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Research of deformation of valve throttling characteristics under gravitational influence in hydraulic systems

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Abstract: Control valve operation influences the efficiency of hydraulic systems. The deformation of the throttling characteristics in control valves by hydraulic resistances in a single-circuit regulated circuit is well studied. Nevertheless, there are other significant reasons for the deformation. This paper will focus on gravitational influences. The results show significant deformations. They are described by multiplying the valve authority by 0.6-1.7.

Keywords: hydraulic system, throttling characteristic, valve authority, natural pressure

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Introduction

In all heating, ventilation and air conditioning (HVAC) installations, as well as water supply etc. there are hydraulic systems. In such systems, a combination of a central pump control and valve control at terminal units is used. For proportional control of radiator heat flow or stable water mixing in water supply, throttling characteristics of valves are very important. If pressure loss in a valve is not enough, it is possible to obtain the worst on-off control, which cannot change the flow rate smoothly.

The Eurointegration of Ukraine with other world countries has significantly increased the energy efficiency of buildings (Gumen et al., 2017; Shapoval et al., 2017). Nevertheless, there are still too many systems remaining from the 20th or the early beginning of 21st century. When deciding to renovate such systems, the effect of each action needs to be known. Therefore, simulating the deformation of the throttling characteristics is important.

1. Literature review and problem statement

Usually deformation of the throttling characteristics of valves is analysed using a simple single-circuit regulated circuit (r.c.) with a constant pressure drop between the beginning and the end of the circuit (Betschart, 2016; Pyrkov, 2009; Ross, 2009). The beginning and the end of the regulated circuit in a closed system may be connected to a pressure drop stabilizer or relief valve or to a pump with stable pressure etc. The end of the regulated circuit of an open hydraulic system may have an outflow ending in open-air or a room. The outflow opening is acted on by atmospheric pressure. At the stem position h [mm or revolutions], the flow rate is G [kg/s]. In a rough-pipe regime, pressure loss of the regulated opening in the valve (index v,o), of the valve (index v), of k-th pipe (index k) serially connected to the valve in the regulated circuit, and of the complete regulated circuit (index $r.c.$) is, correspondingly [Pa]:

$$\Delta p_{v,o} = S_{v,o}G^2; \Delta p_v = S_v G^2; \Delta p_k = S_k G^2; \Delta p_{r.c.} = S_{r.c.}G^2 = (S_v + \Sigma S_k)G^2 \quad (1)$$

where S_i is the specific characteristic of hydraulic resistance [Pa/(kg/s)^2] of the corresponding element (system). At the the fully opened valve, the flow rate is G_s [kg/s]. Corresponding pressure losses [Pa] $\Delta p_{v,s,o}$, $\Delta p_{v,s}$, $\Delta p_{r.c.,s}$ should be found by the equation (1) substituting G for G_s [kg/s]. The numeric characteristic of the valve control efficiency in a single-circuit regulated circuit is at full external authority (Betschart, 2016; Pyrkov, 2009; Ross, 2009): $a^+ = \Delta p_{v,s,o}/\Delta p_{r,c}$. The authority decrease causes significant controlability degradation to the on-off control.

If the valve has a current stem position h [mm or revolutions], the stem position at full open h_s [mm or revolutions], the flow factor of the regulated opening $k_{v,o}$ [m^3/(h·bar$^{1/2}$)], flow factor of the regulated opening at full open $k_{v,s,o}$ [m^3/(h·bar$^{1/2}$)] and ideal (at $a^+ = 1$) throttling characteristic $G / G_s = k_{v,o}(h/h_s)/k_{v,s,o}$, then the deformed flow characteristic by hydraulic resistances should be found (Betschart, 2016) from the following equation, obtained from the equations (1):

$$G/G_s = \left(1 + a^+ \cdot \left(\left(k_{v,o}(h/h_s)/k_{v,s,o}\right)^{-2} - 1\right)\right)^{-1/2} \quad (2)$$

Thus, the influence of hydraulic resistances in single-circuit regulated circuits with a constant density fluid (gas) has been researched at a suitably scientific level.

