Control Valves - Modeling and Simulation

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Abstract: - The paper presents the researches of the authors in the modeling and the simulation of the control valves. The control systems with the control valves are complex structures and non-linear characteristics because the construction and the hydraulic phenomena associated of control valves. The authors have elaborated a mathematical model for the control valve. The model may be utilized to verify the work characteristic of the control valve for all operating points. The paper has four parts. First part describes the structure of the control valve. The second part contains the control valve model elaborated by the authors. The elements of the model are: the centrifugal pump model, the pipe model, the intrinsic and the work model of the control element. The third part is destined to elaboration of the simulation program. In the last part, the authors have presented and have analyzed the numerical results of the simulation.

Key-Words: - model**,** control valve, hydraulic system, pump, pipe, numerical simulation

1 Introduction

The control valve represents an important element of the control systems. The control valve is a non-linear element, characterized by the complexity of the mechanical construction and the hydraulic phenomena.

One important problem of the control engineers is the work characteristic of the control valve. This problem forces the control engineers to model and simulate the control valves. The fundament of the control valve's mathematical modeling is represented by [1, 2].

The model of the control valve is used into mathematically model of the control system. If the control system is equipped by centrifugal pump, the numerical modeling of the control valves is an actual problem [3, 4]. Usually, the authors present the solutions associated to the operational characteristic of the control valve determined by using the simplifying hypothesis, which consider that the pipe drop pressure is not modified.

The authors of this paper have focused the researches in the domain of the numerical modeling and simulation of the control valves into control system equipped by centrifugal pumps.

The first part of the researches has been presented in the papers [5, 6]. In the present article, the authors have continued the development and numerically solved of the control valve model.

2 Control valve – element of the control system

The control valve is an element of the control system and it is the most widespread control element in the field of chemical and petrochemical industry. The industrial control valve contains an electronic-pneumatic converter, a pneumatic actuator with membrane and a control element with a seat, to see the structure presented in figure 1.

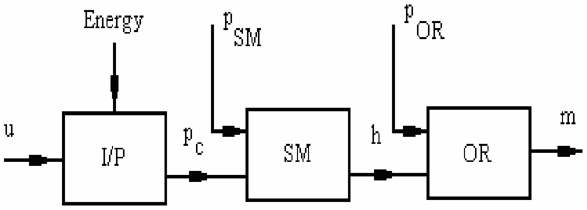


Fig. 1. The structure of the control valve

The significance of the variables and the subsystems: *I/P* –electro-pneumatic converter; *SM* – actuator; *OR* – control element; *u* – electrical signal command; p_c – pneumatic signal command; *h* – the stroke of the actuator; p_{SM} – disturbances associated to the actuator; p_{OR} – disturbances associated to the control element.

For the control system, the control valve is considered a mono-variable system, the input is the *u* command of the controller and the output is the manipulated variable *m*, associated to the process.

Many factories made the control valves characterized by many constructive tips, by standardized flow module and geometric dimension. An example of the industrial control valve is presented in figure 2 [7].

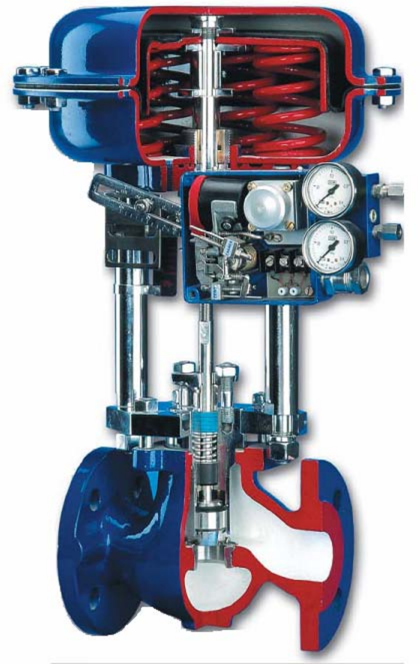


Fig.2. The control valve made of the Pre-Vent [7].

3 The model of the control valve in hydraulic systems

The authors have elaborated a mathematical model of control valve. It is based on the following elements: the model of the centrifugal pump; the model of the pipe; the work characteristic model of the control element; the intrinsic characteristic of the control element and the energetic balance of the hydraulic system [1, 3, 4, 5 6]. The model is defined by the diagram presented in figure 3. The input of the control valve's mathematical model is the *h* stroke of the actuator and the output is the *Q* flow which goes through the valve.

