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Research on the water hydraulic pressure relief valve

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Abstract Water hydraulics is increasingly becoming a viable alternative to oil hydraulics due to its environmental sustainability. The leakage of water hydraulic components is one of the reasons why water hydraulics is not more widely used. One of the missing water hydraulic components is also the two- stage pressure relief valve. Various valve designs have been investigated. FEM and CFD analyses of the relief valve were performed. Some prototypes were made and tested in the pressure range of 50 to 200 bar at a maximum flow rate of 30 lpm. The functional characteristics of the valve were studied, and the influence of each component was determined. It was found that the manufacture of a two-stage water valve is technologically feasible with appropriate design adjustments.

Keywords: • water hydraulics • relief valves • internal leakage • numerical analyses • measurements •

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1   Introduction

Nowadays, we cannot imagine life without technology. It is present everywhere, in medicine, agriculture, forestry, food industry, automobile industry, construction, shipping, aviation etc. We use different principles for energy transmission in technology, from electrical, mechanical, pneumatic to hydraulic transmission. Hydraulic power transmission was used before our era when Ctesibius made the first hydraulic pump. The advantages of hydraulics are the simple design with standard components, the independence of location, the high-power density, the good dynamic behaviour, the simple conversion of rotational to translational movements, the simple change of direction, the stepless change of gear ratio, the simple overload protection, the simple parameter control, and the good possibilities of automation.

From then until the beginning of the 20th century, water was the only hydraulic fluid used. After 1906, mineral hydraulic oil began to gain acceptance due to its many advantages (Figure 1). It is still the most commonly used oil today with a market share of 85 % [1]. The main advantages of using mineral hydraulic oil are its very good lubricating properties, good sealing effect due to its high viscosity and corrosion protection. The disadvantages of using mineral oil are the risk of pollution of the natural environment and drinking water, the strong dependence of viscosity on temperature, the high price, etc.

In 1978, new research was initiated in United Kingdom [2] and Japan [3] on the possibility of using water as a hydraulic fluid. Since then, numerous research have been carried out in the field of water hydraulics [2], [4], [5] and many new components and systems have been developed [6].

Despite the aforementioned development, water hydraulics is still very little used. There are several reasons for this: higher cost of existing water hydraulic components compared to oil hydraulic, problems with freezing of water below 0° C, more expensive production and use of more expensive materials and lack of necessary water hydraulic components to make the whole hydraulic system.

One of the missing components is also pressure relief valve. Despite some research [7] and mass production of water hydraulic pressure relief valves [8], they are missing for flows up to 50 l/min and pressures up to 350 bar. Within the scope of this article, the development of the above-mentioned water-hydraulic two-stage pressure relief valve is presented.
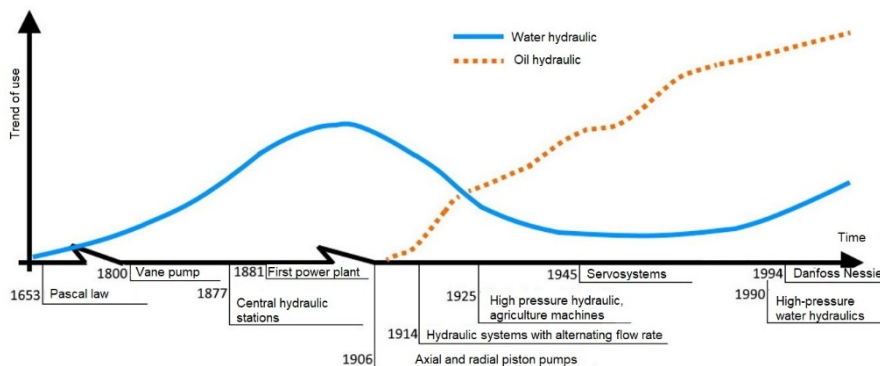
Figure 1: Trend of use of water hydraulics [4].

