Improvement of the Static Characteristics of Pilot Operated Pressure Relief Valves

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Abstract - Theoretical and experimental investigations of the static characteristics of pilot operated pressure relief valves is presented in this article. A mathematical model of pressure drop vs. flow depending of pilot operated pressure relief valves is developed. An experimental test stand was created for experimental investigation of the static characteristics and compared with each other which confirm the mathematical model. The results of solving the mathematical model and experimental investigation are presented in few diagrams. A few directions for improvement of the static characteristics are given, especially at the moment of opening of the main valve. Advantages and disadvantages of the static characteristics are discussed.

Keywords: flow, mathematical model, pressure, relief valve, static characteristics

I. INTRODUCTION

Main feature of the static characteristic of the pressure relief valves is its slope, i.e. increasing of the adjusted value of the pressure when increasing the flow through the valve. This means that there is an error in the static characteristic. As an example, at fig.1 schematic layout of the theoretical static characteristic of direct operated and pilot operated pressure relief valve is shown [1].

With blue color a static characteristic of direct operated pressure relief valve is presented. The valve opens at pressure value p_1 and with increasing of the inlet flow through the valve the pressure increasing up to p_0 when the entire flow q_0 passes through the valve. As can be seen, there is a deviation from the ideal static characteristic and at flow q_0 through the valve, the error of the static characteristic is $\Delta p_1 = p_0 - p_1$. This error is caused by the deformation of the spring and the hydrodynamic force of the streaming flow [1].

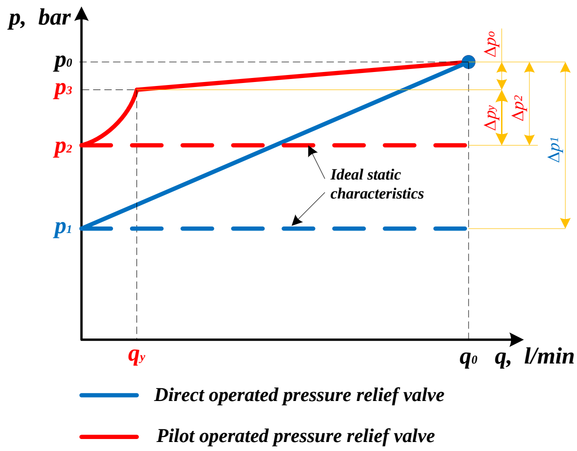


Figure 1. Static characteristic of pressure relief valves

On the same figure a theoretical static characteristics of pilot operated pressure relief valve is shown. At the static characteristic of pilot operated pressure relief valves, two zones are noted: the first one for inlet flow from *0* to q_y when only pilot valve is opened and the second one for inlet flow from q_y to maximal flow q_0 when both the pilot and the main valve are opened [2],[3].

Increasing the system pressure in the hydraulic circuit, at pressure value p_2 the pilot valve opens and a little amount of pilot oil flows through it. The main valve is still closed. The pressure in front of the valve continues to increase parabolic until the pressure value p_3 is reached when the main valve opens. At the second zone the pressure increases linearly from p_3 until p_0 as inlet flow increasing up to the maximal value q_0. Total error of the valve is sum of the error of the pilot valve $\Delta p_y = p_3 - p_2$ and of the error of the main valve $\Delta p_0 = p_0 - p_3$ i.e. $\Delta p_2 = \Delta p_y + \Delta p_0$.

Comparing the static characteristics of direct operated and pilot operated pressure relief valve it can be seen that the accuracy of the adjusted pressure is higher with pilot operated pressure relief valve, i.e. $\Delta p_2 << \Delta p_1$. A disadvantage of the static characteristic of pilot operated pressure relief valve is pressure difference between opening of the pilot and the main valve at first zone of the static characteristic i.e. error of the static characteristic at the beginning of opening of the valve. This error reduces the accuracy of the set pressure value. This error also increases energy loss and converted it into heat which leads to increasing of the temperature of the oil and decreasing the efficiency coefficient of the entire hydraulic system [2].

Additional decrease of the slope of the static characteristics of the conventional pilot operated pressure relief valves and additional reducing of the difference between the pressures of opening of the pilot valve and the main valve, $\Delta p_y = p_3 - p_2$, can be obtain with built-in compensating control piston in front of the pilot valve, presented in this article. [8], [9].