The intern variables of the model are: the flow module of the control valve K_v, the pump output pressure P_0,, the drop pressure of the control valve ΔP_v, the drop pressure of the pipe ΔP_p and the pressure of the exit of the pipe P_{out}.

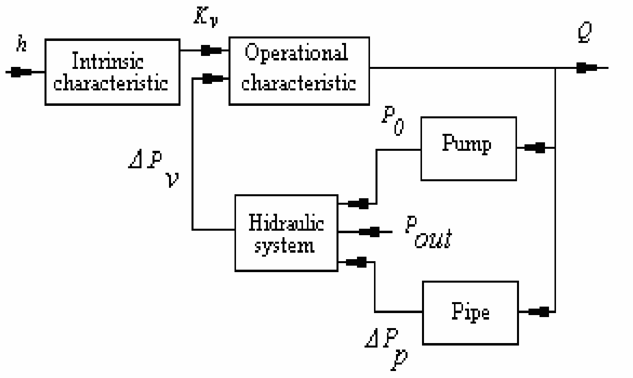


Fig. 3. The model of the control valve in hydraulic systems

3.1 The model of the centrifugal pump

For the chemical and oil refining industry, the most usually hydraulic power source is the centrifugal pump. In figure 4 is presented a usual centrifugal pump and the various pressure-flow rate characteristics.

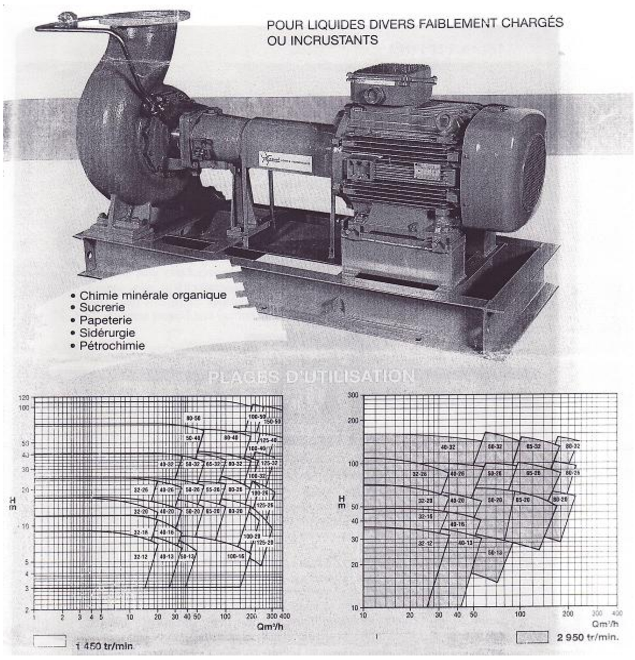


Fig. 4. The centrifugal pumps and the pressure-flow rate characteristics

The mathematical model of the centrifugal pump may be approximated using the following equation:

$$P_0 = a_0 + a_1 Q + a_2 Q^2 + a_3 Q^3 \;, \qquad (1)$$

where P_0 represents the pump output pressure and *Q* – the flow rate. Using the polynomial regression method, the authors have determinate the numerical coefficients of the relation (1), associated to static characteristic pumps presented in figure 4, table 1.

Table 1. The numerical coefficients of the mathematical model (1)

Pump tip	Numerical coefficient			Standard deviation [m H_2O]
	a_0	a_1	a_2	
32-13	6.614213E+00	4.727929E-02	-3.938231E-02	6.621437E-02
32-16	8.851658E+00	7.501579E-01	-1.081358E-01	3.631092E-01
50-20*	1.418321E+01	-2.746576E-02	-1.080953E-03	2.887783E-01
150-26	2.037071E+01	-7.850898E-03	-3.007388E-05	4.614905E-01
32-12	9.351883E+00	-1.262669E-01	3.939355E-04	1.890947E-01
50-13	8.227606E+00	-4.412075E-02	-1.679803E-05	1.578524E-01
40-16	1.258403E+01	-9.795947E-02	7.796262E-05	5.434285E-01
32-20	1.781198E+01	-2.755295E-01	1.361482E-03	3.952989E-01
40-20	1.742569E+01	-1.339487E-01	2.504382E-04	2.826216E-01

*selected pump for the simulation

3.2 The model of the pipe

The model of the pipe is represented by the drop pressure for a straight pipe, with circular section, where the fluid flows in a turbulent regime [11]

$$\Delta P_p = \lambda \frac{8L}{\pi^2 D^5} Q^2 \quad \left[\frac{N}{m^2}\right]. \tag{2}$$

where λ is the friction coefficient; L – pipe length, in m; D – pipe diameter, in m; Q – volume flow of the fluid, in m^3/s.