2 Water as hydraulic fluid

The most important properties of water as a hydraulic pressure medium are power transfer, lubrication, sealing, cooling, kinematic viscosity, compressibility, evaporation pressure, and air consumption [1], [5], [6]. Power transfer is the basic function of a hydraulic fluid. The hydraulic pump transfers the mechanical energy to the hydraulics, which transfers it with fluid through the hydraulic system to the actuators. Water has no significant differences in terms of power transfer compared to the most commonly used hydraulic mineral oil. Lubrication is an important property of a hydraulic fluid as it reduces the friction and wear in sliding contacts inside the hydraulic components. Water has very poor lubrication properties in the contacts of steel surfaces as it is in general used in oil hydraulics. Sealing, which is connected to the kinematic viscosity of the fluid, has an important role in low-gap sliding contacts inside the hydraulic components. Due to the significantly lower kinematics and the viscosity of the water compared to mineral hydraulic oil, the gaps in the water hydraulic components should be at least half the size. The kinematic viscosity of water is fifteen times lower than mineral oil (ISO VG 46 at 50 °C). The cooling properties of water are significantly better than those of mineral hydraulic oil. The compressibility modulus of water is $2.1 \ 10^5$ MPa, which is 46 % lower than for hydraulic mineral oil. A very important advantage of water is its availability everywhere in nature and its friendless to the environment (no pollution).

3   Development of pressure relief valve

Pressure-relief valves are primarily used to protect hydraulic systems against overloading, which can lead to failure of the hydraulic system [2], [7]. Almost all relief valves are setTable. For lower flows (in general up to 10 l/min) a one-stage pressure-relief valve is used; higher flows require a two-stage pressure-relief valve. A one-stage valve consists of a conical closing element, a spring, a seat and a valve body. A two-stage pressure-relief valve consists of a one-stage valve on top of its construction, while on the lower part of the valve there is a main body housing with a larger conical closing element and a spring. The advantage of a two-stage pressure-relief valve is good pressure-oscillation damping; the disadvantage is its slower response.

3.1   First design of the valve

A two-stage, water-hydraulics, pressure-relief valve was designed. Figure 2. shows the first tested concept. An external view of the assembled valve in shown on Figure 2a. A cross-section of the two-stage pressure-relief prototype valve is shown in Figure 2b.
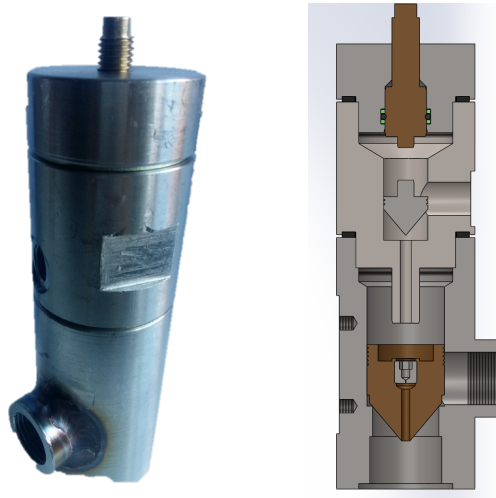

Figure 2: The first concept of WH pressure-relief valve: prototype (left), cross-section (Φ50 mm × 175 mm) (right).

The first concept of a two-stage valve was developed and measurements of its properties were performed (presented in the Results chapter). The first concept was tested with different material pairs (spool/housing). It turned out that the valve did not work as expected, mainly due to manufacturing inaccuracies. Therefore, we developed an improved valve concept.

3.2   The new design of the valve

At the second, improved design of the pressure relief valve (Figure 3), the next modifications were done:

- new housing without welded connector,
- new main spool,
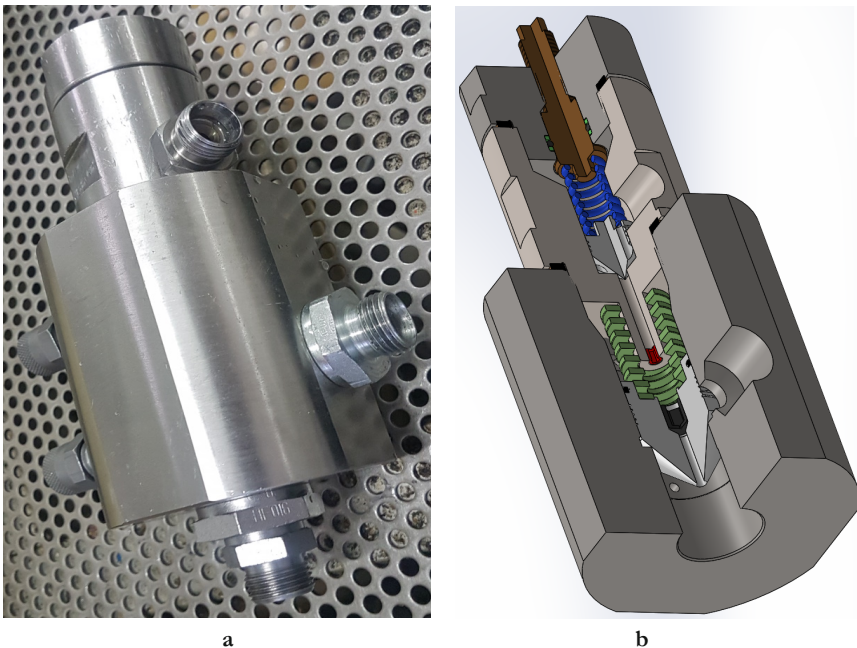- new control spool,
- new nozzle in the main spool.

