International Journal of Mechanical Engineering and Technology (IJMET)
Volume 9, Issue 8, August 2018, pp. 160–166, Article ID: IJMET_09_08_017
Available online at http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=9&IType=8
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

INVESTIGATION OF THE ENERGY OF THE STOCHASTIC MOTION OF CAVITATION BUBBLES IN THE SEPARATOR OF THE AXIAL VALVE, DEPENDING ON THE DEGREE OF ITS OPENING

Kapranova Anna and Lebedev Anton
Department of theoretical mechanics and materials resistance,
Yaroslavl State Technical University, Yaroslavl, Russia

Neklyudov Sergey and Meltser Alexandr
JSC «Regulyator», Yaroslavl, Russia

ABSTRACT

The analysis of the constructed function for the energy of the stochastic motion of cavitation bubbles in the separator of the axial valve is performed, depending on the degree of its opening in the initial stage of hydrodynamic cavitation. The relationship of this energy at the moment of stochastization of the macrosystem of bubbles and the state of the gas-vapor system inside the bubble with the diameter of the conditional pass of the separator is shown.

Keywords: axial valve, separator, hydrodynamic cavitation, model, bubble stochastic energy, valve-opening degree.

Cite this Article: Kapranova Anna, Neklyudov Sergey, Lebedev Anton and Meltser Alexandr, Investigation of the Energy of the Stochastic Motion of Cavitation Bubbles in the Separator of the Axial Valve, Depending on the Degree of its Opening, International Journal of Mechanical Engineering and Technology, 9(8), 2018, pp. 160–166.
http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=8

1. INTRODUCTION

The problem of describing the mechanism of behavior of cavitation bubbles formed during the operation of control valves in the first stages of the evolution of hydrodynamic cavitation is closely related to the directions of improving the designs of the corresponding equipment. As noted in [1, 2], the behavior in a liquid of vapor-filled bubbles (nucleons) is traditionally described using stochastic models of three types. The first is the homogeneous model [3, 4], when the nucleation rate in a liquid without additional inclusions is represented in the form of an exponential dependence on the Gibbs number. The second kind of models is related to the modification of homogeneous [5] with the introduction of a partial account of the presence of impurities in the working medium. The third type is heterogeneous models that are valid for fluid flow with suspended particles, near walls with cracks, and so on. [6].

Earlier, the authors used the stochastic approach [7] in the Ornstein-Uhlenbeck formalism [8, 9] to simulate the formation of cavitation bubbles in the flowing part of the valve during the initial stage of hydrodynamic cavitation, taking into account the structural and regime parameters of the device and the physico-mechanical properties of the working substances [2, 9, 10].

In the present presentation, when stochastic modeling of the stationary solution of the Fokker-Planck equation is proposed, we introduce an additional parameter - the degree of valve opening, as one of the main characteristics of the operating mode of the regulating equipment.

2. MODELING THE ENERGY OF A STOCHASTIC BUBBLE MOTION

In contrast to the modified models in which postulating the number distribution of nucleons by their sizes in the form of normal or equiprobable laws [11], the authors propose, similar to the model [2, 8-10], to apply the formalism of the random process A. A. Markov to the description of the formation of the macrosystem of bubbles in the separator of the axial valve in the absence of additional energy inflow along the Gibbs ensemble.

Modeling the energy of the stochastic motion of a cavitation bubble in a cylindrical separator with throttle openings for an axial valve with an external locking body corresponds to the following initial stages of hydrodynamic cavitation, which will be briefly enumerated.

First, the appearance of cavities in the flow of liquid, which is associated with a sharp drop in pressure during its flow in the flowing part of the valve. Then these cavities acquire a spherical shape under the influence of the external pressure of the liquid and are filled with its condensed vapor, as well as by the percolating gas. The resulting gas-vapor system inside the cavitation bubble undergoes vortical displacements of a random nature. It is obvious that the interaction of the bubble itself with the surrounding liquid and the motion in the flow of the liquid medium are observed.

Thus, when describing the energy of the stochastic motion of a cavitation bubble

$$E(\xi,\eta,x)=\sum_{m=1}^{6}E_m\,, \qquad 1$$

The corresponding forms of energy are taken into account: the formation of the cavity (E_1) and the free spherical surface (E_2), its filling with gas and vapor (E_3), hydrodynamic interaction with the environment (E_4), kinetic energies for motion spheres in the liquid (E_5) and for the gas-vapor system inside this sphere (E_6).

