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DETERMINATION OF THE AVERAGE PARAMETERS OF CAVITATION BUBBLES IN THE FLOWING PART OF THE CONTROL VALVES

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ABSTRACT

A stochastic model of bubble formation during the cavitation mode of the valve is proposed on the basis of the Ornstein-Uhlenbeck process formalism. The obtained differential bubble distribution function by their radii is used to determine the average parameters of the initial stage of hydrodynamic cavitation.

Keywords: control valve, cavitation regime, bubble formation, stochastic model, average parameters.

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1. INTRODUCTION

Determination of the average parameters of cavitation bubbles in the flowing part of the control valves. The effect of cavitation in the flow-through part of the control valve has a significant effect on the movement of the working medium and adversely affects the performance of this device. The task of revealing the constructive and regime parameters that determine the cavitation regime of the valve can be solved with the help of a stochastic study of the initial stage of the bubble formation process. This task does not lose its relevance even in the presence of many models with both a deterministic and a stochastic approach [1-3].

The describing of the behavior of a single bubble by using the equation of Rayleigh-Lamb (Rayleigh-Plesset) or its modifications [4] which take into account inertial, thermal and diffusion effects, belong to the classical deterministic models. There are three main types of stochastic models that are related to the description of the formation in the fluid steam nuclei (the nucleons): homogeneous [5-7], heterogeneous [8, 9] and the modified homogeneous taking into account the factor of heterogeneity of the environment [10]. In some works [11] proposed postulated the laws of the distribution of heterogeneous nuclei (normal, lognormal, equally likely) based on experimental data. The laws of the distribution of heterogeneous nuclei (normal, lognormal, equally likely) based on experimental data are proposed as postulates in some works [11]. A combined approach based on the description of the motion of the carrier phase as a continuum in space-time variables, Euler and the dispersed phase in the Lagrange variables for the selected system report in a given time [12]. A combined approach is based on the description of the motion of the carrier phase as a continuum in space-time variables, Euler and the dispersed phase in the Lagrange variables for the selected system report in a given time [12].

The target of this investigation is research of the average parameters of cavitation bubbles in the flowing part of the control valves.

A stochastic model of bubble formation during the cavitation mode of the valve is proposed on the basis of the Ornstein-Uhlenbeck process formalism [13]. The obtained differential bubble distribution function by their radii is used to determine the average parameters of the initial stage of hydrodynamic cavitation.

2. STOCHASTIC MODEL

The formation of bubbles is proposed to be described by a random process Markov A. A., when the transition to the subsequent state of the macrosystem of the bubbles is determined by its instantaneous state. It is believed that the conditions of stationarity (in the sense of the possible origin offset time) and homogeneity (with the possible dependence of the probability distributions from the time intervals) are met for this process.

It is assumed that there is the energy isolation of macro bubbles of spherical shape according to the Gibbs ensemble. Due to the implementation of the principle of maximum entropy (in case the increasing order of it and the saving after reaching the equilibrium state of the system) we use the equation of Fokker-Planck with diffusion and drift terms relative to the equilibrium distribution function of the state of formed bubbles depending on the time t and the stochastic energy of a single bubble E. The radius *r* and the velocity of center of mass *v* of the bubble are selected as micro parameters of the Gibbs ensemble. In the case where the element of phase space is selected as $d\Omega' = vdvdr$ the energy representation of the equation Fokker-Planck [15] has the form

$$\frac{d\Phi(t,E)}{dt} = \frac{dE_0}{dt}\left[\frac{\partial}{\partial E}\left(E\frac{\partial\Phi}{\partial E}\right) + \frac{1}{E_0}\frac{\partial(E\Phi)}{\partial E}\right] \tag{1}$$

with its solution in the form $\Phi(t,E(t,r,v)) = A'\exp[-E(t,r,v)/E_0]$ and with the normalization condition for $\int_{\Omega'}\Phi(t,E(t,r,v))d\Omega' = 1$ for constant A', where t is the time parameter; E_0 - the energy of the macrosystem of bubbles at the time of stochastic. The use (1) allows to determine the number of bubbles

$$dN = A\exp[-E(u,q)/E_0]d\Omega \tag{2}$$

In the element of phase volume $d\Omega = r_c v_L dudq$, $u = r/r_c$, $q = v/v_L$ and build a differential distribution function of bubbles in the specific radius of the element of phase volume

$$F(u) \equiv N^{-1}(dN/du). \tag{3}$$

where are r_c и v_L - typical values for the radius of the bubble and the speed of movement of the liquid; $A = N^{-1}\int_{\Omega}\exp[-E(u,q)/E_0]d\Omega$.