a   b

Figure 3: The second design of water hydraulic pressure relief valve:
a) prototype, b) cross-section (Φ78 mm x 175 mm).

4   Numerical simulations

To compare the accuracy of the numerical analysis with the analytical calculations, simulations of the fluid flow through the fixed position of each of the spools were also performed. This chapter describes the process of performing an analysis. We started the CFD analysis process by fitting the 3d model in Solidworks. Due to the speed of the simulation and also the correctness of the finite element shape, the model should be simplified as much as possible before using it. Due to the asymmetric shape of the valve, we used a 3d model. Preliminary analysis has shown that the original model has backflow problems at the outlet. This problem is caused by vortices intersected by the boundary surface. The outlet location was therefore moved further away from the valve. We also accounted for changes in the geometry of the tube due to the connections as used in the actual assembly. The spring was excluded from the model due to its complex shape. The distance of the spool from the seat is defined by the distance relationship. The simplified model is used only to define the space occupied by the fluid. Mosaic and polyhedral meshes were used to construct the mesh. Due to the faster convergence of the solution, a polyhedral mesh was used for the final results. Three sides of equilateral elements were added at the contact of the fluid with the walls, allowing a more accurate inventory of the velocity profile near the wall. The inlet mass flow and the outlet pressure were defined in the model, which was zero in all cases. We neglected the pressure due to the height difference with the tank. An anti-slip condition was defined on the valve walls. After comparing the rescue models, the Transition k-kl-ω model was selected for use. The convergence data show the reliability and accuracy of the obtained results. The values depend on the quality of the network and all the settings related to boundary conditions, fluids, choice of rescue models, etc. In general, the residuals in the calculations should be less than 10-4, and for excellent results 10-5. The Transition k-kl-ω model was used because it achieves lower residuals. The success and speed of the rescue were affected by the low viscosity of the water and the associated occurrence of turbulence. Since a total of 18 simulations were performed (three positions of each of the two spools at three different flows), parameterization was used for acceleration. As a key result of the simulations, we defined the average pressure at the inlet face, which represents the pressure drop through the valve at a given flow. Figure 4 shows one of the final results.
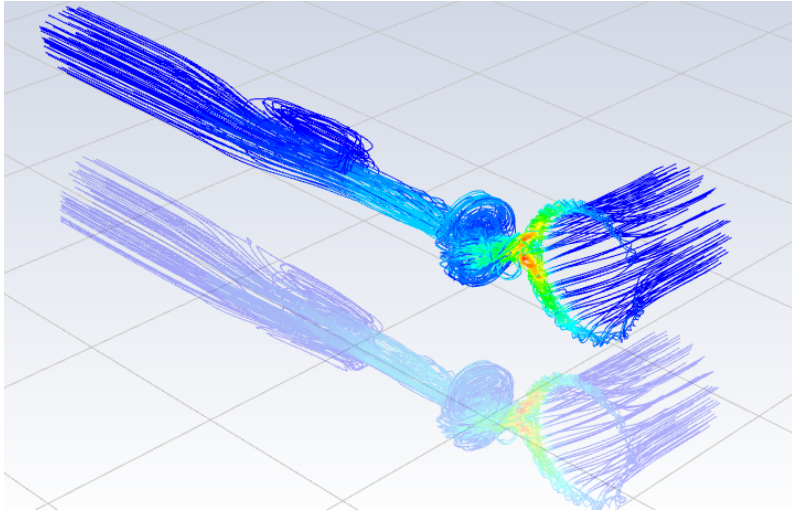
Figure 4: Streamlines from numerical calculations of flow through the valve.