If the density of liquid or gas (heat carrier or coolant) changes in a hydraulic system (for example, due to temperature change), the available pressure is dependent on the density change because of gravitational influences, whose numeric characteristic is gravitational acceleration g [m/s^2]. The flow rate change and the density change are usually dependent because of heat transfer dependence on the flow rate [kg/s]. Therefore, at a constant pressure difference [Pa] between the beginning and the end of the regulated circuit, the available pressure [Pa] is a function of the valve stem position. V. Konstantinova introduced in (Konstantinova, 1976) the „factor of hydraulic characteristic”

$$\Gamma = \Delta\, p_{n,s} / \left(\Delta p_{n,s} + \Delta p_{pump}\right) = \Delta\, p_{n,s} / \Delta\, p_{r.c.,s} \tag{3}$$

where: $\Delta p_{n,s}$ - natural pressure of the system [Pa] at calculated conditions (in this work, it is assumed a fully opened valve); ΔP_{pump} - pump pressure [Pa] (assumed as constant); $\Delta p_{r.c.s}$ - total pressure drop [Pa] (in the regulated circuit at the fully opened valve). Nevertheless, systematic research into throttling characteristics under natural pressure influences has not been found.

Computational fluid dynamics (Barbarelli et al., 2017; Conceicao, 2016; Mirkov et al., 2015; Mirkov & Rasuo, 2015; Pajayakrit, 1997; Skanavi, 2008; Yang, 2017) allows simulation of such a process. However, it requires a lot of computational time and is not so efficient for complex systems. Effective simulation may be based on known efficient methods used in hydraulic system design (Staroverov & Shiller, 1990).

2. Mathematical model of natural pressure influence

When considering a simple single-circuit regulated circuit with one heat source and one heat exchanger/radiator (Fig. 1). Vertical distance between the two components is H [m]. Between the beginning of the r.c. (the medium temperature is θ_S [°C]) and the end r.c.′ (the medium temperature is θ_R [°C]), there is constant pump pressure drop $\Delta p_{pump} = \text{const}$ [Pa] (the regulated circuit condition). Nevertheless, the variable natural pressure Δp_n [Pa] has an additive effect and disturbs the regulated circuit. The following term will be used: „disturbed regulated circuit" which describes a regulated circuit with constant initial pressure drop and additional changeable influences that are dependent on the valve position.

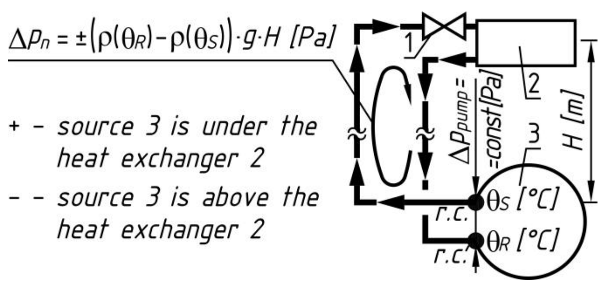

Fig. 1. Disturbed regulated circuit: 1 - valve; 2 - heat exchanger (for example, radiator); 3 - heat or cold source

If the available pressure $\Delta p_n + p_{pump}$ [Pa] is constant, but the valve stem position is changeable, then equation (2) is acceptable. If the available pressure changes without operation of the valve, the flow rate changes proportionally to the square root of the pressure by the equation (1). If the pressure drop and the valve position changes simultaneously, the equations (1)-(3) and the gravitational pressure equation (Fig. 1) gives the following result:

$$\frac{G}{G_s}=\left(\frac{(\Delta p_{pump}+\Delta p_n)/(\Delta p_{pump}+\Delta p_{n,s})}{1+a^+\cdot\left(\left(k_{v,o}(h/h_s)/k_{v,s,o}\right)^{-2}-1\right)}\right)^{\frac{1}{2}}=\left(\frac{1+\Gamma\left((\Delta p_n/\Delta p_{n,s})-1\right)}{1+a^+\cdot\left(\left(k_{v,o}(h/h_s)/k_{v,s,o}\right)^{-2}-1\right)}\right)^{\frac{1}{2}}=$$
$$=\left(\frac{1+\Gamma\cdot\left(\left[\frac{\rho(\theta_R)-\rho(\theta_S)}{\rho(\theta_{R,s})-\rho(\theta_{S,s})}\right]-1\right)}{1+a^+\cdot\left(\left(k_{v,o}(h/h_s)/k_{v,s,o}\right)^{-2}-1\right)}\right)^{\frac{1}{2}}\approx\left(\frac{1+\Gamma\cdot\left(\left[\frac{\theta_R^\gamma-\theta_S^\gamma}{\theta_{R,s}^\gamma-\theta_{S,s}^\gamma}\right]-1\right)}{1+a^+\cdot\left(\left(k_{v,o}(h/h_s)/k_{v,s,o}\right)^{-2}-1\right)}\right)^{\frac{1}{2}} \tag{4}$$

