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ANALYSIS OF THE MAIN CHARACTERISTICS OF THE PROCESS OF THROTTLE OF A LIQUID IN A CONTROL AXIAL VALVE

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This paper presents the results of a study of the main characteristics of the process of throttling a liquid in a control axial valve, taking into account the dependence of the modeled coefficient of hydraulic resistance on the design and operating parameters. In particular, the calculation of the throughput and throughput characteristics of the separator of the specified valve from the standpoint of varying the degree of its opening has been performed. The most significant factors influencing the change in these indicators of the axial valve operation are revealed. For example, at the maximum degree of valve opening, an increase in the diameter of the throttling holes by 2 times leads to an increase in the nominal throughput by 1.66 times and the throughput characteristic by 1.19 times. It is shown that in the selected ranges of changes in the design parameters of the throttling process of the working medium, an increase in the valve opening degree up to 60% leads to a smooth increase in the throughput characteristic to values not exceeding 0,3. The specified nonlinear dependence of the flow characteristic of the control axial valve creates the prerequisites for choosing the profiling of this indicator. The practical application of the issues discussed in this study was reflected in the development of an engineering methodology for calculating design parameters for the corresponding control valve with the implementation of the process of throttling the flows of the working medium.

Introduction

Accident-free operation of control valves within process regulations is a basic requirement for various branches of chemical production and an issue for leading manufacturers of pipeline valves. Fluid flow in the flowing working areas of the corresponding adjustment devices is accompanied by cavitation phenomena of hydrodynamic and acoustic nature [1-3]. In particular, the occurrence of hydrodynamic cavitation is directly related to the main purpose of valves as fluid flow adjustment equipment [4-6], and due to sharp pressure drop, it becomes possible for cavitation cavities to form in the working fluid [2, 3]. Behavior of a system of formed cavitation bubbles in the main nodes of pipeline valves requires a comprehensive study of the conditions of the specified adjustment process with minimum consequences of the hydrodynamic cavitation phenomenon and maximum possible flow capacity. Using a number of structural devices for fluid flow separation allows to throttle the fluid in the main valve node. The purpose of this study is to research main characteristics of fluid throttling in the axial control valve with outer shell [7]. The study takes into account the dependence of the simulated hydraulic resistance factor on the design and operating parameters. The problem becomes especially interesting when the working fluid throttling is simulated stochastically [8] by energy method [9] [10-14] in contrast to other numerous simulation models [15-17].

Brief description of the assessment approach for the flow capacity of an axial control valve with external separator gate

The assessment of the main characteristics of control valve throttling is a priority task for industrial designers when selecting design and operating parameters of the valve [18-20]. In particular, there are two most important indicator [19, 21] - the flow capacity $K_{V\tau}$ and the flow rate, depending on the degree of valve opening $\tau \in [0;1]$

$$\sigma_\tau = K_{V\tau}/K_{VI}, \tag{1}$$

The value σ_τ in expression (1) is determined by the ratio of flow capacities at the current ($K_{V\tau}$) and full (K_{VI}) opening of throttle channels.

Fluid flow throttling can be designed either with a single separator [22, 23] or with a set of fluid flow splitter stages [24]. At the same time, there are orifices of different configurations that can be drilled in axial valve separators. The design of the axial valve at the external gate of a cylindrical separator [7] with outlet diameter D_S, thickness, h_S and length L_S of the perforated part has S_r rows of round radial orifices with the same diameter d_h as their number S_h in each row and distance h_r between the rows. To regulate pressure drops, these channels are closed by using an outer shell which moves along the central axis of the flow splitter with a nominal bore diameter $D_{y\tau} = d_h(S_h S_r \tau)^{1/2}$.

With the empirical ratio in mind [18], the flow capacity of the valve $K_{Vy\tau}$ is calculated depending on the hydraulic resistance factor $\zeta_{12\tau}$ in the transition region of the fluid flow (in the interval of change of Reynolds criterion $10 < Re < 10^4$).

$$K_{Vy\tau} = 5.04 \cdot 10^4 \pi D_{y\tau}{}^2 \zeta_{12\tau}{}^{-1/2}. \tag{2}$$

