Numerical and experimental determination of static characteristics of a pilot operated pressure relief valves

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Numerical and experimental determination of static characteristics of a pilot operated pressure relief valves: *In this article a mathematical model of pressure drop vs. flow depending for pilot operated pressure relief valve type 1502-PPT is developed. An experimental test stand is created for practical determination of the pressure drop vs. flow depending which confirm the mathematical model. The results of solving the mathematical model and experimental investigation are presented in two diagrams. A few directions for improving the static characteristics at the moment of opening of the main valve are given.*

Key words*: pilot-operated pressure relief valve, flow, pressure, static characteristics, mathematical model, experiment.*

INTRODUCTION

The pressure relief valve is a basic component in every hydraulic system. Its function is to limit maximal pressure in the system. Depending of the construction of the valve, there are two types of pressure relief valves: direct acting pressure relief valves and pilot operated pressure relief valves. Direct acting pressure relief valves are with limited application because of their bad static characteristics at high flow and pressure ranges. To avoid this disadvantage, a pilot operated pressure relief valves are introduced.

Many authors [5], [6], [7], [8], have investigated the characteristics of this type of valves and different mathematical models have been obtained which described their characteristics. In this article an attempt has been done, with contemporary mathematical approach, to determine the static characteristics of a specified pressure relief valve and its experimental confirmation.

PRINCIPAL OF OPERATION

On fig.1. a functional diagram of the specified pilot operated pressure relief valve is shown.

This valve can be observed as a system consisted of three subsystems: main valve 1, pilot valve 2 and fixed orifices (R_1 and R_2). In neutral position both pilot and main valves are closed under the influence of the springs 3 and 4, and there is a balance of forces at the closing element of the main valve 1. When inlet pressure p_1 will reach higher value than the preset spring force 4 of the pilot valve, the closing element of the pilot valve 2 is opening and through the orifices R_1 and R_2 beginning to flow some little amount of pilot flow q_y. The pressure p_3 in the upper part of the main valve is maintaining approximately constant by the pilot valve. With further increase of the inlet pressure p_1 the pressure drop $p_{1,3} = p_1 - p_3$ continues to increase up to:

$$p_{1,3} = \frac{F_{pr,o}}{A_1} = \frac{c_o \cdot h_o}{A_1}$$

at which the main valve is opening and the flow $q_1 = q_3 + q_y$ is flowing to the tank. By changing the flow q_1 the pressure drops $p_{1,2}$ and $p_{1,3}$ also change which leads to moving the closing element of the main valve 1. This provides constant pressure drop $p_{1,2}$ which is preset at the pilot valve. If the outlet port of the valve is directly connected to the tank, than pressure p_2 will not act at the closing element of the pilot valve 2. In that case the pressure relief valve is going to provide a constant pressure at the inlet port p_1, not pressure drop $p_{1,2}$.

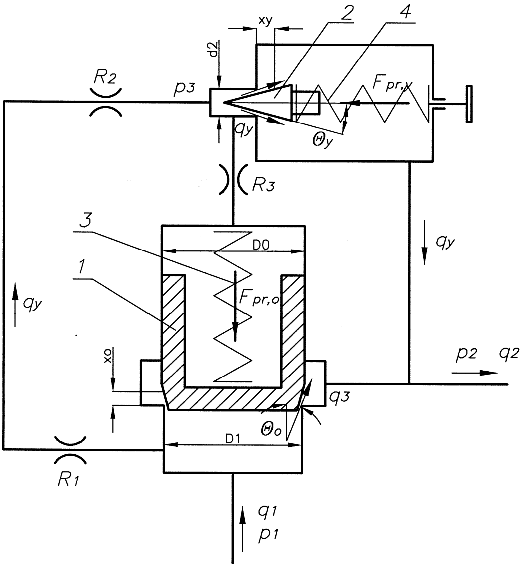

Fig.1. Functional diagram of pilot operated pressure relief valve

MATHEMATICAL MODEL OF THE STATIC CHARACTERISTICS

The static characteristics of the pilot operated pressure relief valves are described with following equations [3], [4]:

- *Flow equation across the pilot valve*

$$q_y = \mu_y \cdot d_2 \cdot \pi \cdot x_y \cdot \sin(\theta_y) \cdot \sqrt{\frac{2}{\rho} \cdot p_{3,2}} \qquad (1)$$

where: $q_y \left[\frac{m^3}{s}\right]$- flow across the pilot valve; μ_y-flow coefficient of the pilot valve; $d_2\ [m]$-seat diameter of the pilot valve; $x_y\ [m]$-displacement of the closing element of the pilot valve; $\theta_y [^\circ]$-angle of flowing of the oil at the pilot valve, $\rho\ [\frac{kg}{m^3}]$-density of the oil; $p_{3,2} = p_3 - p_2\ [Pa]$-pressure drop in the pilot valve.