The modeling of the stochastic energy of a single bubble [14] is based on the stages of its formation during the liquid flow in the flow path of control valve

$$E(u,q)=v_L^2 q^2 f_1(u)+f_2(u)\,, \tag{4}$$

$$f_1(u)\equiv(b_1 r_c^4 u^4+b_2)/(r_c u)\,, \tag{5}$$

$$f_2(u)\equiv b_3 M^2/(r_c u)^5+(b_4+b_5 r_c u)r_c^2 u^2\,. \tag{6}$$

The expressions (5), (6) contain: constants $b_0=\alpha_g\rho_g+\alpha_s\rho_s$, $b_1\equiv 2\pi b_0/3$, $b_2\equiv\rho_L k_\zeta \zeta_{12}/4$, $b_3\equiv 5\pi b_1/12$, $b_4\equiv 4\pi\sigma$, $b_5\equiv 8\pi P_s/3$; α_g, α_s - the volume fractions of gas and vapor in the cavity of the bubble; ρ_g, ρ_s, ρ_L - the densities of gas, vapor and liquid; M - the random component of the angular momentum for a single bubble; k_ζ - the coefficient of proportionality; $\zeta_{12}=\zeta_1+\zeta_2$ - the coefficient of resistance of liquid for its transition region movement (the range of variation of the Reynolds criterion $10<\mathrm{Re}<10^4$), which by the principle of superposition of local losses is defined by two components ζ_1, ζ_2 for laminar ($\mathrm{Re}\le 10$) и and turbulent ($\mathrm{Re}\ge 10^4$) plots of the current; σ - the surface tension coefficient; P_s - the saturated steam pressure.

The values ζ_1, ζ_2 are determined by the design parameters of the regulating device (e.g., a nominal diameter D_y or diameter and length of the throttle channels, etc.), physico-mechanical properties of the fluid (its viscosity) and the inner surface of the flow part of the valve (the value of the absolute equivalent roughness). The function includes: the formation energy of a cavity (in case of equal pressures of the liquid and saturated vapor) and free spherical surface; the energy of filling of the bubble by the condensed steam; the kinetic energies for the motion of a bubble in the liquid and vortex motion of gas and vapor inside the bubble; the energy of interaction of bubble with a liquid (according to the formula of Weisbach for the differential of pressure in the valve). In accordance with the expressions (2), (4)-(6) the sought-for function (3) has the form

$$F(u)=\beta\left[E_0/f_1(u)\right]^{1/2}\exp\left[-f_2(u)/E_0\right]\mathrm{erf}\left\{v_L\left[f_1(u)/E_0\right]^{1/2}\right\}, \tag{7}$$

where are $\beta\equiv\lambda_0^2/\left[4\pi^2 r_c(\mu_1+\mu_2/2+\mu_3/3)\right]$, $\lambda_0\equiv(8/3)\pi^{3/2}/\omega_y-b_5$, $\mu_1\equiv(\psi_0-\psi_1)(\varphi_0-\varphi_1)$, $\mu_2\equiv\psi_1(\varphi_0-\varphi_1)+\varphi_1(\psi_0-\psi_1)$, $\mu_3\equiv\psi_1\varphi_1$, $\lambda_4\equiv v_L^2(b_1 r_c^4+b_2)$, $\varphi_0\equiv\exp\left[-f_2(1)/E_0\right]$, $\varphi_1\equiv\varphi_0(5b_3M^2/r_c^5-\lambda_2)/E_0$, $\psi_0\equiv\left[f_1(1)/E_0\right]^{1/2}\mathrm{erf}\left\{\left[E_0/f_1(1)\right]^{1/2}/v_L\right\}$, $\lambda_2\equiv r_c^2(2b_4+3b_5r_c)$, $\omega_y=\pi D_y^2/4$.