In [6] the authors have shown theoretically and experimentally the advantage of the pilot operated pressure relief valves-lower slope of the static characteristic of the valve. But it cannot be clearly seen the pressure difference between opening of the pilot and the main valve. In [5] a special attention has been taken to the influence of the hydrodynamic reaction force to the valve characteristics. Also, the author has investigated different designs of the resistance orifices in the pilot line to improve the characteristics of the valve. Most comprehensive theoretical mathematical model is presented in [4], in details explained and included all the factors influencing the quality of the static characteristics. This model was developed for valve with “pilot flow through main valve”. In this study this model has been little modified for valve with conventional design, mostly used nowadays. Another mathematical model of the static characteristics of pilot operated piston type pressure relief valve is presented in [10]. Experiments have proved the proposed model. Then fluid force exerted on a poppet of the pilot valve has been neglected, whereas that on a piston has been taken into consideration.

To improve the static characteristic of the valve the built-in compensating control piston with resistance orifice in it in the pilot line is taken into consideration. Expressions for the pressure-flow coefficient of the valve without compensating control piston and with compensating control piston are obtained numerically to determine the pressure-flow coefficient of the valve. The influence of the diameter of the compensating control piston to the static characteristics of the valve is presented, as well. This study has experimentally proved the validity of this model.

II. FUNCTIONAL DIAGRAM OF THE VALVE

On Fig. 2 a functional diagram of the pilot operated pressure relief valve with conventional design is shown.

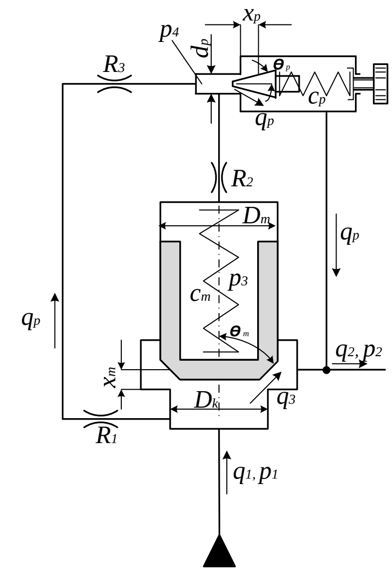


Figure 2. Functional diagram of conventional design of the pilot operated pressure relief valve

This valve can be observed as a system consisted of three subsystems: main valve, pilot valve and fixed orifice R_1. In neutral position both pilot and main valves are closed under the influence of the springs, and there is a balance of forces at the poppet of the main valve. When inlet pressure p_1 reach the value of the preset spring force of the pilot valve, the poppet of the pilot valve is opening and through the orifices R_1 and R_3 beginning to flow some little amount of pilot flow q_p. The pressure $p_3 \equiv p_4$ 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 $p_{1,4} = p_1 - p_4$ continues to increase until the main valve opens and the flow $q_1 = q_3 + q_p$ is flowing to the tank.

III. MATHEMATICAL MODELING

Static characteristic of a pressure relief valve shows deviation of the inlet pressure in front of the valve p_1 as a control parameter, depending on the inlet flow q_1 as an inlet parameter .

To model the static characteristics of the studied valve, the following assumptions are made in developing the mathematical model:

- The hydraulic fluid is ideal, nonviscous and incompressible. This assumption is close to reality under most conditions.
- The tank pressure and the pressure in the outlet line is constant and $p_2 = 0$.
- The flow rates through the throttling orifices of the valve are of high Reynolds number.

For theoretical determination of the static characteristics a methodology presented in [4] is used.

The static characteristics of the pilot operated pressure relief valves are described analysing the balance of forces acting on the pilot and the main poppet and the flow equation through the pilot valve, main valve and the orrifices.

The flow rate q_y passing through the throttling area of the pilot valve is given by the following equation:

$$q_p = C_{d,p} \cdot d_p \cdot \pi \cdot x_p \cdot sin\,\theta_p \cdot \sqrt{\frac{2}{\rho} \cdot p_4} \qquad (1)$$

where $C_{d,p}$ – the discharge coeficient of the opening area of the pilot valve; d_p – the diameter of the seat of the pilot valve; x_p – the displacement of the pilot valve; θ_p – the angle of the poppet of the pilot valve and p_4 – the pressure drop in front of the pilot valve.