where: $\theta_{S,s}$, $\theta_{R,s}$ - temperature of the supply and return medium at the heat (cold) source [°C] at a fully opened valve (in most of cases, $\theta_{S,s} = \theta_S$), γ - approximate power. By putting the main denominator (the valve influence) of the expression (4) as one (no valve operation), this gives the known equation (Konstantinova, 1976). Additionally, an equation for density $\rho(\theta)$ [kg/m^3] is necessary. For gases (such as in air or exhaust gas heating systems), the Clapeyron equation is used ($\gamma = -1$ using all temperatures θ in K instead of °C). For water, Table 1 can be used.

Table 1. Approximation of water density

Range of all temperatures [°C] in the equation (4)	Approximation of the VDI data (Betschart, 2016) for water, kg/m^3	Recommended (optimized) value of the power γ achieving minimum deviation of the equation (4)	Deviation of the expression in square brackets, %
20-100	$\rho(\theta) = 1001 - 0.015906\,\theta^{1.7149} \pm 0.09$	1.743	2.83
10-100	$\rho(\theta) = 1000.52 - 0.01289\,\theta^{1.7585} \pm 0.18$	1.8958	11.96
0-100	$\rho(\theta) = 1000.14 - 0.01007\,\theta^{1.811} \pm 0.35$	Deviation is too high	

Finally, the relation between the return temperature θ_R [°C] and the flow rate G [kg/s] is necessary. In post-socialist countries, there is a complex expression for heat transfer [W] of radiators after substitution of equations (9.1), (9.3), (9.5), (9.6) in (Staroverov & Shiller, 1990):

$$\Phi=\Phi_{nom}\cdot\left(\frac{0.5\cdot(\theta_S+\theta_r)-\theta_I}{\Delta\theta_{T,nom}}\right)^{1+n}\left(\frac{G}{G_{nom}}\right)^{p}\cdot b\cdot c\cdot[1-a_{bt}(\theta_S-\theta_R)]=$$
$$=c_p\cdot G\cdot(\theta_S-\theta_R) \tag{5}$$

where: Φ - heat transfer at calculation conditions [W]; Φ_{nom} - nominal heat transfer at test conditions or in datasheet [W]; θ_I - internal temperature [°C]; $\Delta\theta_{T,nom} = 0.5\,(\theta_{s,nom} + \theta_{r,nom}) - \theta_{int,nom}$ - nominal temperature drop [°C] in test conditions or by the datasheet (at $\theta_s = \theta_{s,nom}$, $\theta_r = \theta_{r,nom}$, $\theta_{int} = \theta_{int,nom}$ [°C]); G_{nom} - nominal flow rate [kg/s]; b - amendment for barometric pressure; n, p and c - experimental parameters of the radiator; a_{bt} - parameter for medium movement direction „from bottom to top”, otherwise $a_{bt} = 0$; c_p - isobar specific heat of medium [J/(kg·K)].

Instead of nominal conditions, it is possible to use any conditions (such as at the fully opened valve) with known parameters.

Accepting $c \approx$ const, $p \approx 0$ (for radiators $p = 0.02$, but for convectors it is significant), and $a_{bt} = 0$, the following equations are obtained:

$$\begin{cases} \left((2 - A_r)\left(\frac{\Phi}{\Phi_S}\right)^{\frac{1}{1+n}} - 2\right) \cdot \frac{G}{G_S} + A_r \cdot \frac{\Phi}{\Phi_S} = \\ = \frac{G}{G_S} \cdot \left((2 - A_r) \cdot \left(\frac{G}{G_S} \cdot \frac{\theta_S - \theta_R}{\theta_{S,s} - \theta_{R,s}}\right)^{\frac{1}{1+n}} - 2\right) + \\ + A_r \cdot (G/G_S) \cdot (\theta_S - \theta_R)/\left(\theta_{S,s} - \theta_{R,s}\right) = 0, \qquad if\ \theta_R > \theta_I; \\ \Phi/\Phi_S = (G/G_S) \cdot (\theta_S - \theta_I)/\left(\theta_{S,s} - \theta_{R,s}\right), \qquad if\ \theta_R \leq \theta_I \text{by the 1}^{\text{st}} \text{ equ.,} \end{cases} \tag{6}$$

where $A_r = (\theta_S - \theta_{R,s}) / (\theta_S - \theta_I)$ is a-factor for radiators (or heat exchangers, as it will be shown) (Betschart, 2016). For a numeric solution of the first equation (6), the universal root isolation interval is $G/G_s \leq \Phi/\Phi_s \leq 1$.