5   Experimental results

All tests and measurements were performed on a dedicated water test rig (Figure 5). The test rig (Figure 6) consists of a high-pressure hydraulic pump, an electric motor, a water tank, a system pressure relief valve, an adjusTable throttle and measuring devices. In addition, there are other components installed on the trolley that were not used in these measurements. The test rig allows pressures up to 300 bar and a maximum flow rate of 30 l/min.
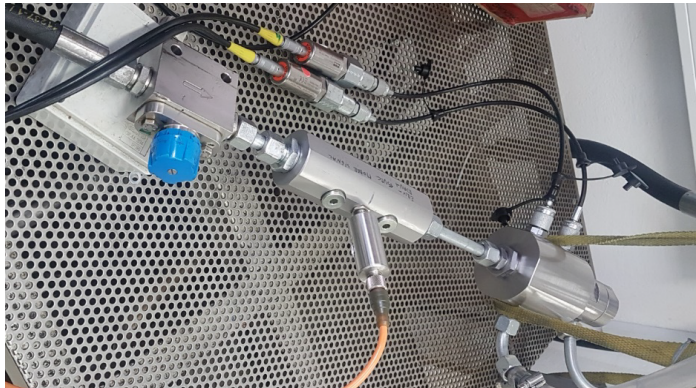

Figure 5: Water hydraulic test rig with specimen.

Water hydraulic test rig:
1 ... Electric motor
2 ... Water hydraulic pump
3 ... Unloading valve
4 ... Pressure relief valve
5 ... Flow control valve
6 ... Flow meter
7 ... Pressure sensor
8 ... Pressure sensor
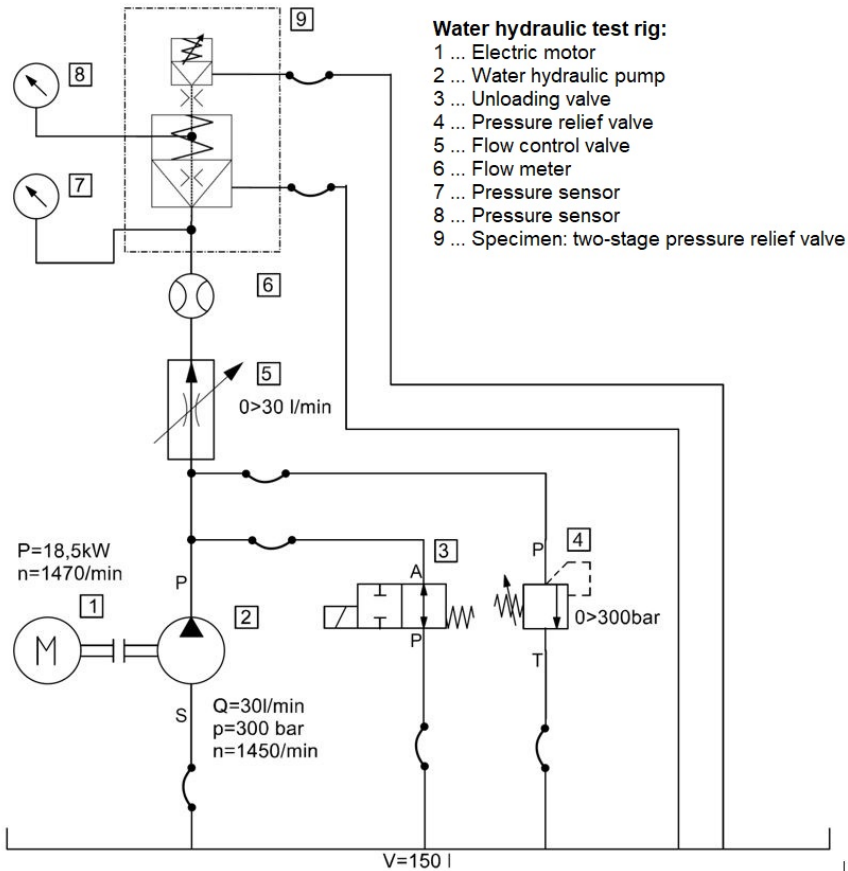9 ... Specimen: two-stage pressure relief valve

Figure 6: Hydraulic circuit of the water hydraulic test rig with specimen.

6   Results

The test and measurement results of the first prototype showed inadequate performance, so we systematically searched for the faults and produced an improved prototype.