Analysing the balance of forces acting on the poppet of the pilot valve, the motion of the pilot poppet can be described by the following equation:

$$c_p \cdot (h_p + x_p) = p_4 \cdot A_p - r_p \cdot x_p \cdot p_4,$$

or

$$x_p = \frac{p_4 \cdot A_p - c_p \cdot h_p}{c_p + r_p \cdot p_4} \qquad (2)$$

where A_p - the area of the seat of the pilot valve where the pressure p_4 acts; c_p – the spring constant of the pilot valve spring; h_p – the previous spring deformation of the pilot valve; $r_p = 2 \cdot C_{d,p} \cdot \pi \cdot d_p \cdot \sin\theta_p \cdot \cos\theta_p$ - the hydro-dynamic force coefficient of the pilot valve.

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

$$q_p = C_{d,p} \cdot d_p \cdot \pi \cdot sin\,\theta_p \cdot \sqrt{\frac{2}{\rho} \cdot p_4} \cdot \frac{p_4 \cdot A_p - c_p \cdot h_p}{c_p + r_p \cdot p_4} \qquad (3)$$

The pressure drop through the fixed orifices in the pilot line is given by the following equation:

$$p_{1,4} = R_l \cdot q_p + R_m \cdot q_p^2 \qquad (4)$$

where $p_{1,4}$ – the pressure drop through the orifices R_1 and R_3; $R_l = R_{1l} + R_{3l}$ - the linear hydraulic resistance in the orifices R_1 and R_3;

$R_m = R_{1m} + R_{3m}$- the local resistance in the orifices R_1 and R_3.

The total pressure drop through the main valve can be expressed by the following equation:

$$p_{1,2} = p_{1,4} + p_{4,2} \qquad (5)$$

Analysing the balance of forces acting on the poppet of the main valve, the motion of the main valve poppet can be described by the following equation:

$$p_{1,4} \cdot A_k - p_{1,2} \cdot \Delta A = c_m \cdot (h_m + x_m) + r_m \cdot x_m \cdot p_{1,2}$$

or

$$x_m = \frac{p_{1,4} \cdot A_k - p_{1,2} \cdot \Delta A - c_m \cdot h_m}{c_m + r_m \cdot p_{1,2}} \qquad (6)$$

where x_m – the displacement of the poppet of the main valve; A_k - the area of the seat of the main valve; $\Delta A = A_m - A_k$ - the unbalanced area at the popet of the main valve; h_m – the previous deformation of the spring of the main valve; c_m – the spring constant of the main valve spring; $r_m = 2 \cdot C_{d,m} \cdot \pi \cdot D_k \cdot \sin\theta_m \cdot \cos\theta_m$ - the hydrodynamic force coefficient of the main valve; $C_{d,m}$ - the flow coefficient of the main valve; D_k - the diameter of the seat of the main valve; θ_m - the angle of flowing of the oil in the main valve.

The flow rate q_3 passing through the throttling area of the main valve is given by the following equation:

$$q_3 = C_{d,m} \cdot D_k \cdot \pi \cdot x_m \cdot \sin\theta_m \cdot \sqrt{\frac{2}{\rho} \cdot p_1} \quad (7)$$

The continuity equation at inlet port of the valve can be expressed by the equation:

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

The static characteristics of the pilot operated pressure relief valves are fully described by the equation (1) to (8). From equations (1) – (8) theoretically can be expressed the pilot flow (9) at the moment of opening of the main valve and by the iterative procedure can be calculated by the equation:

$$q_{p,mo} = \sqrt{\frac{p_{1,mo} \cdot \varphi + \frac{c_m \cdot h_m}{A_k} - (R_{1l} + R_{3l}) \cdot q_{p,mo}}{R_{1m} + R_{3m}}} \quad (9)$$

where $q_{p,mo}$ – the pilot flow at the moment of opening of the main valve; $p_{1,mo}$ – the pressure in front of the valve at the moment of opening of the main valve; $\varphi = {}^{\Delta A}/_{A_k}$ - geometric parameter of the valve.

According to equation (9), the pilot flow directly depends on the geometric parameter of the valve φ and the resistance in the pilot orifices R_1 and R_3.