Note that the turbulent flow formation theory is not complete [25], assessment methods for the hydraulic resistance factor are actively developed in three directions: use of empirical relationships [4, 18, 20, 26], use of simulation models [27-30], simulation of analytical dependencies [10]. In particular, the authors propose the following way to calculate this characteristic

$$\zeta_{12\tau} = \lambda_{1\tau}\lambda_0^{-1}[(L_S\tau - h_r) - 2^{-1}\lambda_0] + \lambda_{2\tau} + \lambda_{4\tau}\{1 - \lambda_0\lambda_3(\lambda_6\tau + \lambda_0)[2(L_S\tau - h_r)\varepsilon_\tau]^{-1}\}^2, \tag{3}$$

modeled depending on design and mode parameters of throttling of working liquid [10] based on the superposition principle for pressure drops in elementary local resistances [4, 26]. Expression (3) contains notations:

$$\lambda_0 \equiv h_r + d_h;\ \lambda_{2\tau} \equiv S_h j D_{y\tau}^4 (90°)^{-1}[(D_{iCE} - 2h_C)^2 - D_{eCI}{}^2]^{-2};\ \lambda_3 \equiv 4D_S(\pi S_h d_h{}^2)^{-1};$$
$$\lambda_5 \equiv 4S_r(h_h + d_h)(\pi d_0{}^2)^{-1};\ \lambda_6 \equiv 7L_S/2;\ \lambda_{4\tau} \equiv 2[(D_{iCE} - 2h_C)^2 - (D_S + h_S)^2]^2 / D_{y\tau}^4;$$
$$\lambda_{1\tau} \equiv 64 S_h h_S D_{y\tau}{}^2 (Re_{y\tau} d_h{}^3)^{-1};\ \lambda_7 \equiv S_h h_h h_S [1 + D_S(D_S + h_S)^{-1}]\{90°[(D_{iCE} - 2h_C)^2 - D_S{}^2]\}^{-1},$$

here: D_{iCE} – inner diameter of outer chamber with thickness h_C; D_{eCI} – outer diameter of the inner chamber; h_h – distance between orifices in one row; φ – bevel angle for outer separator cage made as a cylindrical shell. For flow compression factor ε_τ, expression (3) suggests to use modified formula of Alshtul [26] in the form of

$$\varepsilon_\tau = 0.57 + 4.3 \cdot 10^{-2}\{1.1 - 2^{-1}[\lambda_7 + \lambda_{8\tau}]\}^{-1}, \quad (4)$$

where $\lambda_{8\tau} \equiv 2S_r(h_h + d_h)(h_r + d_h + \lambda_6 \tau)(\pi d_0{}^2)^{-1}$. The link between the Reynolds criterion $Re_{y\tau}$ and the nominal bore diameter $D_{y\tau}$ in the calculation of factor $\lambda_{1\tau}$ in expression (3) is reflected by the well-known relation $Re_{y\tau} = 353\, Q_{1\max}(v_1 D_{y\tau})^{-1}$ [18] at a valve opening degree $\tau \in [0;1]$, where $Q_{1\max}$ – a maximum the working medium flow (m^3/h); v_1 – its kinematic viscosity value (cm^2/s) at a fixed temperature value t (°C).

Thus, the simulation of the analytical dependence of the hydraulic resistance factor on the opening of the valve *with an external separator gate* [7] is performed using (3) and after taking (4) into account. This makes it possible to estimate the flow capacity $K_{V\tau}$ and flow rate σ_τ according to (1) for the control valves of the specified type [31].

Using hydraulic resistance factor simulation results to calculate basic characteristics of fluid throttling in axial valve with external separator gate

We used the offered method of estimation of liquid throttling parameters $y = \{K_{V\tau}, \sigma_\tau\}$ in the axial valve with an external separator gate [7] and tested it with throttling water as per the working environment selection set for tests of pipeline valves [19, 21, 32].

The input data $x = \{a, b\}$ for calculation of indicators $y = \{K_{V\tau}, \sigma_\tau\}$ of the specified process (flow capacity $K_{V\tau}$ and flow rate σ_τ) are values of mode $a = \{a_j, j = \overline{1, n_1}\}$ and design $b = \{a_j, j = \overline{1, n_2}\}$ parameters. Table 1 presents the obtained values of nominal bore diameter, Reynolds criterion, and hydraulic resistance factor depending on degree of opening of external separator gate as per (3), (4).