The value of the λ friction coefficient depends of the flow regime, characterized by the Reynolds number Re, by the rugozity coefficient ε/D and the diameter D of the pipe. The number Reynolds is defined by the relationship

$$Re = \frac{Dw}{\nu}, \tag{3}$$

where w represents the linear velocity of the fluid, in m/s; ν - the cinematic viscosity of the fluid, in m^2/s.

The friction coefficient is calculated using the Moody's formula based on curve-fit on the experimental data [7, 8, 9, 10]:

$$\lambda = \frac{64}{Re}, \qquad Re < 2300; \tag{4}$$

$$\frac{1}{\sqrt{\lambda}} = 1.74 - 2\,lg\left(2\frac{\varepsilon}{D} + \frac{18.7}{Re\sqrt{\lambda}}\right),$$

$$2300 < Re < 3000; \tag{5}$$

$$\frac{1}{\sqrt{\lambda}} = -2\,lg\left(\frac{D}{3.7\varepsilon} + \frac{2.51}{Re\sqrt{\lambda}}\right),$$

$$Re > 3000. \tag{6}$$

The relationships (5) and (6) represent two non-linear equations. For the intermediary flow regime, $2300 < Re < 3000$, will be utilized the equation

$$f(\lambda) = 1.74 - 2\,lg\left(\frac{2\varepsilon}{D} + \frac{18.7}{Re\sqrt{\lambda}}\right) - \frac{1}{\sqrt{\lambda}} = 0\ . \tag{7}$$

For the turbulent flow regime, $Re > 3000$, will be utilized the equation

$$f(\lambda) = -2\,lg\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{\lambda}}\right) - \frac{1}{\sqrt{\lambda}} = 0. \tag{8}$$

3.3 The intrinsic and the work characteristic of the control element

The intrinsic characteristic represents a mathematical model of the control element in standard working and this represents the dependence between the standard flow module K_v and the stroke h

$$K_v = f(h)\ . \tag{9}$$

The standard flow module depends only on the mechanical and hydraulic characteristics of the control element. The geometrical construction of the control element may be: valve shut – off type with one seat, valve shut – off type with two seats, three-way valve shut – off type, corner valve shut – off type, flap valve shut – off type, spherical valve shut – off type. The most important mathematical models of the intrinsic characteristic associated to the valve shut – off type with one seat are the linear characteristic and the logarithmic characteristic.

The mathematic model has the forms [2]:

a) the linear characteristic

$$\frac{Kv}{Kvs}=\frac{Kv_0}{Kvs}+\left(1-\frac{Kv_0}{Kvs}\right)\frac{h}{h_{100}}\ ; \tag{10}$$

b) the logarithmic characteristic

$$\frac{Kv}{Kvs}=\frac{Kv_0}{Kvs}\ exp\left(\frac{h}{h_{100}}\ ln\frac{Kvs}{Kv_0}\right), \tag{11}$$

where h is the valve shut – off stroke versus the seat; H_{100} – the nominal value (maximum) of the valve shut – off stroke; K_{v0} – the value of K_v for $h=0$; K_{vs} – the value of K_v at H_{100} nominal stroke.

The work characteristic of the control element represents the dependency between the Q flow rate and the flow module, the control valve drop pressure and the density of the fluid

$$Q=K_V\sqrt{\frac{\Delta P_v}{\rho}}\ . \tag{12}$$

3.5 The energetic balance of the hydraulic system

The hydraulic system may be associated to: hydraulic system without ramifications, hydraulic systems with ramifications, hydraulic systems with three-way control valves. The authors have focused their researches on the hydraulic system without ramifications, figure 5. This hydraulic system is characterized by the pump output pressure P_{0},, the pressure drop of the control valve ΔP_v, the pressure drop of the pipe ΔP_p, the pressure of the exit of the pipe P_{out} and the flow rate Q.

