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CALCULATION OF THE VELOCITY OF PROPAGATION OF SHOCK PRESSURE IN A GAS-LIQUID STREAM

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Аннотаця.Ушбу мақолада реал суюқликлар таркибида 0,5-2,5 фоиз миқдорида эримаган газлар мавжудлиги тадқиқотлар билан асосланади. Реал суюқликни қувурларда газли суюқлик оқими эканлигини инобатга олиб қувурларни гидравлик зарбага ҳисоблашда зарба тўлқини тарқалиш тезлигини аниқлаш илмий аҳамият касб этади. Бу ишда босим қувури узунлиги бўйича газли суюқлик оқимида босим ўзгарганда газ ва суюқлик ҳажмлари(зичликлари) ўзгаришлари ҳисобга олиниб гидравлик зарба тўлқини тарқалиш тезлигини аниқлаш учун боғланиш олинган.

Таянч иборалар: гидравлик зарба тўлқини тарқалиш тезлиги, газли суюқлик оқими, газ ва суюқлик зичликлари, реал(ёпишқоқ) суюқликлар, Пуассон коэффициенти, қувурда босим ўзгарганда газ ва суюқлик ҳажмлари ўзгариши, эримаган газ, босим қувури, насос станцияси, суюқликнинг эластиклик модули, қувур материалининг эластиклик модули, суюқликнинг солиштирма оғирлиги.

Аннотация. В статье обосновано в реальной жидкости содержится 0,5-2,5 % нерастворенные газы, которые известно из проведенных исследований. При расчете напорных трубопроводов на гидравлические удар в газожидкостном потоке определение скорости распространения ударной волны имеет научное значение. В работе получено с учетом изменения объемов (плотности) газа и жидкости при изменение давления по длине напорного трубопровода определение зависимости скорости распространения ударного давления в газожидкостном потоке.

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Ключевые слова: скорость распространения ударной волны, газожидкостный поток, плотности газа и жидкости, реальная (вязкая) жидкость, коэффициент Пуассона, приращение объема газа и жидкости при изменение давления, нерастворенный газ, напорный трубопровод, насосная станция, модуль упругости жидкости, модуль упругости материала труб, удельный вес жидкости.

Abstract. The article substantiated in real fluid contains 0.5-2.5% undissolved gases, which are known from the conducted studies. When calculating pressure pipelines for hydraulic shock in a gas-liquid flow, determining the velocity of propagation of a shock wave is of scientific importance. In this work, taking into account changes in the volumes (density) of gas and liquid with a change in pressure along the length of the discharge pipe, we determined the dependence of the velocity of propagation of shock pressure in a gas-liquid flow.

Key words: shock wave propagation velocity, gas-liquid flow, gas and liquid densities, real (viscous) fluid, Poisson's ratio, gas and liquid increment with pressure change, undissolved gas, pressure pipe, pumping station, liquid elastic modulus, material elastic modulus pipes, the specific gravity of the fluid.

A variety of viscous liquids (water, oil, and fuel oil) are often pumped through pressure pipelines along with gases. In pressure pipelines of water supply systems, oil pipelines, hydrotransport, irrigation, etc. at atmospheric pressure and a temperature of 10-150 ° C, 0.5-2.5% undissolved air is contained [4,5]. The softening effect of undissolved air was pointed out by N.E.Zhukovsky when describing experiments performed under his supervision at the Alekseevsky pumping station [1]. Therefore, a method for determining the propagation velocity of a hydraulic shock wave in gas-liquid streams is of interest. In particular, the work [2] is devoted to this issue. However, the author [2], when deducing the calculated dependence for determining a, neglected the change in the volume of gas in the pipe with a change in pressure during the impact process and took this circumstance into account only when determining the flow density. It is difficult to agree with this, since it is known that the presence of even a small volume of gas in a liquid significantly reduces the velocity of wave a, mainly due to the compressibility of gases [1-11], while the flow density does not change significantly.