The pressure in front of the valve at the moment of opening of the main valve is given by the following equation:

$$p_{1,mo} = \frac{1}{1-\varphi}\left(p_{1,op} + \frac{c_m \cdot h_m}{A_k} + \frac{x_p \cdot (c_p + r_p \cdot p_{4,op})}{A_p}\right) \quad (10)$$

where $p_{1,op} = {}^{c_p \cdot h_p}/_{A_p}$ – the perrssure in front of the valve at the moment of opening of the pilot valve; $p_{4,op}$ – the pressure in front of the pilot valve at the moment of opening of the pilot valve.

IV. EXPERIMENTAL AND THEORETICAL STATIC CHARACTERISTICS

A pressure transducer type *HM17* manufactured by *BoschRexroth* was used for pressure measurement. For displacement of the valve a position sensor manufactured by *BoschRexroth* was used. The measurement instruments were previously calibrated. The data are stored in the computer through 14 bit data acquisition card NI USB-6009 manufactured by *National Instruments.*

The subject of investigation was *Denison* pressure relief valve type *R4V 06*, shown on Fig. 3 [7].

The parameters of the specified pressure relief valve are: $d_p = 5\,mm$, $c_p = 250\,\frac{N}{mm}$, $C_{d,p} = 0.8$, $\nu = 34\,cSt$, $\rho = 890\,\frac{kg}{m^3}$. $d_{dr1} = d_{dr3} = 0.8\,mm$, $l_{dr1} = l_{dr3} = 1\,mm$, $D_k = 28.5\,mm$, $D_m = 28\,mm$, $c_m = 7\,\frac{N}{mm}$, $h_m = 16.5\,mm$, $C_{d,m} = 0.8$.

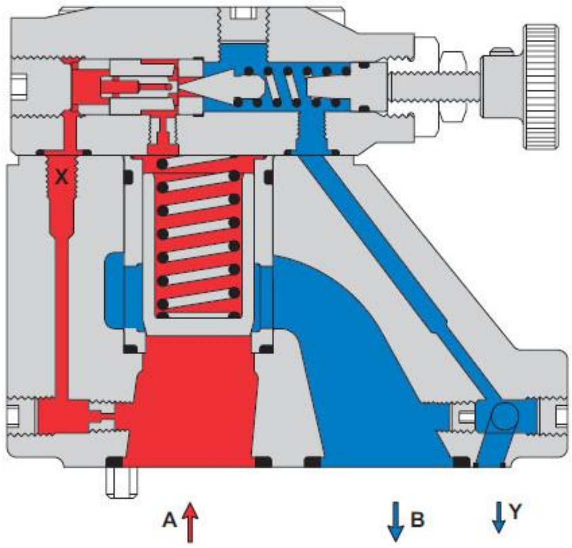
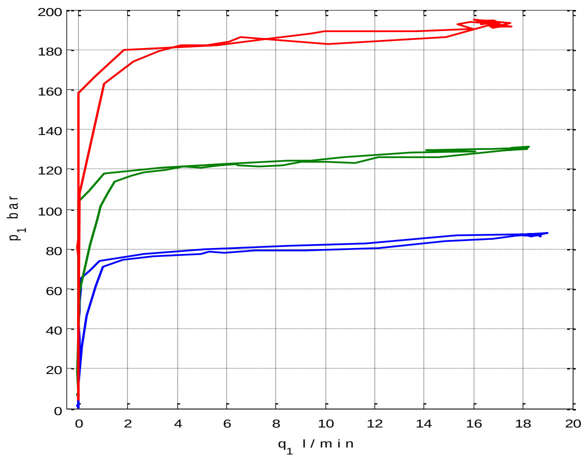


Figure 3. The studied pressure relief valve

Theoretical and experimental static characteristics are presented on Fig. 4. On the right side of the figures zoomed detail around the values of opening of the pilot and the main valves are presented.