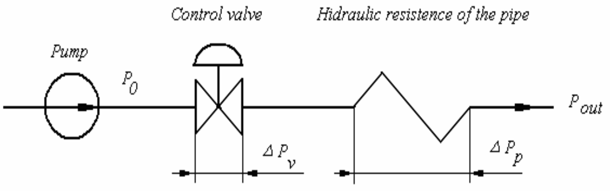


Fig. 5. The structure of the hydraulic system with control valve

The energetic balance of the hydraulic system is defined by the relation

$$P_o=P_{out}+\Delta P_v+\Delta P_p\ . \tag{13}$$

4 The Simulation Program

The authors have elaborated a special program for the calculus and the graphical representation of the work characteristic of the control valve. The input variables of the simulation program are presented in table 2. The hydraulic system has the structure presented in figure 5. The program calculates the Q flow rate corresponding to the relative value of the stroke of the control valve, $h/h_{100}\in[1\ldots100]\%$. The model of the control valve presented in figure 3 is represented by the non-linear equation

$$f(Q)=Q-K_v\sqrt{\frac{\Delta P_v}{\rho}}=0\ . \tag{14}$$

The link between the stroke of the control valve h/h_{100} and the flow rate Q are the relation (10) or (11), dependent by the intrinsic characteristic (linear or logarithmic). The pressure drop of the control valve ΔP_v is calculated using the energetic balance of the hydraulic system (13).

Table 2. The input variables of the simulation program

Variable	Measure unit	Value
Pipe		
Diameter	m	0.05
Length	m	20
Rugozity	-	0.03
Fluid		
Viscosity	$m^2 s^{-1}$	0.92e-6
Density	Kg m^{-3}	476
Control valve		
Intrinsic characteristic	Linear	
K_{vs}	$m^3 h^{-1}$	25
K_{v0}	$m^3 h^{-1}$	1
Pump		
Type 50-20	The coefficient of equation (1) are presented in table 1	

The elements of the energetic balance are defined by the output pressure pump (1) and the pipe drop pressure (2).

5 Numerically results

The numerically results are represented by the next graphically correlations: the dimensional flow rate – the valve stroke, the flow module – the valve stroke, the pipe drop pressure – the valve stroke, the valve drop pressure – the valve stroke and the friction coefficient – the valve stroke.

The flow module versus the valve stroke correlation describes the intrinsic linear characteristic of the control valve, figure 6.

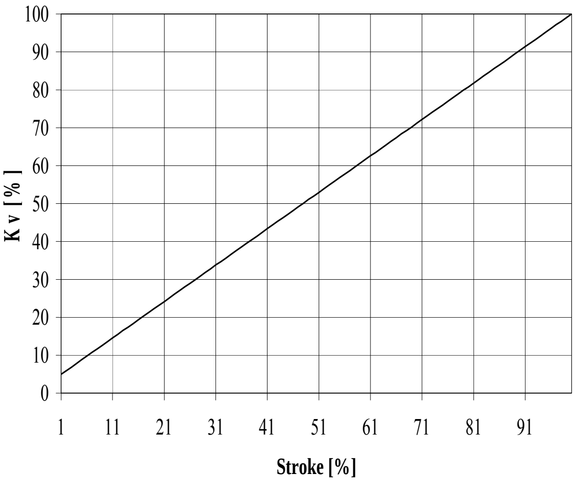


Fig. 6. The intrinsic characteristic of the control valve

Because has used the linear model of the flow module, the intrinsic characteristic has resulted linear also.

The work flow rate characteristic is quasi linear, figure 7. This control valve characteristic determines the control system characteristic and in this case, the characteristic of the control system is linear if the transducer characteristic is linear too.

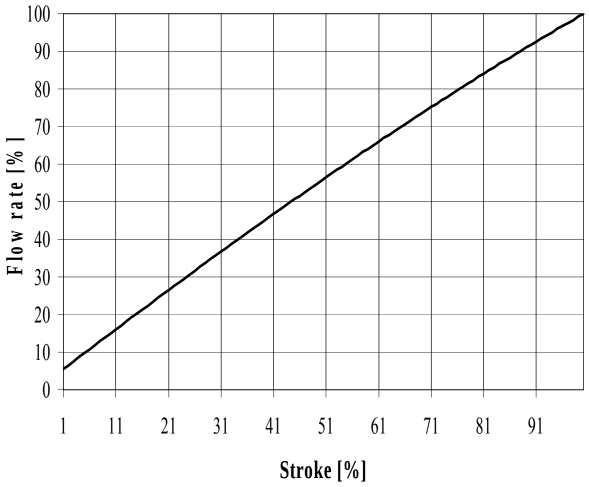


Fig. 7. The work characteristic of the control valve

In the example presented in table 2, the authors have considered a relative small pipe, without the local hydraulic resistors. In this case, the pipe drop pressure has small values, figure 8.