Table 1. Nominal bore diameter, Reynolds criterion, and hydraulic resistance factor depending on degree of opening of external separator gate

τ	$D_{y\tau}$, 10^{-2}, m	$Re_{y\tau}$, 10^4	$\zeta_{12\tau}$, 10^3
0.23	1.40	1.5564	3.1857
0.62	2.21	0.9844	0.2658
0.81	2.80	0.7782	0.1128
1.0	3.13	0.6961	0.0919

Here are the basic values of operating parameters $a=\{Q_{1\max};\Delta P_{\min};t;v_1\}$, $n_1=4$ of the given throttling process: maximum fluid flow rate $\Delta P_{\min}=1{,}5$ m³/h; minimum pressure drops $\Delta P_{\min}=1{,}5$ kPa; temperature $t=30$ °C; kinematic viscosity $v_1=0{,}81\cdot10^{-2}$ cm²/s. The values of design parameters $b=\{D_S;h_S;L_S;d_h;h_h;S_h;S_r;h_r;D_{iCE};h_C;D_{eCI};\varphi;h_L\}$, $n_2=13$ are divided into three groups:

1) for the separator: (output diameter $D_S=3{,}4\cdot10^{-2}$ m; thickness $h_S=0{,}15\cdot10^{-2}$ m; the perforated part length L_S=$2{,}35\cdot10^{-2}$ m; number of rows of circular radial orifices S_r=5; number of these orifices in one row $S_h=16$; orifice diameter $d_h=3{,}5\cdot10^{-3}$ m; distance between rows $h_r=0{,}1\cdot10^{-2}$ m; distance between orifices in one row $h_h=0{,}3\cdot10^{-2}$ m);

2) for the cylindrical part of the chamber: (inner diameter $D_{iCE}=6{,}5\cdot10^{-2}$ m and thickness $h_C=0{,}28\cdot10^{-2}$ m of the outer chamber; outer diameter of the inner chamber $D_{eCI}=5{,}3\cdot10^{-2}$ m);

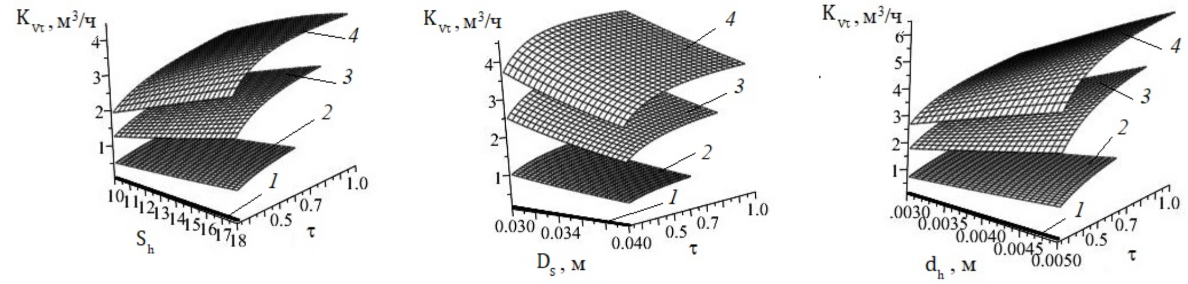
3) for the external gate of a cylindrical shell form (bevel angle φ = 45°; thickness $h_L=0{,}15\cdot10^{-2}$ m).

Fig. 1 and 2 show the results of estimation of parameter set y=$\{K_{V\tau},\sigma_\tau\}$ for fluid throttling in axial valve with external separator gate [7] as per (1), (2) and after taking (3), (4) into account. The analysis of calculation results for the parameter set y=$\{K_{V\tau},\sigma_\tau\}$ allowed us to identify the most important design parameters that have the greatest impact on the specified indicators of the studied process. In particular, such parameters include: outer diameter D_S, number of orifices in one row on the cylindrical surface of the separator S_h, diameter of orifices d_h.

The observed general behavior of the dependencies for the flow capacity $K_{V\tau}$ (Fig. 1, *a*; 1, *b*; 1, *c*) and flow rate σ_τ (Fig. 2, *a*; 2, *b*; 2, *c*) on the parameter set c=$\{D_S;S_h;d_h\}$ Î b for fluid throttling in axial valve with external separator gate is explained by the ratios of these parameters according to expression (1). For example, at the maximum valve opening degree ($\tau=1$), the diameter of the orifices d_h is twice as large (it widens from $2{,}5\cdot10^{-3}$ m to $5{,}0\cdot10^{-3}$ m), and because of that, the conditional flow capacity $K_{V\tau}$ is 66% (from 2.7 m³/h to 4.5 m³/h; Fig. 1, *c*) and the flow rate σ_τ is 19% (from 0.70 to 0.83; Fig. 2, *c*) higher.