In the book (Betschart, 2016), there is a simpler equation for all heat exchangers used in EU countries. Using the right part of the equation (5) at $c_p \approx$ const:

$$\frac{\Phi}{\Phi_S} = \left(1 + A \cdot \frac{1 - (G/G_S)}{(G/G_S)}\right)^{-1} = \frac{G}{G_S} \cdot \frac{\theta_S - \theta_R}{\theta_S - \theta_{R,s}} \tag{7}$$

where A is a-factor for any heat exchanger. For radiators, the work (Betschart, 2016) recommends $A = A_r^{1/2}$, but the results are very different from the equation (6) and may be checked for misprints. At a closed valve, the water cools to the internal temperature $\theta_{R,min} = \theta_I$ [°C]. This paper suggests substituting the recommended a-factor and $\theta_R = \theta_I$ [°C] to the equation (7). The solution (except $G = 0$) of the equation (7) is

$$A = \left(\frac{\theta_{S,s} - \theta_{R,s}}{\theta_S - \theta_R} - \frac{G}{G_S}\right) \Big/ \left(1 - \frac{G}{G_S}\right); \lim_{G/G_S \to 0} A = \frac{\theta_{S,s} - \theta_{R,s}}{\theta_{S,0} - \theta_I} \tag{8}$$

where $\theta_{S,0}$ is the temperature [°C] of the supply medium at a closed valve. Because in the equation (7) $A =$ const is assumed, the correct formula for the a-factor is the right part of the equation (8). Therefore, the correct a-factor at $\theta_S =$ const is $A = A_r = (\theta_S - \theta_{R,s}) / (\theta_S - \theta_I)$. For other heat exchangers see (Betschart, 2016).

The equations (4) at $\theta_s = \theta_{s,100}$ [°C] using the a-factor:

$$\frac{G}{G_S} \approx \left(\frac{1 + \Gamma \cdot \left(\frac{\left(\frac{\theta_{R,s}}{\theta_S}\right)^{\gamma} - \left(1 - \frac{1 - (\theta_{R,s}/\theta_S)}{(G/G_S) + A \cdot (1 - (G/G_S))}\right)^{\gamma}}{1 - (\theta_{R,s}/\theta_S)^{\gamma}} \right)}{1 + a^{+} \cdot \left(\left(k_{v,o}(h/h_s)/k_{v,s,o} \right)^{-2} - 1 \right)} \right)^{\frac{1}{2}} \tag{9}$$

The equation (7) gives a very similar result to (5) using the last expression for a-factor in most cases. Nevertheless, the equation (6) gives the return temperature $\theta_r = \theta_{int}$ [°C] at some critical value $G_0/G_{100} > 0$, dependant on the supply temperature θ_S [°C] and the radiator size. Closing the valve below G_0/G_{100} cause a state, at which the medium fully cools in the radiator, and the bottom part of its surface does not take part in the heat exchange. The heat transfer [W] is proportional to the related flow rate below G_0/G_{100} (ideal characteristic). This result is more adequate. However, for rough calculations, it is possible to use the equation (7), because this range of G/G_{100}, $G - \Phi$ characteristics is sufficiently close to linear.

If chemical reactions are running in the system, in equation (4) θ means (instead of temperature [°C]) the parameters that determine the density ρ [kg/m^3] in the system simulated. The equation (7) may be replaced by the equation (equation system) that connects the parameter θ and the flow G [kg/s].

3. Discussion of the results

The resulting throttling characteristic (computed in SciLab) by the equation (9) is similar to the throttling characteristic at some authority value a'^{+}. It will be called the „equivalent authority of the control valve". It has been found by the method of least square and described using an amendment a_e, which can be called „equivalent authority of gravitational pressure influence":

$$a_e = a'^{+}/a^{+} \tag{10}$$

It has low dependency on the full external valve authority at $a^{+} = 0.0001$-1 (Fig. 2). Its range is 0.6-1.7. Figure 2 allows engineering estimation of the throttling characteristic.