Expression (1) for the energy of the stochastic motion of a cavitation bubble assumes the assignment of dimensionless phase variables

$$\xi=r/r_c, \quad \eta=v/v_L, \quad x=x'/l\,, \qquad 2$$

for a phase volume element

$$d\Omega=d\xi d\eta dx\,, \qquad 3$$

where r, v is the bubble radius and the velocity of its center of mass with characteristic values, respectively r_c, v_L; x - the degree of opening of the valve, as the ratio of the current position x' for the moving shutter along its axis to the conditional position l; l - length of the separator part with throttling openings.

Taking into account the explicit form of the components E_m of (1), the function $E(\xi,\eta,x)$ is represented in the form

$$E(\xi,\eta,x)=\left[W_{11}(\xi)+W_{12}(\xi)\zeta_{tr}(x)\right]v_L^2\eta^2+W_{22}(\xi), \quad (4)$$

where $W_{11}(\xi)$, $W_{12}(\xi)$, $W_{22}(\xi)$ are additional functions defined by expressions

$$W_{11}(\xi)\equiv\lambda_1 r_c^3\xi^3, \quad (5)$$

$$W_{12}(\xi)\equiv\rho_L s_\zeta/(4r_c\xi), \quad (6)$$

$$W_{22}(\xi)\equiv\lambda_3 M^2/\left(r_c^5\xi^5\right)+r_c^2\xi^2\left(\lambda_4+\lambda_5 r_c\xi\right). \quad (7)$$

And the notation $\lambda_1=2\pi(\alpha_g\rho_g+\alpha_s\rho_s)/3$, $\lambda_3\equiv 5\lambda_1/8$, $\lambda_4\equiv 4\pi\sigma$, $\lambda_5\equiv 8\pi P_s/3$,; α_g, α_s - volume fractions of gas and steam; ρ_g, ρ_s, ρ_L - density of gas, vapor and liquid; σ - coefficient of surface tension of the liquid; s_ζ - coefficient of proportionality; P_s - saturated vapor pressure; M - random component of the angular momentum.

In expression (4): $\zeta_{tr}(x)$ - the dependence of the coefficient of hydraulic resistance on the parameter x for the transition zone of the flow of liquid in the separator with throttling holes [12, 13] according to the principle [14-16] of super positions of pressure losses in elementary local resistances [17]

$$\zeta_{tr}(x)=\mu_2+\mu_1 g_1(x)+\mu_4[g_2(x)]^2, \quad (8)$$

where $g_1(x)$, $g_2(x)$ are the auxiliary functions given by formulas

$$g_1(x)\equiv\left(lx-L_0\right)/\mu_0-1/2, \quad (9)$$

$$g_2(x)\equiv\mu_0\mu_3(\mu_0+\mu_6 x)/\left[2(Lx-l_0)g_3(x)\right]-1, \quad (10)$$

$$g_3(x)=b_0+b_1/\left\{b_2-[\mu_7-\mu_5(\mu_0+\mu_6 x)/2]/2\right\}, \quad (11)$$

when $\mu_0\equiv L_0+d_0$, $\mu_1\equiv 64a_1\delta D_y{}^2/\left(\mathrm{Re}_y d_0{}^3\right)$, $\mu_2\equiv a_1\beta D_y^4/\left\{90^0[(d_{ies}-2\Delta)^2-d_{eis}{}^2]^2\right\}$, $\mu_3\equiv 4d_{id}/\left(\pi a_1 d_0{}^2\right)$,
$\mu_4\equiv 2[(d_{ies}-2\Delta)^2-d_{ed}{}^2]^2/D_y^4$, $\mu_5\equiv 4a_2(u+d_0)/\left(\pi d_0{}^2\right)$, $\mu_6\equiv 7l/2$, $b_0=0{,}57$; $b_1=0{,}043$; $b_2=1{,}1$;
$\mu_7\equiv a_1 u\delta(1+d_{id}/d_{ed})/\{90^0[(d_{ies}-2\Delta)^2-d_{id}{}^2]\}$; L_0 -

The distance between the rows; a_2 - a total number of rows; a_1 - number of holes in each row; δ - the thickness of the separator; d_{ies} - the inner diameter of the cylindrical part of the outer shell of a thickness Δ; β (grad) - the bevel angle for the cylindrical part of the shell; d_{id}, d_{ed} - respectively internal and external for the separator (a flow divider); u – arc distance between throttles in one row ; d_{eis} - outer diameter of the inner valve body.