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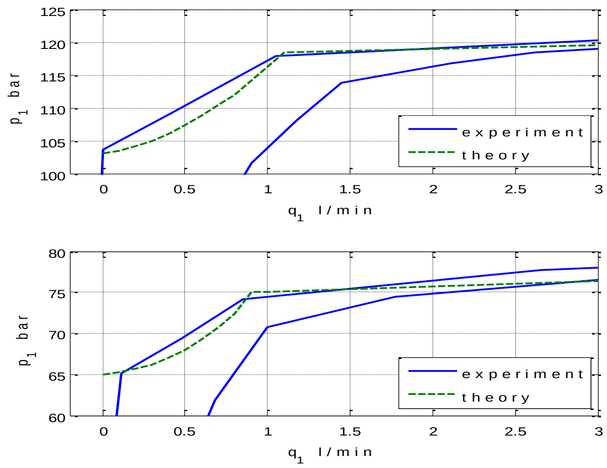


b)

Figure 4. Theoretical and experimental static characteristic of the studied valve

Fig. 4 shows the static characteristics of the studied valve. The beginning of the static characteristic, at a lower flow rate is shown in Fig. 4-b. It can be seen that the static characteristic is characterized by the pressure difference between the pressure of opening of the pilot and the main valve. At lower pressures this difference is of the order of 10 bar. While at higher pressure this difference is of the order of 15 bar. At even higher pressures, this difference is even higher - about 20 bar. The pilot flow at the moment of opening the main valve is from 0.8 *l/min* at lower pressure - about 65 bar, 1.1 *l/min* for pressure about 100 bar, to 2 *l/min* at higher pressure – about 160 bar.

If the unbalanced area of the main valve poppet is higher, the mistake of the controlled pressure at the beginning of opening of the main valve is even higher. The experimental static characteristic of the studied with higher φ is presented in Fig. 5.

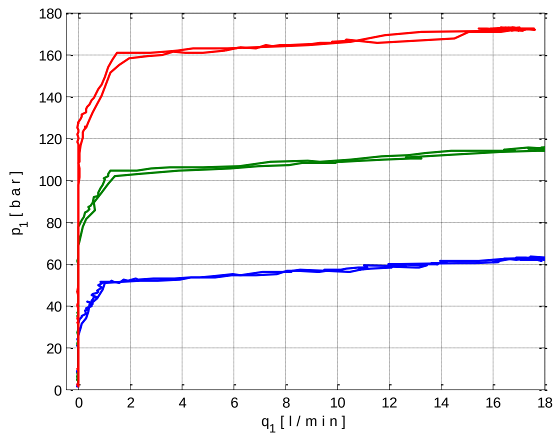


Figure 5. Experimental static characteristic of the studied valve with higher φ

On the presented figures it is clearly visible that there is an error in the static characteristic of pilot operated pressure relief valves, especially at the beginning of opening of the valve. This error can be reduced with decreasing of the geometric parameter of the main valve spool φ or with inserting of a compensating control piston in front of the pilot valve.

V. INFLUENCE OF THE COMPENSATING CONTROL PISTON ON THE STATIC CHARACTERISTICS

On Fig. 6 a functional diagram of the pilot operated pressure relief valve with compensating control piston is shown.

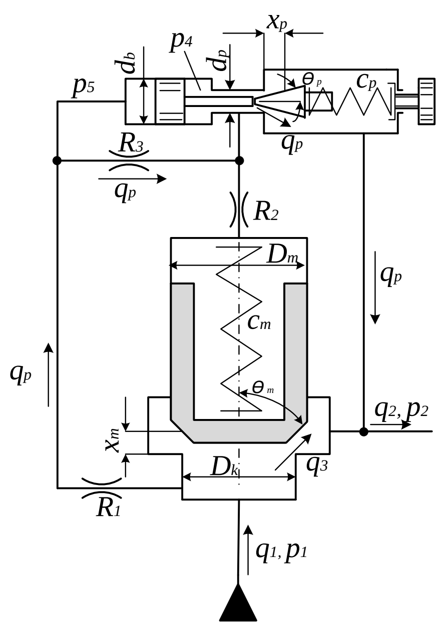


Figure 6. Functional diagram of pilot operated pressure relief valve with compensating control piston

The mathematical model of the static characteristics of the pilot operated pressure relief valve with compensating control piston is slightly modified. Taking into account the compensating control piston in front of the pilot valve, the equation (2) in converted into:

$$c_p \cdot (h_p + x_p) = p_4 \cdot A_p + p_{5,4} \cdot A_b - r_p \cdot x_p \cdot p_4,$$

or

$$x_p = \frac{p_4 \cdot A_p + p_{5,4} \cdot A_b - c_p \cdot h_p}{c_p + r_p \cdot p_4} \qquad (11)$$

Where $p_5 -$ the pressure in front of the compansating control piston; A_b – the section area of the compansating control piston.