6.1   The first prototype

Figure 7 shows the results of the measurement of the pressure-relief valve containing both spools of the POM polymer. The behaviour of the second configuration of the investigated pressure valve was like the first one. Also, during the second measurement an unaccepTable leakage occurred. The maximum pressure was only 64 bar at a leakage flow rate in the range of 6 litres/min.
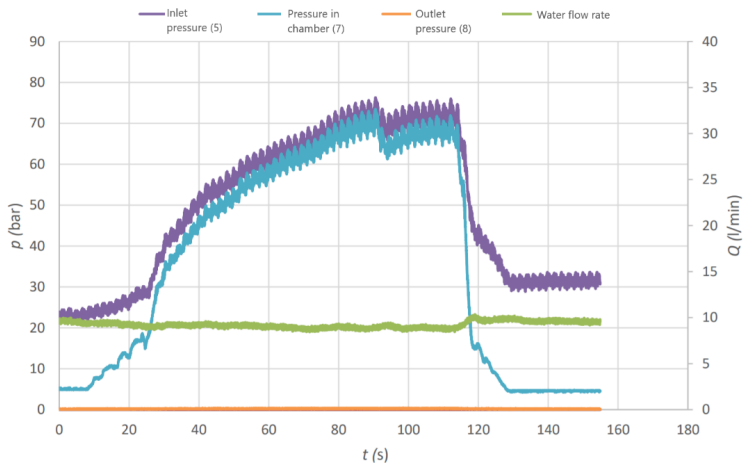

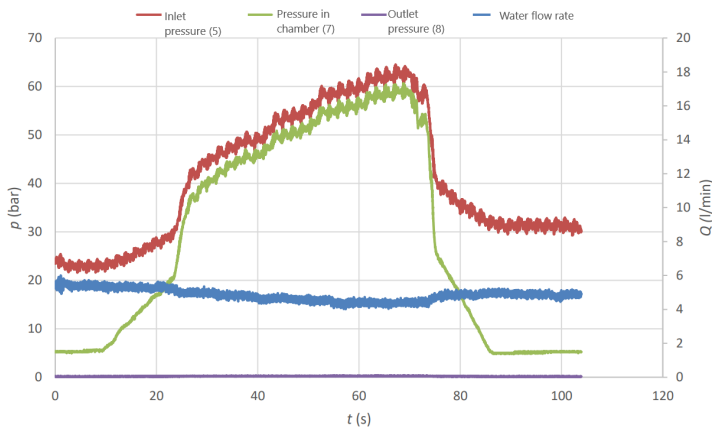**Figure 7: Results with closing conical elements made of PA66GF30.**

Figure 8: Results with closing the conical element made of POM.

6.2   The second prototype

In final assembly, with all improvements, the valve operates according to its function. Figure 9 shows the process of opening and reclosing the valve at a variable inlet pressure. The valve in the appropriate assembly shows stimulating performance characteristics. From the point of view of the opening process, important features are: Exceeding the set pressure, maintaining stability of the set pressure, internal leakage at an inlet pressure approaching the set pressure, and rapid reclosing of the valve when the inlet pressure falls below the set pressure. Figure 9 shows that in the most successful configuration, the pressure overshoot is less than 10 % of the set pressure. The variation in set pressure is accepTable and the setting does not change over time. Internal leakage at pressures near the setting is significant, but accepTable compared to a standard oil-seat valve. Lowering the inlet pressure abruptly reduces the flow as desired.
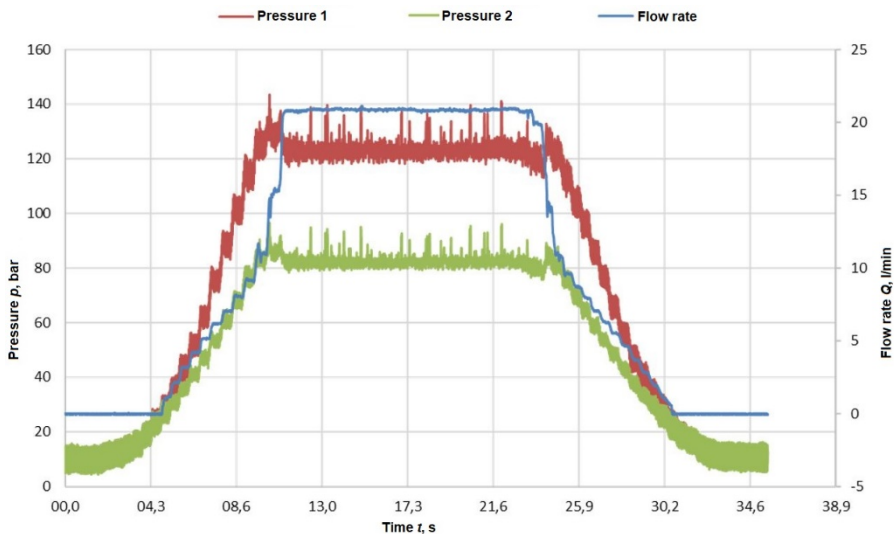