Note that for the transition zone of the flow of liquid in a separator with throttling holes of diameter d_{10} (cm), d_0 (m), a double inequality $10<\mathrm{Re}<10^4$ holds with respect to the Reynolds number, the value of which for a conditional cross-section with a diameter D_{1y} (cm), D_{1y} (m)

$$D_{1y}(x)=d_{10}\left(m_1 m_2 x\right)^{1/2}, \qquad D_y(x)=d_0\left(m_1 m_2 x\right)^{1/2} \quad (12)$$

is calculated by the formula

$$\mathrm{Re}_y(x) = 353Q_{1m} / [\nu_1 D_{1y}(x)] \,, \qquad 13$$

In the expression (13): ν_1 - kinematic viscosity (cm^2 / s) for a given temperature of the medium t_1 (^0C); Q_{1m} (m^3 / h) is the maximum achievable liquid flow through the regulating device.

3. ESTIMATION OF THE STATIONARY VALUE OF ENERGY OF BUBBLE AT THE MOMENT OF STOCHASTIZATION OF MACROSYSTEM

The application of the formalism of the Ornstein-Uhlenbeck random process [7, 8] leads to the calculation of the number of cavitation bubbles N in an isolated phase volume with an element $d\Omega E_0$ of (3) with the help of expression

$$N = A\int_{\Omega} \exp[-E(\xi,\eta,x) / E_0] dN \,, \qquad 14$$

where A is the normalization parameter; E_0 - stationary value of energy at the moment of stochastization of the macrosystem of the formed bubbles.

The parameter E_0 is proposed to be calculated similarly to the approach of [9] using the energy balance equation $E_1 = E_2$, where E_1 is the energy of the stochastic motion of the bubble system in the initial stage of hydrodynamic cavitation in the axial valve separator; E_2 - energy spent for hydraulic rupture of fluid for a specified period of time $\Delta\tau = 4 < V > N / (\pi d_0^2 a_1 a_2 x v_L)$ with considering (12), (14) and consists of the terms: the kinetic energy of the cavity motion after the liquid rupture, the energy expended on the formation of the spherical surface, and the energy of interaction of the cavity with the surrounding medium

$$E_1 = \int_{\Omega} E(\xi,\eta,x) dN \,, \qquad 15$$

$$E_2 = \left[3\varphi_1 (4\pi)^{-1} N < V > + \varphi_2 / r\right] v_L^2 + 4\sigma d_0^{-1} (a_1 a_2 x)^{-1/2} N < V > \,, \qquad 16$$

In expression (16), the coefficients $\varphi_1,\ \varphi_2$ are determined by the constants $\lambda_j,\ j = \overline{1,5}$ from (5) - (7); the mean value of energy is equal $< V > = 4\pi (3N)^{-1} \int_{\Omega} r^3 dN$ to (14).

For the energy balance equation formed according to (15) and (16), Maclaurin expansion is used up to terms of order $O(z^3)$ in the error function, and also up to $O(z^2)$ in the exponential dependence, then the sought expression for the parameter E_0, depending on the degree of valve opening, has the form

$$E_0(x) = q_0 \left\{ f_1(x)\varepsilon_1(x) + 60 f_3(x) f_4(x) \right\} / \left\{ \varepsilon_2(x) - 20 r_c \left[1 + f_3(x)\right] \right\}^{-1} , \qquad 17$$

where it is denoted: $f_1(x) \equiv \left[r_c / f_4(x)\right]^{1/2} \mathrm{erf}\left\{ v_L \left[f_4(x) / r_c\right]^{1/2} \right\}$, $f_5(x) \equiv r_c[3W_{11}(1) - \zeta_{tr}(x) W_{12}(1)]$, $f_2(x) \equiv f_5(x) v_L{}^2 / f_4(x) \left[v_L \pi^{-1/2} \exp\left(-[f_4(x)]^{1/2} / r_c\right) - f_1(x)/2 \right]$, $f_3(x) \equiv W_{11}(1) T_{21}(x) + \zeta_{12}(x) W_{12}(1) T_{22}(x)$, $f_4(x) \equiv r_c[W_{11}(1) + \zeta_{tr}(x) W_{12}(1)]$, $\gamma_3 \equiv 3r_c(5\lambda_4 + \gamma_0 r_c)$, $\gamma_2 \equiv (2\lambda_4 + 3\lambda_5 r_c) r_c{}^2$, $\gamma_0 \equiv 32\pi^{1/2} / (3D_y{}^2) - \lambda_5$, $\varepsilon_1(x) \equiv 3\gamma_2 + (\gamma_2 - \gamma_3 r_c) f_2(x) + 15\gamma_0 r_c{}^3$, $\varepsilon_2(x) \equiv 2\pi^2 f_1(x) \left[2(q_1{}^{1/3} - 1)\left[3 + f_2(x)\right]\gamma_2 \right]$, $q_0 \equiv 2^{1/2}\pi^{1/4}\gamma_2 q_2 \delta / 12$,