Similarly, increasing the number of orifices in one row of cylindrical separator S_h by 80% according to Fig. 1, *a* and Fig. 2, *a* is reflected in a 75% increase in the conditional flow capacity $K_{V\tau}$ and a 15% increase in the flow rate σ_τ. In this case, increasing valve opening τ influences the specified parameters in the set y=$\{K_{V\tau},\sigma_\tau\}$ the most. For example, increasing the valve opening degree to 60% leads to a smooth increase in the flow rate to values not exceeding 0.3 (Fig. 2, *c*). Previously, we have determined that the flow rate of a regulating axial valve with an external separator gate σ_τ depends on the valve opening degree τ nonlinearly. This dependence can be used to profile the flow rate, which is the main task of pipeline valve designers. Note that the solution of issues considered in this study was obtained during the development of engineering methodology for calculating the design parameters [33, 34] for the corresponding control valve, as well as the implementation of the flow throttling in the work environment.

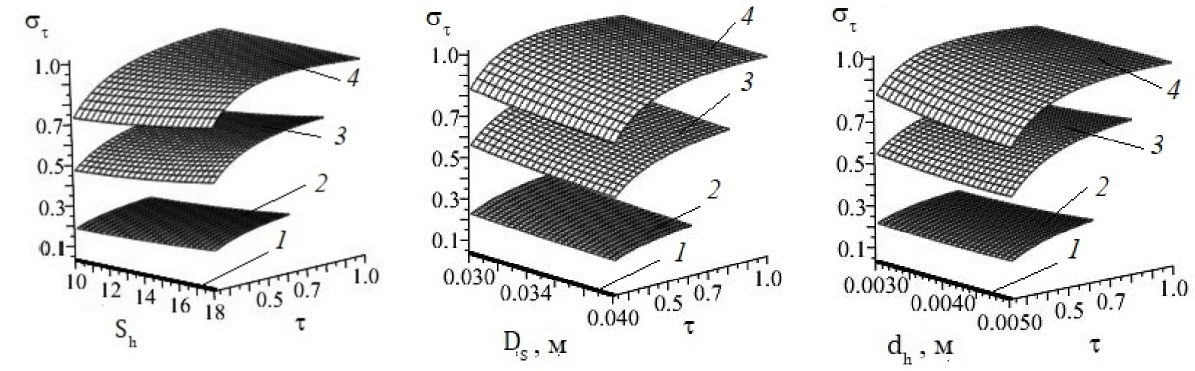
a)



a) *b)* *c)*

Fig. 1. Dependence between nominal capacity of axial valve with external gate and parameters of throttling of liquid flows:

$a - K_{V\tau}(S_h, \tau)$; $D_S = 3.4 \cdot 10^{-2}$ m; $d_h = 3.5 \cdot 10^{-3}$ m; $b - K_{V\tau}(D_S, \tau)$; $d_h = 3.5 \cdot 10^{-3}$ m; $S_h = 16$; $c - K_{V\tau}(d_h, \tau)$; $D_S = 3.4 \cdot 10^{-2}$ m; $S_h = 16$; $1 - D_{y\tau} = 1.4 \cdot 10^{-2}$ m; $2 - D_{y\tau} = 2.2 \cdot 10^{-2}$ m; $3 - D_{y\tau} = 2.8 \cdot 10^{-2}$ m; $4 - D_{y\tau} = 3.1 \cdot 10^{-2}$ m;



a) *b)* *c)*

Fig. 2. Dependence between flow rate of axial valve with external gate and parameters of throttling of liquid flows:

$a - \sigma_\tau(S_h, \tau)$; $D_S = 3,4 \cdot 10^{-2}$ m; $d_h = 3,5 \cdot 10^{-3}$ m; $b - \sigma_\tau(D_S, \tau)$; $d_h = 3,5 \cdot 10^{-3}$ m; $S_h = 16$; $c - \sigma_\tau(d_h, \tau)$ $D_S = 3.4 \cdot 10^{-2}$ m; $S_h = 16$; $1 - D_{y\tau} = 1.4 \cdot 10^{-2}$ m; $2 - D_{y\tau} = 2.2 \cdot 10^{-2}$ m; $3 - D_{y\tau} = 2.8 \cdot 10^{-2}$ m; $4 - D_{y\tau} = 3.1 \cdot 10^{-2}$ m;

Conclusion

The study discusses the assessment of main characteristics for liquid throttling in axial valve with external separator gate. The results of the study are:

1. The design features of control equipment proposed by the authors were proven to be efficient. This equipment is used to implement the flow throttling of the working environment. The proposed changes result in a promising direction for the creation of control valve devices designed to solve the problem of local production.