Figure 9: Measurement result of the second valve prototype.

6.3   Numerical simulation in comparison to measurement

The results of the numerical analysis are also accepTable. The results are consistent but differ from the measured values (Figure 10). We estimate that the error could be due to an incorrectly measured spool position during the measurements or to an unintended spool movement. Both the measurements and the numerical analysis show that the

sensitivity of the pressure drop to spool displacement is high. Therefore, even small measurement errors can lead to large deviations.
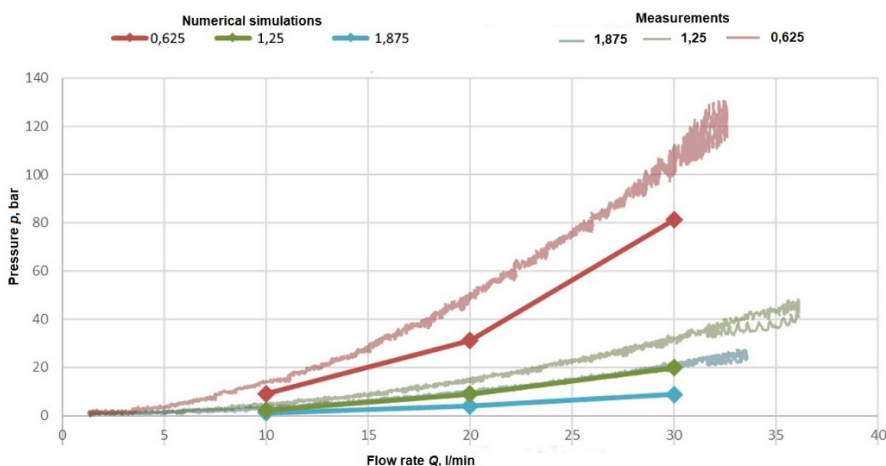

Figure 10: Comparison of the results of numerical calculations and measurements.

7   Conclusions

This paper shows the development of a two-stage water relief valve. The result is a working valve. We started by studying the existing, first prototype valve and the reasons why it did not work. We designed and manufactured new components. Throughout the development, we took measurements and monitored the success and effects of the interventions made. The measurements were also compared with the results of numerical and analytical calculations. After all necessary repairs were made to the valve, we isolated and demonstrated the effects of each of the components that make up a two-stage pressure relief valve with a series of measurements in which we replaced each element individually. Based on the findings from these measurements, we also performed measurements at various pressures, in the most appropriate valve composition.

The main results are:
1) A perfect seal was obtained at the seat of the main spool with a main spool made of polymer. The body was made by conventional turning, without additional technological processes.

2) The sealing of the main spool at the periphery was achieved by using O-rings adapted to the application. No increase in friction or wear of the O-ring was observed when the seal was used.

3) An additional orifice was necessary for proper operation. Installation drastically improved the stability of the valve.

4) Flow downstream of the spool seat must be unobstructed. By changing the geometry of the spool, we were able to get the control portion of the valve to operate properly and maintain the set pressure.

5) By replacing the prototype control section of the valve with a serial single stage valve, we found that the leakage and operation of the control section were accepTable.

6) We found that the valve operated properly in the range of 50 bar to 150 bar when properly assembled. At higher settings, there was a pressure fluctuation in the valve.

7) According to the results of the measurements, the choice of orifice has the most important influence on the operation. An orifice that is too large or too small will cause the valve to malfunction. The soft spring of spool can also cause malfunction of operation. The choice of spool springs does not bring significant differences in performance.

The main contribution of this work is to demonstrate that with suiTable design adjustments, it is possible to produce a satisfactorily operating two-stage water pressure relief valve using simple technological procedures.

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