics are very expensive and suffer from fracture. Therefore, none of these materials can be easily introduced and would require detailed optimisation for any specific application. In our preliminary tribological pin-on-disc study with various pairs using alumina, PEEK, polyimide and stainless steel [15] we observed that ceramics may be one of the best materials for such an application. However, stainless steel, which is the easiest to apply and manufacture and is quite inexpensive, also showed reasonably good wear performance, although the friction was the highest among the tested materials. Thus, it is of interest to observe how the stainless steel would perform under real water-hydraulic conditions. Accordingly, in this work we have performed an experimental long-term validation test of a stainless-steel proportional 4/3 valve operating under water-lubrication conditions using our own-designed test rig and valve [16,17].

2. Water-hydraulic test rig

2.1. Requirements for the test rig

A new proportional water 4/3 directional control valve was designed to study the water-based hydraulic system. In order to reduce the testing costs, the testing valve needed to have a simple design, which could allow the fast and easy exchange of materials and provide good surface control of the spool and the sleeve. The spool and the sleeve should be small enough to fit into various surface-analyses devices (SEM, AFM, etc.). The selected material pair for the spool and the sleeve should allow precise manufacturing in order to provide low internal leakage; the gap between them should be around 1 μm.

The water-hydraulic test rig should also allow measurements of pressure, flow, temperature, internal leakage and mechanical movement at different functional positions. It should be able to maintain a constant, stable working temperature (between 20 and 80 °C), controllable filtering conditions and, for general purposes, a comparable working flow (settable from 1 to 35 lpm) and pressure (settable from 50 to 16 MPa). It should also have its own electronic regulation.

2.2. Design characteristics

Fig. 1a shows the hydraulic circuit block-diagram of the water-hydraulic test rig. It contains a standard, commercially available axial piston pump with a flow of 35 lpm [17] at 1450 r/min and a volumetric efficiency of 97%. This pump delivers water to the actual specimen, which is in our case a proportional 4/3 directional control water valve (Fig. 2). This valve was operated with a PC in a closed loop. On the connection port A (outlet pressure) of the proportional valve, we connected a stainless-steel tube to which the pressure transmitter and the fixed orifice with a diameter of 1.5 mm at the end were connected (Fig. 3). Fixed orifices were used to simulate the load at the ports A and B of the water proportional valve. The second branch on the connection B was the same as the first one. The water relief valve was set to 16 MPa. A centrifugal water pump was used to maintain a constant temperature (air cooler) and to enable off-line filtering. The pressures on the P and T connection ports of the water proportional valve were measured during the test using two pressure transmitters. A pressure-line water filter with a rating

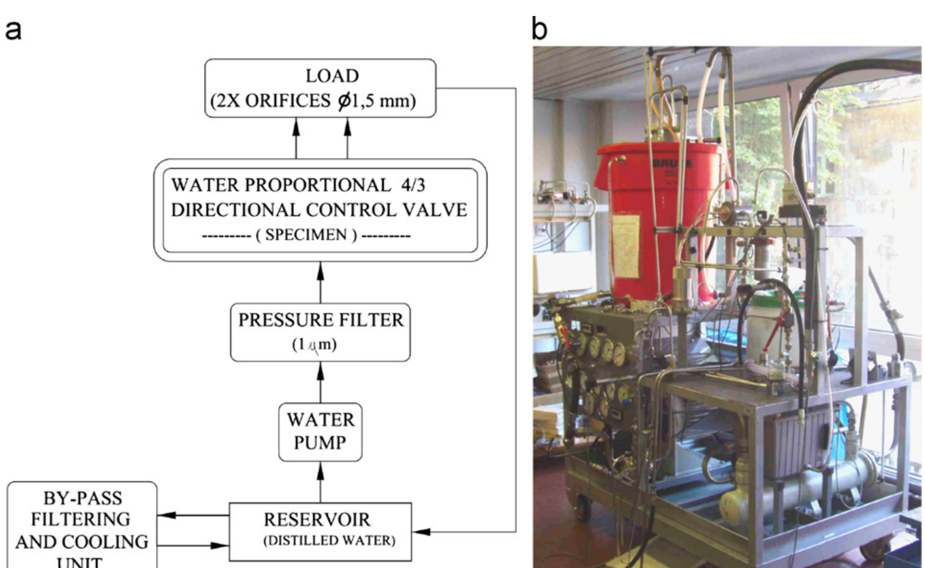

Fig. 1. (a) Hydraulic circuit block-diagram of the water test rig, (b) photo of test rig.