2. We have determined a number of the most impactful design parameters in liquid throttling in an axial valve with an external separator gate. They contribute to the development of specific design guidelines for the new control equipment. For example, at the maximum valve opening degree, the diameter of the orifices is twice as large, and because of that, the conditional flow capacity is 66% and the flow rate is 19% higher. In addition, increasing the valve opening degree up to 60% results in a smooth increase of the flow rate up to values not exceeding 0.3.

3. We have determined that the flow rate of an axial control valve with an external separator gate depends on the valve opening degree nonlinearly. This dependence can be used to

profile the flow rate when changing the ranges of the design parameters. It also has wide practical application when developing an engineering method of calculation of these characteristics.

References

1. **Knapp R.T., Daily J.W. Hammitt F.G.** *Cavitation. Moscow: Peace.* 1974. 6688 p. (in Russian).
2. **Oksler G.** Armature cavitation? Let's figure it out! *Armaturostroyeniye.* 2012, N 2(77). P. 74-77 (in Russian).
3. **Kapranova A., Neklyudov S., Lebedev A., Meltser A**. Determination of the average parameters of cavitation bubbles in the flowing part of the control valves. *Int. J. Mech. Eng. Technol.* 2018. V. 9, No. 3. P. 25-31.
4. **Arzumanov E.S.** Hydraulic regulatory bodies of automated control systems. Moscow: Mashinostroyeniye, 1985, 256 p. (in Russian).
5. **Chernoshtan V.I., Kuznetsov V.A.** Pipeline fittings for thermal power plants. Reference manual. Moscow: MEI Publishing House, 2001. 368 p. (in Russian).
6. **Lerner D.G., Spiridonov E.K., Forental V.I.** An integrated approach to the study of a throttling valve. *Izvestiya SNTS RAN –Proceedings of the SNTS RAN*. 2011. Vol. 13. N 1(2). P. 469-462. (in Russian).
7. Patent on the model 175776 Russian Federation. Direct-acting control valve / A.E. Lebedev, A.B. Kapranova, A.M. Meltser, S.A. Solopov, D.V. Voronin, S.V. Neklyudov. Published by May 2018 (in Russian).
8. **Kapranova A.B., Lebedev A.E., Meltser A.M., Solopov S.A., Serov E.M.** Methods of modeling the developmental stages of hydrodynamic cavitation. Fundamental'nyye Issledovaniya. 2016. N 3(section 2). P. 268-273.
9. **Klimontovich Y.L.** Turbulent Motion and Chaos Structure: A New Approach to the Statistical Theory of Open Systems. Moscow: LENAND, 2014. 328 p. (in Russian).
10. **Kapranova A., Neklyudov S., Lebedev A., Meltser A.** Qualitative evaluation of the coefficient of hydraulic resistance in the area of the divider of the fluid flow of the axial valve. *Int. J. Mech. Eng. Technol.* 2018. V. 9, N. 8. P. 153-159.
11. **Kapranova A.B., Lebedev A.E., Meltser A.M., Solopov S.A.** The application process of the Ornstein-Ulenbek to the formation of cavitation bubbles. *Czas. Tech. Mech.* 2016. V. 113. N. 2. P. 136-144. DOI:10.4467/2353737XCT.16.101.5500.
12. **Kapranova A., Miadonye A**. Stochastic simulation of cavitation bubbles formation in the axial valve separator influenced by degree of opening. *Journal of Oil, Gas and Petrochemical Sciences.* 2019. V. 2. N. 2. P. 70-75. DOI: 10.30881/jogps.00026
13. **Kapranova A., Lebedev A., Meltser A., Neklyudov S.** The ensemble-averaged characteristics of the bubble system during cavitation in the separator. *E3s Web of Conference.* 2019. V. 140. 06005. DOI: 10.1051/e3sconf/201914006005
14. **Kapranova A.B., Lebedev A.E., Meltser A.M., Neklyudov S.V.** Stochastic model of process of formation of cavitation bubbles in the flow path of control valve. *Vestnik. IGEY*. 2016. N 4. P. 94-107.). DOI: 10.17588/2072-2672.2016.4.024-029 (in Russian).
15. **Franc J.-P., Michel J.-M**. Fundamentals of Cavitation. *Fluid Mechanics and Its Applications.* 2005. V. 76. N 11. DOI:10.1007/1-4020-2233-6
16. **S. Xu, Y. Qiao, X. Liu, C.C. Church, M.** Wan Fundamentals of Cavitation. In: Wan M., Feng Y., Haar G. (eds). Cavitation in Biomedicine. Dordrecht: Springer, 2015. DOI:10.1007/978-94-017-7255-6_1
17. **Qian J., Liu B., Jin Z., Zhang H., Lu A.** Numerical analysis of flow and cavitation characteristics in a pilot-control globe valve with different valve core displacements. *J. Zhejiang Univ. Sci. A.* 2016, V. 17, N. 1. P. 54-64.DOI:10.1631/jzus.A1500228
18. **Arzumanov E.S.** Calculation and selection of regulatory bodies of automatic systems. Moscow: Energia, 1971. - 112 p. (in Russian).
19. GOST 12893-2005. Single-seat, double-seat and cage control valves. General technical conditions. Moscow, Standartinform Publ., 2008. 26 p. (in Russian).
20. **Idelchik I.E.** Hydraulic resistance reference book. Moscow: Mashinostroyeniye, 1975. 559 p. (in Russian).
21. GOST R 52720-2007. Pipefittings. Terms and Definitions. Moscow: Standartinform Publ., 2007. 30 p. (in Russian).