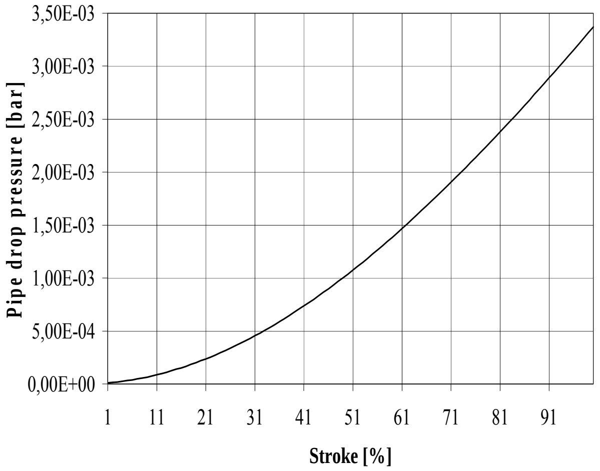


Fig. 8. The pipe drop pressure versus the valve stroke

The same cause determines the variation of the valve drop pressure. Because the pipe drop pressure is very small, the valve drop pressure is very big, figure 9.

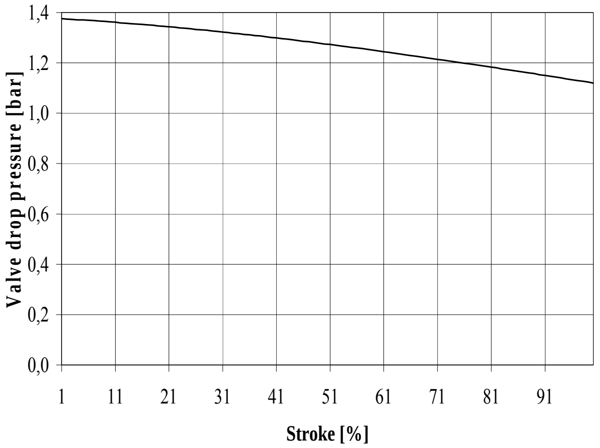
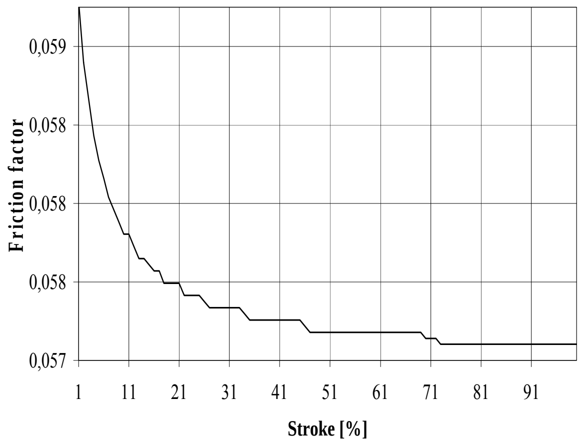


Fig. 9. The valve drop pressure versus the valve stroke

The characteristic of the valve drop pressure is similarly as the pump characteristic (theses characteristics are calculated versus the valve stroke). The conclusion of this result is that 99% of the hydraulic energy of pump is lost into control valve. Though the control valve work characteristic is linear, that is a wrong solution for the control system because is an expensive solution due to the lost energy of the control valve.

The results of the simulation program have validated the model of the friction factor. In the figure 10 is presented the correlation between the friction factor value and the control valve stroke.



6 Conclusion

The paper has presented the following:

- The structure analysis of the control valve;
- The mathematical model of the control valve;
- The simulation program and an example of the input data of the model;
- The results of the simulation program.

The structure of the control valve mathematical model is properly of the authors. The elements of the model are presented in literature. The authors have solving the model and they have elaborated a special simulation program. The numerical results are: the dimensional flow rate, the flow module, the pipe drop pressure, the valve drop pressure and the friction coefficient, all results are depended of the valve stroke.

The model and the simulation program will be used to study the work characteristic of the control valve and to study the performances of the control systems.

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