In [3, 4], a dependence is given for determining the velocity of a shock wave in a three-phase liquid. This dependence for the gas-liquid flow has the form

$$a = \frac{\sqrt{\frac{\varepsilon_1 g}{\gamma_1}}}{\sqrt{m_1\left[1+\frac{(1-\mu^2)D}{E\delta}\varepsilon_1\right]+m_3\frac{\gamma\ R\varepsilon_1}{\gamma_1 \Delta p}}}, \qquad (1)$$

where ε_1 – modulus of elasticity of a liquid (volumetric), kN/m^2; γ_1 – specific gravity of the liquid, N/m^3; m_1 and m_2 – concentration of liquid and air in the gas-liquid stream, fractions of a unit; μ – Poisson's ratio of pipe material; D and δ – pipe wall diameter and thickness, mm; E – modulus of elasticity of the pipe material, kN/m^2; γ – specific gravity of the gas-liquid flow, N/m^3; Δp – impact pressure, N/m^2;

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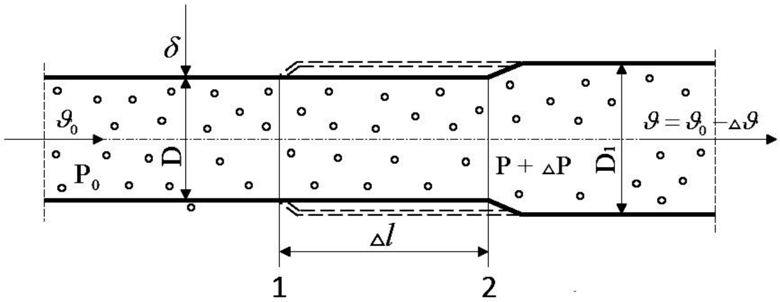
$$R = 1 - \left(\frac{p_0}{p_0+\Delta p}\right)^{\frac{1}{\chi}}, \quad (2)$$

p_0 – initial pressure, N/m^2; χ – the adiabatic index (χ=1,41).

Formula (1) is suitable mainly for low gas contents. The use of the formula is unsuccessful because it does not indicate whether the concentration of m_3 gas refers to atmospheric pressure pa or to the initial pressure p_0. In the first case, the formula should take into account the change in gas volume with increasing pressure from p_a to p_0, and in the second case, the value m_3 is variable and difficult to use when calculating pressure pipelines of pumping stations for hydraulic shock.

In [3,4], for the first time, the effect of gas on the flow of the hydraulic shock process in a liquid was taken into account, which is a great merit of the authors of [3,4].



When deducing the formulas below, it can be assumed that the hydraulic shock in the pipeline with gas-liquid molasses occurred due to a decrease in velocity by $\Delta\vartheta$ (see Figure), while the pressure increases by Δp. The increased pressure ($p + \Delta p$) began to move along the length of the pipe at a speed of; by the time t, it had reached section 2, and by the time $t + \Delta t$, it had reached section 1. At the same time, the volume of compartment 1-2 (W) increased and became equal

$$W' = W + \Delta W. \quad (3)$$

The increment of the mass of the gas-liquid flow in compartment 1-2 during the time Δt is equal to the difference between the mass entering during this time through section 1 (m_1) and the mass exiting through section 2 (m_2), i.e.

$$\Delta M = M_1 - M = m_1 - m_2, \quad (4)$$

where M_1 and M are the masses of the gas–liquid flow in compartment 1-2, respectively, at pressures ($p + \Delta p$) and ρ.

The mass M1 can be expressed by the formula

$$M_1 = \rho_{ж} W_{ж} + \rho_{г} W_{г}, \quad (5)$$

where $\rho_{ж}$ and $\rho_{г}$ - densities of liquid and gas in compartment 1-2 at absolute pressure ($p + \Delta p$), kg/m^3; $W_{ж}$ and $W_{г}$ - volumes of liquid and gas at the same pressure, m^3.