The values of the model parameters E_0 and M are determined from system of equations

$$r_c\psi_0\varphi_0/(N\gamma)^3=\int_0^1 u\left[E_0/f_1(u)\right]^{1/2}\exp\left[-f_2(u)/E_0\right]\mathrm{erf}\left(v_L\left[f_1(u)/E_0\right]^{1/2}\right)du, \tag{8}$$

$$\int_\Omega E(u,q)dN=v_L^2\left\{b_2/(r_c u)+\left[r_c^3 b_1+(8/3)\pi^{3/2}r_c^3\sigma\omega_y^{1/2}/v_L^2\right]\int_\Omega u^3 dN\right\}, \tag{9}$$

where are $\gamma\equiv(P_{\max}/P_s)^{1/k}r_c^3$, k - the adiabatic index. The equation (8) follows from the adiabatic ratio $(P_{\max}/P_s)^{1/k}=(r_s/r_c)^3$ for pressures in the center of the bubble at different points in time: in the formation of a cavity (at saturated vapor pressure P_s) and when the minimum value of the radius of the spherical bubble observed (at maximum pressure $P_{\max}$). The equation (9) is the equation of the energy balance between the stochastic energy of the macrosystem bubbles (left part of the equation) and the energy expended on hydraulic fracturing fluid (in particular, in the formation of the surface of the bubble and its interactions with the liquid and the movement, in right side of the equation).

The solution of system (8), (9) has the form

$$E_0 = [\psi_{01}\lambda_2(\mu_4 + \mu_5) + 60\lambda_1\lambda_4] / [12\pi^4\psi_{01}(\mu_6 + \mu_7)], \qquad (10)$$

$$M = \left(r_c^{\,5}[3(2\gamma^{1/3} - 1)E_0 - \lambda_2] / (5b_3)\right)^{1/2}, \qquad (11)$$

where $\mu_4 = (\lambda_2 - \lambda_3 r_c)\psi_{11} / \psi_{01}$, $\mu_5 = 3\lambda_2 + 15\lambda_0 r_c^{\,3}$, $\mu_6 = 20 r_c(1 + \lambda_1)$, $\mu_7 = (2\gamma^{1/3} - 1)(3 + \psi_{11} / \psi_{01})\lambda_2$, $\mu_8 = \lambda_4 / (\lambda_5 v_L)$, $\lambda_1 \equiv b_1 r_c^3 J_{11} + b_2 r_c^{-1} J_{12}$, $\lambda_3 \equiv 3(5b_4 + \lambda_0 r_c) r_c$, $J_{11} \equiv \int_0^1 (b_1 r_c^4 u^4 + b_2) u^4 du$, $J_{12} \equiv \int_0^1 (b_1 r_c^4 u^4 + b_2) du$, $\psi_{01} = \mu_9 \,\mathrm{erf}\left[\lambda_4 / (r_c v_L^2)\right]$, $\psi_{11} = \mu_8 [v_L \pi^{-1/2} \psi_{01}^{-1} \exp(-\lambda_4 / r_c) - 2^{-1}]$, $\mu_9 = (r_c v_L^2 / \lambda_4)^{1/2}$.

Applying expression (7) given (5), (6), (10), (11) the integral characteristics of the process of formation of cavitation bubbles (its average for the ensemble characteristics of the radius, volume and surface) in the flow path of the valve [16]. Applying expression (7) given (5), (6), (10), (11) can calculate

$$\langle r \rangle = r_c \int_\Omega u dN, \ \langle V \rangle = (4r_c^{\,3} / 3) \int_\Omega u^3 dN, \ \langle S \rangle = 4r_c^{\,2} \int_\Omega u^2 dN, \qquad (12)$$

$$\langle r \rangle = 4\pi^3 \beta r_c (\mu_1 / 2 + \mu_2 / 3 + \mu_3 / 4), \qquad (13)$$

$$\langle V \rangle = 3\pi^4 \beta r_b^{\,3} (\mu_1 / 4 + \mu_2 / 5 + \mu_3 / 6) / \lambda_0, \qquad (14)$$

$$\langle S \rangle = 32\pi^5 \beta r_b^{\,2} (\mu_1 / 3 + \mu_2 / 4 + \mu_3 / 5). \qquad (15)$$

Included in expressions (13)-(15) the coefficients μ_1, μ_2, μ_3 depend not only on physico-mechanical properties of the liquid and the inner surface of a flowing part of a control valve, but are functions from constructive-regime parameters.