Combining the equations (1) and (11), the static characteristic of the pilot valve with compensating control piston is given by the equation:

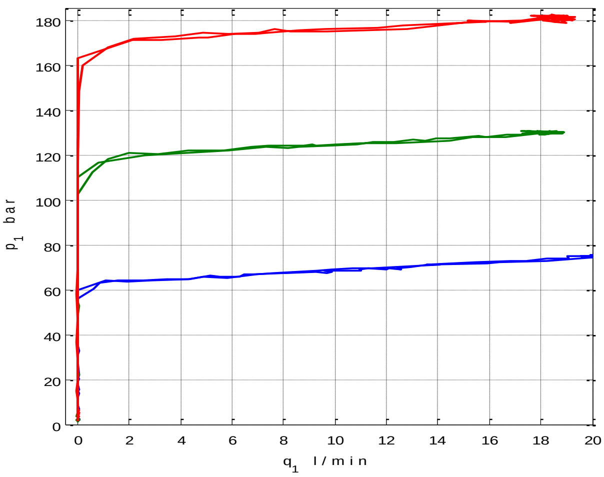
$$q_p = C_{d,p} \cdot d_p \cdot \pi \cdot \sin\theta_p \cdot \sqrt{\frac{2}{\rho} \cdot p_4} \cdot \frac{p_4 \cdot A_p + p_{5,4} \cdot A_b - c_p \cdot h_p}{c_p + r_p \cdot p_4} \qquad (12)$$

Then, the equation for the pressure in front of the valve at the moment of opening the main valve is converted into the following equations:

$$p_{1,mo} = \frac{1}{1-\varphi}\left(p_{1,op} + \frac{c_m \cdot h_m}{A_k} + \frac{x_p \cdot (c_p + r_p \cdot p_{4,op})}{A_p} - \frac{A_b}{A_p} \cdot \left(R_{3l} \cdot q_{p,mo} + R_{3m} \cdot q_{p,mo}{}^2\right)\right) \qquad (13)$$

Comparing the equations (10) and (13), the pressure in front of the valve at the moment of opening of the main valve with compensating control piston (eq. 13) is lower than the pressure in front of the valve at the moment of opening of the main valve without compensating control piston for the value of the $\frac{A_b}{A_p} \cdot \left(R_{3l} \cdot q_{p,mo} + R_{3m} \cdot q_{p,mo}{}^2\right)$. Increasing the diameter of the compensating control piston, the value of this expression is higher, and the error of the static characteristic is lower.

Experimental confirmation of this statement is presented on the following figures.



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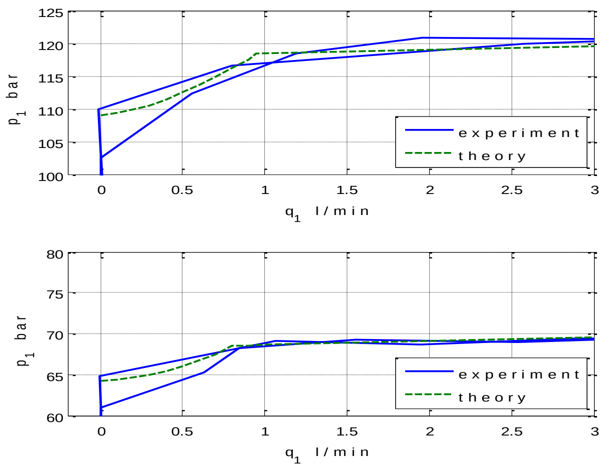
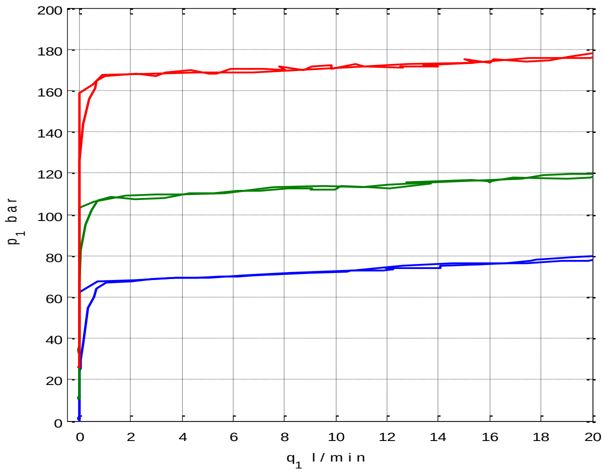


b)