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Using the theory of elasticity, we can write that

$$\rho_{ж}' = \rho_{ж} + \triangle \rho_{ж} = \rho_{ж}\left(1+\frac{\triangle p}{E_{ж}}\right), \qquad (6)$$

$$\rho_{г}' = \rho_{г} + \triangle \rho_{г} = \rho_{г}\left(1+\frac{\triangle p}{E_{г}}\right) = \rho_0 \frac{(p+\triangle p)}{p_a}, \qquad (7)$$

where $\triangle \rho_{ж}$ and $\triangle \rho_{г}$ - increment of liquid and gas densities as pressure changes; $\rho_{ж}$ - the density of a liquid at absolute pressure p (it is assumed that it is the same at atmospheric pressure, T/m^3); $E_{ж}$ and $E_{г}$ - elastic modulus (volume) of liquid and gas, kN/m^2.

Here, the isothermal process of changing the volume of gas with a change in pressure is adopted. Apparently, it would be more correct to use an adiabatic process, as it was done by other authors [3,4], however, as calculations show, this refinement does not give a significant difference in the final result and at the same time significantly complicates the form of the formula if extended to the case of not only small but also large gas contents.

In the case of an isothermal process, formula (7) assumes $E_{г} \approx p$.

Volumes $W_{ж}$ and $W_{г}$ from equation (5) during the isothermal process, we express

$$W_{г}' = \varphi \frac{p_a W}{(p+\triangle p)100}, \qquad (8)$$

$$W_{ж}' = W' - W_{г}' = W' - \varphi \frac{p_a W}{(p+\triangle p)100} = W\left[1+\frac{\triangle pD}{E\delta} - \varphi \frac{p_a}{100(p+\triangle p)}\right], \qquad (9)$$

where the expression known from the theory of elasticity is used

$$W' = W\left(1+\frac{\triangle pD}{E\delta}\right). \qquad (10)$$

New designations are used in the latest formulas: φ is the gas content, % of the volume W, reduced to atmospheric pressure; E – the modulus of elasticity of the pipe material, kN/m^2.

Taking into account the expressions (6), (7), (8) and (9) equation (5) after transformations takes the form

$$M_1 = \rho_{ж} W\left[1+\frac{\triangle pD}{E\delta} - \frac{\varphi p_a}{100(p+\triangle p)} + \frac{\triangle p}{E_{ж}} + \frac{\triangle p^2 D}{E_{ж} E\delta} - \frac{\varphi p_a \triangle p}{100 E_{ж}(p+\triangle p)} + \frac{\rho_0 \varphi}{\rho_{ж} 100}\right]. \qquad (11)$$

Reasoning similarly, one can obtain

$$M = \rho_{ж} W\left(1 - \frac{\varphi p_a}{100 p} + \frac{\rho_0 \varphi}{\rho_{ж} 100}\right). \qquad (12)$$

The difference between the masses entering the compartment during the time Δt and leaving it at the same time is approximately equal to

$$m_1 - m_2 \approx \triangle \vartheta \omega \triangle t \rho_{см}', \qquad (13)$$

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where ω is the living cross–sectional area of the pipe at absolute pressure p, m^2; $\rho_{см}$ - density of the gas-liquid flow at the same pressure, T/m^3.

Substituting expressions (11), (12) and (13) into equation (4), after transformations and exclusion of terms of high order of smallness, we obtain

$$a\rho_{ж}\left(\kappa+\frac{\varphi p_a}{100p}\right)=\triangle\vartheta\rho'_{CM}, \qquad (14)$$

where accepted

$$\kappa=\frac{\triangle pD}{E\delta}-\frac{\varphi p_a}{100(p+\triangle p)}+\frac{\triangle p}{E_{ж}}, \qquad (15)$$

$$W=\omega\triangle l=\omega a\triangle t, \qquad (16)$$

where Δl is the length of compartment 1-2 (see figure).