$$q_2 \equiv 2^{5/2} q_3 (\pi/3)^2 \left\{1 + 3^{3/2}\pi^4 \left[1 - (K_{vy\max}/K_{vy})(D_y/D_{y\max})^2\right]/4\right\},\ T_{21} \equiv \int_0^1 \xi^4 [W_{11}(\xi) + \zeta_{tr}(x) W_{12}(\xi)]^{-1} d\xi,$$

$$q_3 \equiv \left[1 - (r_c/D_y)(K_{vy}/Q_{1\max})^{1/2}\right]\left[(K_{vy}/K_{vy\max})(D_{y\max}/D_y)^2\right]^{3/2},\ T_{22} \equiv \int_0^1 [W_{11}(\xi) + \zeta_{tr}(x) W_{12}(\xi)]^{-1} d\xi.\ q_1 \equiv r_c^3 (P_{\max}/P_s)^{1/k}.$$

Expressions for q_2 and q_3 contain K_{vy} (m3 / h) - the conditional throughput [14-16] of the valve according to the formula, taking into account (8) and (12)

$$K_{vy} = 5{,}04\pi D_{1y}{}^2 [\zeta_{tr}(x)]^{-1/2}, \tag{18}$$

$K_{vy\max}$ - the maximum value with the degree of opening of the valve $z=1$.

In addition, in (7) enters M - a random component of the angular momentum, defined by the expression

$$M(x) = \left\{r_c{}^5 \left[3E_0(x)(2q_1{}^{1/3} - 1) - \gamma_2\right]/(5\lambda_3)\right\}^{1/2}, \tag{19}$$

obtained from the thermodynamic relation $(p_{\max}/p_s)^{1/k} = (\langle r\rangle / r_{\min})^3$, for the adiabatic process inside the cavitation sphere for the gas-vapor system [18], where $\langle r\rangle = N^{-1}\int_{\Omega_1} r dN$ - averaged value of bubble radius; p_s - pressure in the center of the bubble with averaged value of the radius; $p_{\max}$ - the maximum pressure in the center of the bubble, which corresponds to the minimum value of its radius; k - the adiabatic exponent.

4. RESULTS AND DISCUSSIONS

Let's illustrate the calculation of the energy parameter and the state of the gas-vapor system filling the cavitation cavities with the following values of the parameters of the process of formation of cavitation bubbles in the separator of the axial valve with a movable locking organ: constructive (d_0 =3,5·10-3 m; a_1 =16; a_2 =5; H =0,15·10-2 m; d_{id} =3,4·10-2 m; d_{eis} =5,3·10-2 m; d_{ies} =6,5·10-2 m; l =2,35·10-2 m; β =450); regime (medium temperature t_1 = 30,0 ° C ; $\Delta p_{\min}$ =1.5 kPa; $Q_{1\max}$ =0.5 m3/h); physical and mechanical (P_s =10-3 Pa; k=1,3; $_{\max}$ =1,3·108 Pa; r_c =10-3 m; ; σ=7,284·10-4 H/m; ρ_g =1,205 kg/m3; ρ_s =1,44·10-2 kg/m3; ρ_L =103 kg/m3).

For the described input data, the dependences for the energy parameter $E_0(D_y)$ of the model from (17) are given in Fig. 1, taking into account (18) the diameter of the conditional valve cross-section D_y at the corresponding Reynolds numbers according to (13) and different valve opening values x. As the values D_y increase, E_0 smoothly grows (Fig. 1, the end points on graphs *1-4*), in particular, with the transition from the degree of opening of the valve $x=0{,}234$ to its full opening (x =1), parameter E_0 increases by 3.8 times (end points on the graphs 1 and 4).