3. RESULTS AND DISCUSSIONS

In particular, these parameters include the diameter of conditional pass D_y and conditional bandwidth of the valve K_{vy}, m^3/h, which corresponds to the expression $\zeta_{12} = [K_{vy} / (5{,}04 \cdot 10^4 \omega_y)]^2$. According to the following input data (ρ_g =1,205 kg/m^3; ρ_s =1,44·10^{-2} kg/m^3; ρ_L =10^3 kg/m^3; σ=7,284·10^{-4} H/m; k=1,3; P_s =10^{-3} Pa; $P_{\max}$ =1,3·10^8 Pa; r_c =10^{-3} m) and the range of change of parameters of the valve (D_y =(0,22-0,28) m^2; K_{vy} =(1,4-1,8)·10^3 m^3/h) the resulting range of variation of the main characteristics of the model are obtained: E_0 =(9,47-10,79)·10^{-7} j и M =(0,638-3,01)·10^{-11} kg·m^2/c. The simulation results are presented in Fig. 1 and 2.

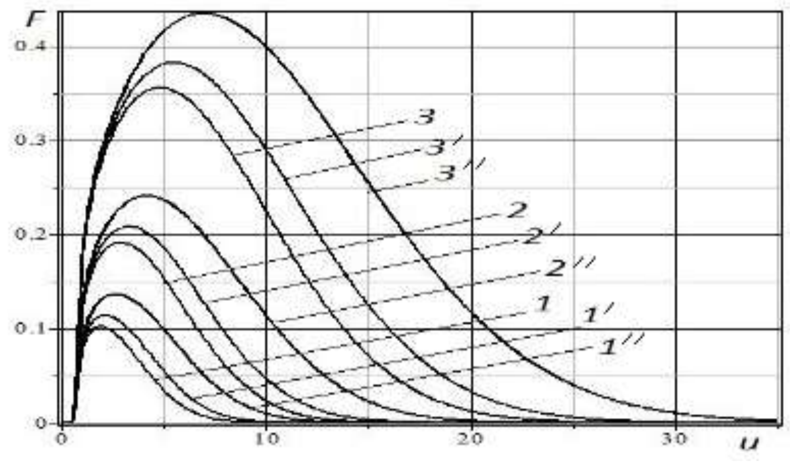
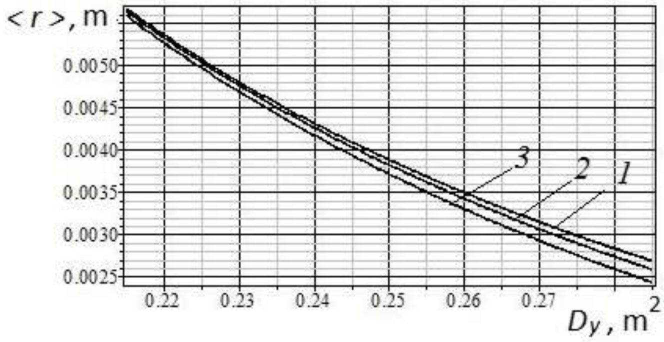


Figure 1 Dependence $F(u)$ for the differential distribution function of the number of cavitation bubbles at a specific radius in the early stages of cavitation in a flowing part of the axial valve:

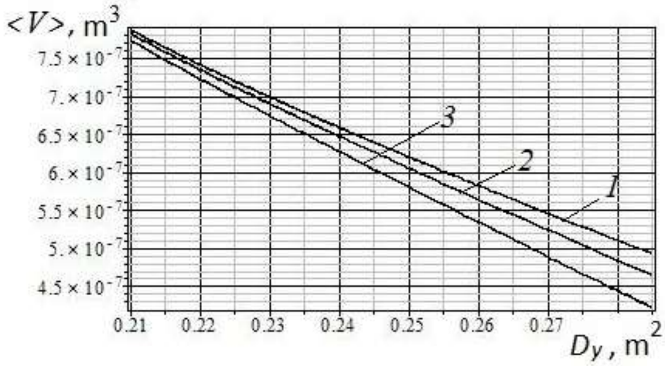
$\alpha_g = \alpha_s = 0,5$; 1, 2, 3 – K_{vy} = 1,4·10^3 m^3/h; 1', 2', 3' – K_{vy} = 1,6·10^3 m^3/h; 1", 2", 3" – K_{vy} = 1,8·10^3 m^3/h; 1, 1', 1" – D_y = 0,28 m^2; 2, 2', 2" – D_y = 0,25 m^2; 3, 3', 3" – D_y = 0,22 m^2.