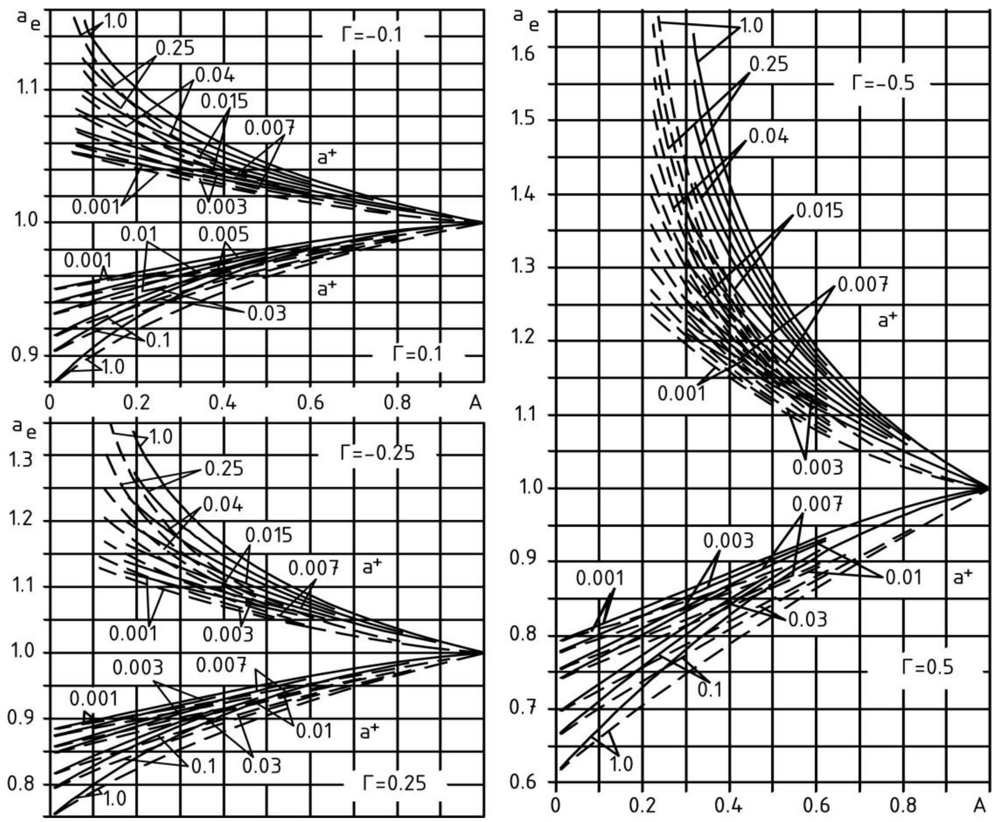

Fig. 2. Equivalent authority of the natural pressure influence a_e at a-factor A, full external authority of the valve a^+, and the factor of hydraulic characteristic Γ for

$$0.1 \le 1 - \frac{1-(\theta_{R,s}/\theta_S)}{A} \le 0.9:$$

dashed - lower boundary of the range of a_e, solid - upper boundary of the range of a_e

Conclusions

Hydraulic resistance is not the only cause of deformation in the throttling characteristics of valves in hydraulic systems. Natural pressure can significantly disturb a regulated circuit as well: a valve can operate as its authority differs 0.6-1.7 times from the full external authority. The most influencing factors on equivalent authority under natural pressure influences are the a-factor of the heat exchanger, full external authority, and the hydraulic characteristics of the system.

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Badania odkształceń charakterystyk dławienia zaworów pod wpływem grawitacji w układach hydraulicznych

Streszczenie: Praca zaworów regulacyjnych wpływa na sprawność systemów hydraulicznych. Odkształcenie charakterystyki dławienia zaworów sterujących spowodowane oporem hydraulicznym w jednoobwodowym obiegu regulowanym było przedmiotem wielu badań, tym niemniej istnieją jeszcze inne istotne przyczyny tego odkształcenia. W artykule analizowano przede wszystkim wpływy grawitacyjne. Analiza wykazała, że wpływ ten skutkuje znaczącymi deformacjami charakterystyki, co można opisać, mnożąc autorytet zaworu przez współczynnik 0,6-1,7.

Słowa kluczowe: układ hydrauliczny, charakterystyka dławienia, autorytet zaworu, ciśnienie naturalne