Figure 7. Theoretical and experimental static characteristic of the studied valve with compensating control piston of $d_b = 5.5\ mm$



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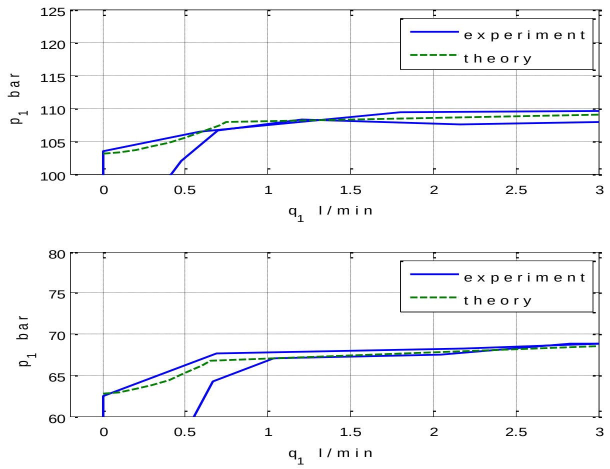

b)

Figure 8. Theoretical and experimental static characteristic of the studied valve with compensating control piston of $d_b = 6\ mm$

On Fig. 7 the static characteristic of the pilot operated pressure relief valve with compensation control piston of diameter $d_b = 5.5\ mm$ is shown. On Fig. 8 the static characteristic of the pilot operated pressure relief valve with compensation control piston $d_b = 6.0\ mm$ is shown. A comparison between experimental and theoretical static characteristic of the specified pressure relief valve, for two pressure settings-around 60 bar and around 100 bar, with compensation control piston $d_b = 5.5\ mm$ (Fig. 7-b) and with compensation control piston $d_b = 6.0\ mm$ (Fig. 8-b) is shown zoomed in for lower flows through the valve. It can be noticed that the presence of the compensating control piston reduces the pilot flow and the pressure difference, according to (13). The experimental investigation of the valve proved the proposed mathematical model for theoretical determination of the static characteristics of the pilot operated pressure relief valves with and without compensating control piston.

VI. CONCLUSION

The static characteristics of the pilot operated pressure relief valves are characterized by a large relative error at the moment of opening of the pilot and the main valve, ie. with a large relative difference between the opening pressures of the pilot and the main valve. This disadvantage of the static characteristic of the pilot operated pressure relief valves can be reduced by various design modifications of some geometric parameters of the valve. This paper presents an improvement of the static characteristic of the pilot operated pressure relief valve by inserting a control piston in front of the control valve.

Experimental investigation proved the theoretical examination (10 and 13) that inserting a compensating control piston in front of the pilot valve can reduce the pilot flow and the pressure difference between opening of the pilot valve and the main valve. The error at the beginning of opening of the valve can be reduced if the relative ratio of the areas of the compensating piston and the seat of the pilot valve is increased. Fig. 4 shows that a valve without compensating control piston has pressure error of around 10 bar at 60 bar pressure setting and around 15 bar at 100 bar pressure setting. Inserting the compensating control piston with d_b=*5.5 mm*, the pressure error is around 4 bar at 60 bar pressure setting and 8 bar at 100 bar pressure setting (Fig. 7). Inserting the compensating control piston with d_b=*6.0 mm*, the pressure error is around 3 bar at 60 bar pressure setting and 5 bar at 100 bar pressure setting (Fig. 8). Theoretical investigation says that higher diameter of the compensating control piston d_b can much more reduce the pressure error (13), but it is possible the pressure-flow coefficient of the static characteristic of the valve to be negative in that case. According to equation (9) and (10) additional improvement – decreasing of the pilot oil flow and pressure difference between opening of the pilot and the main valve can be achieved by minimizing the geometric parameter φ of the main valve. It is experimentally proved by the fig.5.

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