- *Balance of forces acting on the closing element of the pilot valve*

$$c_y \cdot (h_y + x_y) = p_{3,2} \cdot A_2 - r_y \cdot x_y \cdot p_{3,2}$$

or

$$x_y = \frac{p_{3,2} \cdot A_2 - c_y \cdot h_y}{c_y + r_y \cdot p_{3,2}} \qquad (2)$$

where: $A_2 [m^2]$-area of the seat of the pilot valve; $c_y\ [\frac{N}{m}]$-spring constant of the pilot valve; $h_y\ [m]$-previous deformation of the spring of the pilot valve; $r_y = 2 \cdot \mu_y \cdot \pi \cdot d_2 \cdot \sin(\theta_y) \cdot \cos(\theta_y)\ [m]$-hydrodynamic force coefficient of the pilot valve.

If we solve the equations (2) and (1), the static characteristic of the pilot valve will be obtained:

$$q_y = \mu_y \cdot d_2 \cdot \pi \cdot \sin(\theta_y) \cdot \sqrt{\frac{2}{\rho} \cdot p_{3,2}} \cdot \frac{p_{3,2} \cdot A_2 - c_y \cdot h_y}{c_y + r_y \cdot p_{3,2}} \qquad (3)$$

- *Pressure drop at the fixed orifices*

$$p_{1,3} = R_{1l} \cdot q_y + R_{1m} \cdot q_y^2 + R_{2l} \cdot q_y + R_{2m} \cdot q_y^2$$

$$p_{1,3} = (R_{1l} + R_{2l}) \cdot q_y + (R_{1m} + R_{2m}) \cdot q_y^2 = R_l \cdot q_y + R_m \cdot q_y^2 \qquad (4)$$

where: $p_{1,3} = p_1 - p_3$ $[Pa]$-pressure drop at the pilot chain, $R_l = R_{1l} + R_{2l} = \frac{128 \cdot \nu \cdot \rho \cdot l_1}{\pi \cdot d_{dr1}{}^4} + \frac{128 \cdot \nu \cdot \rho \cdot l_2}{\pi \cdot d_{dr2}{}^4}$ $[\frac{Pa \cdot s}{m^3}]$-linear hydraulic resistance in the orifices R_1 and R_2; $R_m = R_{1m} + R_{2m} = \xi_1 \cdot \frac{\rho}{2 \cdot A_{dr1}^2} + \xi_2 \cdot \frac{\rho}{2 \cdot A_{dr2}^2}$ $[\frac{Pa \cdot s^2}{m^6}]$-local quadratic resistance in the orifices R_1 and R_2; $A_{dr} = \frac{d_{dr}^2 \cdot \pi}{4}$ $[m^2]$-area of the orifice R_1 or R_2; d_{dr1} $[m]$-diametar of the orifice R_1; $l_1 [m]$-length of the orifice R_1; d_{dr2} $[m]$-diametar of the orifice R_2, $l_2 [m]$-length of the orifice R_2; ν $[\frac{m^2}{s}]$-viscosity of oil.

- *Pressure drop at the main valve*

$$p_{1,2} = p_{1,3} + p_{3,2} \qquad (5)$$

where: $p_{1,2} = p_1 - p_2$ $[Pa]$-pressure drop at the main valve

- *Balance of forces acting on the closing element of the main valve*

$$p_{1,3} \cdot A_o - p_{1,2} \cdot \Delta A = c_o \cdot (h_o + x_o) + r_o \cdot x_o \cdot p_{1,2}$$

or

$$x_o = \frac{p_{1,3} \cdot A_o - p_{1,2} \cdot \Delta A - c_o \cdot h_o}{c_o + r_o \cdot p_{1,2}} \qquad (6)$$

where: A_o $[m^2]$-area of the closing element of the main valve; ΔA $[m^2]$-unbalanced area at the closing element of the main valve; h_o $[m]$- previous deformation of the spring of the main valve; $x_o [m]$- displacement of the closing element of the main valve; $r_o = 2 \cdot \mu_o \cdot \pi \cdot D_1 \cdot \sin(\theta_o) \cdot \cos(\theta_o) [m]$- hydrodynamic force coefficient of the main valve; μ_o- flow coefficient of the main valve; D_1 $[m]$-diameter of the seat of the main valve; θ_o [°]-angle of flowing of the oil at the pilot valve.

- *Flow across the main valve*

$$q_3 = \mu_o \cdot D_1 \cdot \pi \cdot x_o \cdot \sin(\theta_o) \cdot \sqrt{\frac{2}{\rho} \cdot p_{1,2}} \qquad (7)$$

where: q_3 $[\frac{m^3}{s}]$-flow across the main valve.

- *Flow through pilot chain*

$$q_1 = q_3 + q_y \qquad (8)$$

The static characteristics of the pilot operated pressure relief valves are fully described by the equation (1) to (8).

For the specified pressure relief valve with the following parameters:

- seat diameter of the pilot valve $d_2 = 5\ [mm]$,
- seat diameter of the main valve $D_1 = 24{,}3\ [mm]$,
- closing element diameter of the main valve $D_o = 25\ [mm]$,
- spring constant of the pilot valve $c_y\ = 15\ [N/mm]$,
- spring constant of the main valve $c_0 = 61\ [N/mm]$,
- fixed orifices diameter $d_{dr} = 1\ [mm]$,
- viscosity of oil $v = 46\ [cSt]$.

shown on fig.2., numerical static characteristic is shown on fig.3.