The dependence of the random component of the angular momentum $M(D_y)$ on the diameter of the conditional passage D_y for different values of the degree of opening of the axial valve and the volume fractions of the components of the gas-vapor system α_g, α_s filling the cavitation sphere is shown in Fig. 2.

Similarly, the dependence $E_0(D_y)$ of the parameter $M(D_y)$ also increases smoothly with increasing value D_y. For example, valve opening from 23% to 62% with the following parameters of the gas-vapor system of a cavitation bubble α_g =0,8; α_s =0,2 leads to an increase in the value of the random component of the angular momentum M by 1.1 times (Fig. 2, the end points in Fig. *1* and *2*), and from 62% to 100% - 2.2 times (see Figure 2.14, end points in graphs *2* and *4*). This trend is maintained for other ratios of the volume fractions of the gas-vapor system; $\alpha_g = \alpha_s$ =0,5 (Fig. 2, end points on the graphs *1'-4'*; and α_g =0,2; α_s =0,8 (Fig. 2, end points on the graphs *1"-4"*).

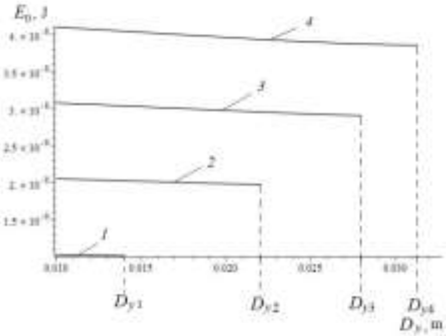

Figure 1 Dependences $E_0(D_y)$ of the energy parameter of the model on the diameter of the conditional passage D_y for different values of the degree opening of the axial valve: α_g =0,8; α_s =0,2; d_0 =3,5·10-3 m; m_1 =16; D_{id} =3,4·10-2 m; 1 – x =0,2340; D_{y1} = 1,40·10-2 m; Re_{y1} =1,5564·104 ; 2 – x =0,6170; D_{y2} = 2,21·10-2 m; Re_{y2} =9,8438·104 ; 3 – x =0,8085; D_{y3} = 2,80·10-2 m; Re_{y3} =7,7822·104 ; 4 – x =1,0; D_{y4} = 3,31·10-2 m; Re_{y1} =6,9606·104

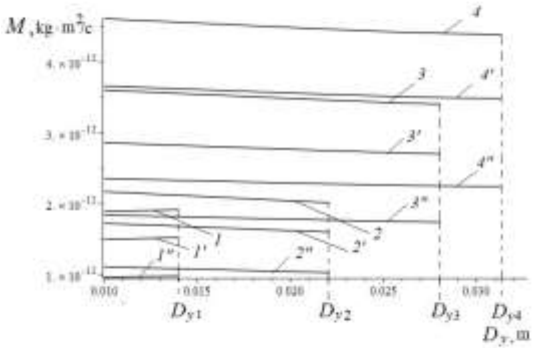

Figure 2 The dependence $M(D_y)$ of the random component of the angular momentum on the diameter of the conditional passage D_y for different values of the degree opening of the axial valve: 1, 2, 3, 4 - $\alpha_g = 0{,}8,\ \alpha_s = 0{,}2$; 1', 2', 3', 4' - $\alpha_g = \alpha_s$ =0,5; 1", 2", 3", 4" –

α_g =0,2; α_s =0,8; d_0 =3,5·10^{-3} m; m_1 =16; D_{id} =3,4·10^{-2} m; *1, 1', 1"* – x =0,2340;

D_{y1} = 1,40·10^{-2} m; Re_{y1} =1,5564·10^4; *2, 2', 2"* – x =0,6170; D_{y2} = 2,21·10^{-2} m;

Re_{y2} =9,8438·10^4; *3, 3', 3"* – x =0,8085; D_{y3} = 2,80·10^{-2} m; Re_{y3} =7,7822·10^4;

4, 4', 4" – x =1,0; D_{y4} = 3,31·10^{-2} m; Re_{y1} =6,9606·10^4

5. CONCLUSION & SIGNIFICANCE

Thus, the proposed simulation of the energy of the stochastic motion of the cavitation bubble in the form of expression (4), taking into account the degree of opening of the axial valve, allows us to calculate the corresponding stationary values of the given energy at the time of stochastization of the macrosystem of the formed spherical bubbles in the form of expression

(17) in the framework of the Ornstein-Uhlenbeck random process and determine parameter of the internal motion of the gas-vapor system filling the cavitation cavity.