The graphs of the dependence $F(u)$ of (7) according to Fig. 1 allow us to estimate the most likely values for the conditional radius of the cavitation bubble u_p = (2-7) or for its size r_p =(0,2-0,7)·10^{-2} m at various values of the parameters K_{vy} and D_y within the specified limits. For example, when the reducing the nominal diameter of 1.27 times takes place the maximum value of the function increases by 3.3 times (the graphs 1 and 3, Fig. 1) with the trend of increasing the energy parameter for stochastic of macro system of bubbles is more than 6 times. In particular, for K_{vy} = 1,4·10^3 m^3/h the value E_0 increases from 9,472·10^{-8} j to 6,546·10^{-7} j when changing D_y from 0,28 m^2 to 0,22 m^2. A similar trend is observed for the random component of the angular momentum of a single bubble (the parameter M), when the same range of change D_y and K_{vy} = 1,4·10^3 m^3/h the value M increases 2.8 times (from 6,38·10^{-12} kg·m^2/c to 1,804·10^{-11} kg·m^2/c). The decrease in throughput of the valve K_{vy} is 1.3 times reduces the most likely values of the conditional radius of the bubbles by 1.4 times (the graphs 3" and 3; 2" and 2; 1" and 1, Fig. 1).

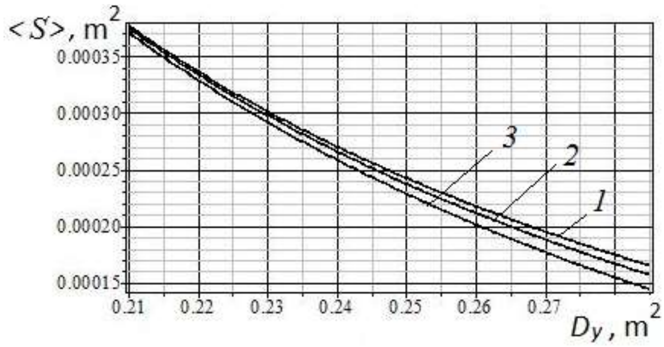
The integral characteristics of the process of formation of bubbles according to the expression (12) shown in Fig. 2, a-c, depending on the parameters D_y and K_{vy}. For the initial values of the nominal diameter D_y of the selected limit (0,22-0,28) m^2 the dependence of the average of the ensemble of bubbles of radius $\langle r \rangle$, volume $\langle V \rangle$, surface area $\langle S \rangle$ from the conditional throughput of the valve K_{vy} observed weak. However, with increasing values D_y up to the maximum specified interval and with increased of parameter K_{vy} 1.28 times the radius value $\langle r \rangle$ is reduced to 1.08% (Fig. 2, a); volume $\langle V \rangle$ - 1.04% (Fig. 2, b); surface area $\langle S \rangle$ - of 1.13 times (Fig. 2, c).



a)



b)



c)

Figure 2 Dependence of averages on the ensemble characteristics of the radius, volume and surface of the bubble from the nominal diameter D_y of the axial valve: $\alpha_g = \alpha_s = 0{,}5$; a) $\langle r \rangle$; b) $\langle V \rangle$; c) $\langle S \rangle$; 1 – K_{vy} = 1,4·10^3 m^3/h; 2 – K_{vy} = 1,6·10^3 m^3/h; 3 – K_{vy} = 1,8·10^3 m^3/h.

4. CONCLUSION & SIGNIFICANCE

The stochastic model of the bubble formation process proposed by the authors is used to calculate the averaged values of the radius, surface area and volume of the bubble in the cavitational operating mode of the control valve.

Stationary and homogeneous process Markov A. is used as the basis for the stochastic description of the initial stage of hydrodynamic cavitation. In the future, this model can be used to improve the engineering methods for calculating the characteristics of control valves as well as ways to choose them.

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