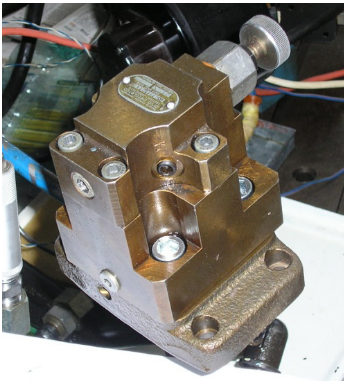

Fig.2. Specified pressure relief

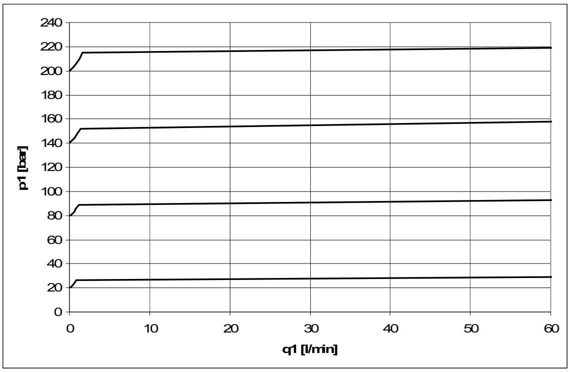

Fig.3. Numerical static characteristic valve

EXPERIMENTAL RESULTS

Basic aim of this investigation was to determine the true static characteristic of the pilot operated pressure relief valve and to compare it with the numerical characteristic. On the diagram of the fig.5 is shown the experimental static characteristic of the specified valve. From the diagrams at fig.3. and fig.5 it is notable identical pressure vs. flow depending. By this fact, the applied mathematical methodology for calculation of static characteristics of pressure relief valves, is confirmed.

On fig.4 a test stand for experimental determination of the true static characteristic of the specified pressure relief valve is shown.

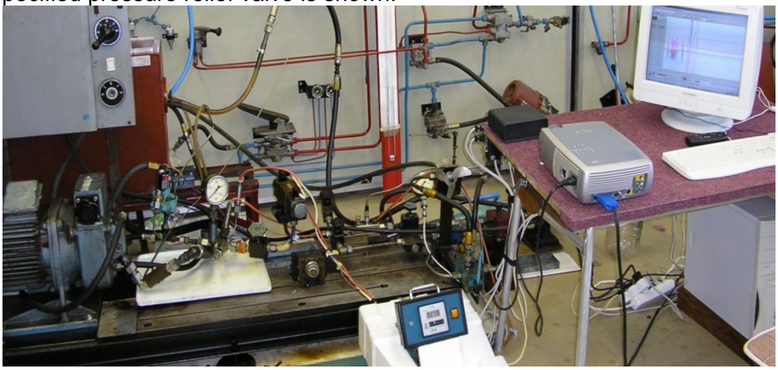

Fig. 4. Experimental test stand

CONCLUSION

The experimental static characteristic has confirmed proposed methodology for numerical obtaining of the static characteristic. But, from the both diagrams generally some features of the static characteristics of pilot operated pressure relief valves can be noticed.

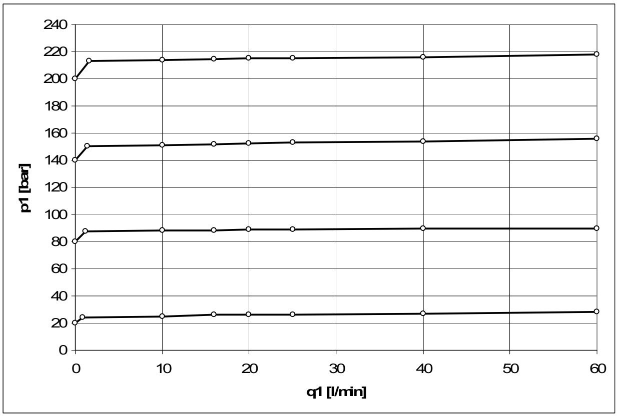

Fig. 5. Experimental static characteristic

The main advantage of the pilot operated pressure relief valves is its low slope, or low statism at higher flow and pressure ranges from the moment of opening of the main valve, compared with the direct acting pressure relief valves. This low statism primarily is due to low spring constant of the main valve. But, main disadvantage of this valves is their high (relative) error of the control value (pressure p_1) at the beginning, to the moment of opening of the main valve. From the both diagrams a difference between the moment of opening of the pilot valve and moment of opening of the main valve is notable. An appropriate designing modification on some details of the valve like orifice diameter and seat diameter of the pilot valve can reduce the pressure difference of opening of the pilot and main valve, but still to keep good dynamic characteristics. It is important to say that some modification can improve static characteristics, but at the same time it can influence negative to dynamic characteristics. So, usually static and dynamic characteristics are investigated simultaneously to get optimal performance of the valve. As inlet pressure p_1 (or pressure drop $p_{1,2}$) increase, pilot flow q_y also increases. Usually, for different designs of pilot operated pressure relief valves, pilot flow q_y moves around $0.5 - 1.6\ [\frac{l}{min}]$.,

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Докладът е рецензиран.