22. Patent N KR 20180055897A. Valve / Preston T.J. Published by May 25, 2018.
23. Patent N US 8297315B2. Throttle valve / V. Esveldt. Published by October 30, 2012.
24. Patent N US 4327757. Control valve / H.H. Weevers. Published by May 4, 1982.
25. **Volgin G.** The hydraulic resistance coefficient in the conditions of simultaneous effect of Re, Fr and B/h. *E3S Web of Conferences*, 2019, Vol. 97, 05031. doi:10.1051/e3sconf/20199705031.
26. **Altshul A.D.** Hydraulic resistance. Moscow: Nedra, 1982. 224 p. (in Russian).
27. **Narasimhamurthy V.D, Andersson H.** Turbulence statistics in a rotating ribbed channel. *International Journal of Heat and Fluid Flow.* 2014. V. 51. DOI: 10.1016/j.ijheatfluidflow.2014.10.008
28. **Kireev V.N., Nizamova A., Urmancheev S.F.** The hydraulic resistance of thermoviscous liquid flow in a plane channel with a variable cross-section. *Journal of Physics Conference Series.* 2019. V. 1158. N 3. 032014. DOI:10.1088/1742-6596/1158/3/032014
29. **Alfonsi G.** Direct Numerical Simulation of Turbulent Flows. *Applied Mechanics Reviews.* 2011. V. 64. N. 2. 0802. DOI: 10.1115/1.4005282
30. **Narasimhamurthy V.D., Andersson H.** DNS of turbulent flow in a rotating rough channel. *8th Workshop on Direct and Large-Eddy Simulation: materials of the International Conference (January 2011).* V. 15. DOI: 10.1007/978-94-007-2482-2_65
31. **Kapranova A.B., Lebedev A.E., Meltser A.M., Neklyudov S.V.** On the influence of the throughput of the axial valve on the parameters of the stochastic model of cavitation. *RHJ Journal of the Chemical Society named after D.I. Mendeleev).* 2018. Vol. 62. N 4. P. 51-53.
32. GOST R 55508-2013. Pipefittings. Method of experimental determination of hydraulic and cavitation characteristics. Moscow: Standartinform Publ., 2014. 38 p. (in Russian).
33. **Kapranova A.B., Lebedev A.E., Neklyudov S.V., Melzer A.M.** Engineering Method for Calculating of an Axial Valve Separator with an External Location of the Locking Part. *Frontiers in Energy Research: Process and Energy Systems.* March 2020. V. 8. article 32. P. 1-17. DOI: 10.3389/fenrg.2020.00032
34. **Kapranova A.B., Lebedev A.E., Meltser A.M., Neklyudov S.V.** Investigation of the behavior of the gas-steam system inside the cavitation bubble during the operation of the axial valve. *Vestnik. IGEY – Bulletin IGEY*, 2020, N. 3. P. 58-64. DOI: 10.17588/2072-2672.2020.3.058-064 (in Russian).
35. **Kapranova A.B., Lebedev A.E., Melzer A.M., Neklyudov S.V.** About Formation of Elements of a Cyber-Physical System for Efficient Throttling of Fluid in an Axial Valve. *In monograph: Cyber-Physical Systems: Advances in Design & Modelling. Studies in Systems, Decision and Control* / eds. A. Kravets, A. Bolshakov, M. Shcherbakov. V. 259. Springer, Cham, 2020. P. 109-119. DOI: 10.1007/978-3-030-32579-4_9

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