The density of the gas-liquid flow, taking into account the above dependencies, can be approximated using the formula

$$\rho'_{CM}=\frac{W'_{ж}\rho'_{ж}+W'_{г}\rho'_{г}}{W'}=\rho_{ж}\left(1+\kappa+\frac{\triangle p\varphi}{100}\right)\left(1+\frac{\triangle pD}{E\delta}\right)^{-1}, \qquad (17)$$

where indicated

$$\triangle p=\frac{\rho_0}{\rho_{ж}}. \qquad (18)$$

Equation (14) includes two unknowns a and Δp, therefore, the well-known formula of Professor N.E.Zhukovsky, written for a gas-liquid flow, should also be used to solve it,

$$\triangle p=a\triangle\vartheta\rho'_{CM}. \qquad (19)$$

Formula (16) is substituted into equation (18), then

$$a=\frac{\triangle p\left(1+\frac{\triangle pD}{E\delta}\right)}{\triangle\vartheta\rho_{ж}\left(1+\kappa+\frac{\triangle\rho\varphi}{100}\right)}. \qquad (20)$$

After substituting formulas (17) and (20) into equation (14), the latter takes the form

$$\triangle p\left(1+\frac{\triangle pD}{E\delta}\right)^2\left(\kappa+\frac{\varphi p_a}{100p}\right)=\triangle\vartheta^2\rho_{ж}\left(1+\kappa+\frac{\triangle\rho\varphi}{100}\right)^2. \qquad (21)$$

At φ = 0, i.e. in the absence of gas in the liquid, a joint solution of formulas (20) and (21) leads to the well-known formula of N.E.Zhukovsky for determining the velocity of propagation of a shock wave in a liquid [1]

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$$a = \frac{\sqrt{\frac{E_{ж}}{\rho_{ж}}}}{\sqrt{1+\frac{E_{ж}D}{E\delta}}}. \qquad (22)$$

As an example of the application of equations (20) and (21) and to compare them with the formulas of other authors, an example calculation is given below.

A gas-liquid steam is pumped through a pipeline (D=400 mm, δ=8 mm, steel material) at $t = 20^0C$ at a speed of $\vartheta = 1.03$ m/s. The absolute pressure developed by the pumps at the beginning of the pressure pipeline, p = 4035 kN/m^2. Gas content φ = 19,8 %. The density of the liquid $\rho_ж = 0.885$ T/m^3, the density of the gas at a given temperature $\rho_0 = 0.00072$ T/m^3, the modulus of elasticity of the liquid $E_ж = 1.4*106$ kN/m^2. When the gate is suddenly closed at the end of the pipeline, the velocity drops to zero, that is, $\vartheta=\vartheta_0-\Delta\vartheta=0$, and therefore $\Delta\vartheta=1.03$ m/sec. In this case, the pressure throughout the pipeline first increases to a value of p, and then begins to fluctuate around this level with an amplitude of ±Δp. It is required to determine the values of Δp and a.

As a result of solving equation (21), we find Δp = 660 kN/m^2 and according to formula (20) a = 746 m/s.

According to the formula of N.E.Zhukovsky (22), we determine that a = 1091.2 m/s.

Given by the formula in [2], we can calculate

$$a = \frac{\sqrt{\frac{gE_ж}{\gamma_ж}}}{\sqrt{C\left[\frac{\gamma_г E_ж}{\gamma_ж \chi p} - 1 + \frac{DE_ж}{\delta E}\left(\frac{\gamma_г}{\gamma_ж} - 1\right)\right] + 1 + \frac{DE_ж}{\delta E}}} = 1195 \text{ м/сек},$$

where C = 0,21 - gas content, fractions of a unit.

According to formula (1), assuming that m_1=0.79 and m_2=0.22, and also considering that the specific gravity of the mixture is $\gamma = \gamma_1 m_1 + \gamma_3 m_3$ and using formula (19) as the second equation, we obtain a=205 m/s and Δp=143 kN/m^2. Such a small wave velocity was obtained mainly because formula (1) was derived for small gas contents.

Based on the above analysis and comparative calculation, conclusions can be drawn:

1. The formula in [2] gives a completely complete result, since according to it the velocity of the shock wave, taking into account the gas, is even higher than for a homogeneous liquid according to formula (22), which, of course, is unrealistic.

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2. The given dependence (21) for calculating the propagation velocity of a hydraulic shock wave in gas-liquid streams can be used in the design of pressure pipelines for water supply systems, oil pipelines, hydraulic transport, irrigation, and others.

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