These sought values are the main parameters of the stochastic model, which makes it possible to construct with the help of expression (14) a differential function for the distribution of the number of cavitation bubbles according to the degree of opening of the valve in the initial stage of hydrodynamic cavitation and to analyze the dependence of this function on the capacity of the axial valve.

REFERENCES

[1] Kapranova, A. B., Lebedev, A. E., Meltser, A. M., Nekludov, S. V. and Serov, E. M. Methods of modeling the developmental stages of hydrodynamic cavitation. Fundamental research, 3(2), 2016, pp. 268-273. www.fundamental-research.ru/ru/article/ view?id=40043

[2] Kapranova, A. B., Lebedev, A. E., Meltser, A. M., Solopov, S. A. and Nekludov, S. V. Determination of the average parameters of cavitation bubbles in the flowing part of the control valves. International Journal of Mechanical Engineering & Technology (IJMET), 9(3), 2018, pp. 25–31. Article ID: IJMET_09_03_003 Available online at http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=3

[3] Frenkel', YA. I. Kineticheskaya teoriya zhidkostey [The kinetic theory of liquids]. Leningrad: Nauka, 1959, pp. 586.

[4] Lienhard, J. H. and Karimi, A. Journal of Heat Transfer, 1 (103), 1981, pp. 61-64.

[5] Ellas, E. and Chambre, P. L. Int J. Multiphase Flow, 26, 2000, pp. 191–206

[6] Hsu, Y. Y. Journal of Heat Transfer, 94, 1962, pp. 207–212.

[7] Klimontovich, Yu. L. Turbulent motion and chaos structure: A new approach to the statistical theory of open systems. Moscow: LENAND, 2014, pp. 328

[8] Kapranova, A. B., Lebedev, A. E., Solopov, S. A. and Melzer, A. M. The application process of the Ornstein-Ulenbek to the formation of cavitation bubbles. Czasopismo techniczne. Mechanika. (Krakov, Poland). 113(2), 2016, pp. 136-144.

[9] Kapranova, A. B., Lebedev, A. E., Meltser, A. M., Solopov, S. A. and Nekludov, S. V. Stochastic model of process of formation of cavitation bubbles in the flow path of control valve. Vestnik IGEY (Herald of IGEY). 4, 2016, pp. 97-104. (DOI) 10.17588/2072-2672.2016.4.024-029.

[10] Kapranova, A. B., Lebedev, A. E. and Meltser, A. M. The definition of the integral characteristics of the process of formation of cavitation bubbles when operating the control valve. 3rd international Conference on Chemical Engineering, J. Chem. Eng. Process Technol., Chicago, Illinois, USA, 8(5), 2017 p. 58. (DOI) 10.4172/2157-7048-C1-009.

[11] Kumzerova, Ye. YU. and Shmidt, A. A. Numerical modeling of nucleation and bubble dynamics with a rapid drop in fluid pressure. Zhurnal tekhn. fiziki (Journal Tehn. Physics). 2(7), 2002, pp. 36-40.

[12] Patent on the model 175776 Russian Federation, IPC F16K 1/12, F16K 47/14, F16K 3/24. Direct-acting control valve / A.E. Lebedev, A.B. Kapranova, A.M. Melzer, S.A. Solopov, D.V. Voronin, V.S. Neklyudov, E.M. Serov. Published on May 12, 2018. Bulletin of Inventions of the Russian Federation. No. 34.

[13] Patent 2645103 Russian Federation, IPC F16K 1/12, F16K 47/02. Direct-flow valve / AE Lebedev, A.B. Kapranova, A.M. Melzer, D.V. Voronin, V.S. Neklyudov, E.M. Serov. Published on February 15, 2018. Bulletin of Inventions of the Russian Federation. No 5.

[14] Arzumanov, E. S. Hydraulic regulating bodies of automated control systems. Moscow: Mechanical Engineering, 1985, pp. 256.

[15] Arzumanov, E. S. Calculation and selection of regulatory bodies of automatic systems. Moscow: Energia, 1971, pp. 112.

[16] Altshul, A. D. Hydraulic resistance. Moscow: Nedra, 1970, pp. 216.

[17] Zaporozhets, E. P., Kholpanov, L. P., Siebert, G. K., Artemov, A. V. Investigation of vortex and cavitation flows in hydraulic systems. Theor. Basic. chem. Technol, 38(3), 2004, pp. 243-252.