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CALCULATION OF WATER HAMMER WITH INCREASE IN PRESSURE WITH RUPTURE OF FLOW CONTINUITY

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Abstract. The article presents a study on the determination of the maximum pressure of a hydraulic shock, taking into account the rupture of the flow discontinuity. Calculated analytical dependences for determining the maximum pressure of a hydraulic shock, taking into account the profile of pressure pipelines, are obtained. The reliability of the obtained dependencies is justified by experimental studies.

Key words: water hammer from pressure increase, pumping unit, pump, flow continuity break, pipeline strength, real liquid.

Аннотация. В статье приведено исследование по определению максимального напора гидравлического удара с учетом разрыва непрерывности потока. Получены расчетные аналитические зависимости для определения максимального напора гидравлического удара с учетом профиля напорных трубопроводов. Достоверности полученных зависимостей обоснованы экспериментальными исследованиями.

Ключевые слова: гидроудар от повышения давления, насосная установка, насос, нарушение сплошности потока, прочность трубопровода, реальная жидкость.

Аннотация. Мақолада оқим бутунлиги узилиши билан содир бўладиган гидравлик зарбанинг максимал напорини аниқлаш бўйича тадқиқоти келтирилган. Напорли қувур узунлиги бўйича ётиш профили ҳолатларини ҳисобга олиб гидравлик зарбанинг максимал напорини аниқлаш бўйича ҳисобий аналитик боғланишлар олинган. Олинган боғланишларнинг ишончилиги экспериментал тадқиқотлар билан асосланган.

Калит сўзлар: босимнинг ортишидан содир бўладиган гидравлик зарба, насос қурилмаси, насос, оқим бўтунлигининг узилиши, қувур мустаҳкамлиги, реал суюқлик.

Introduction. At present, calculations of pressure pipelines for hydraulic shock from pressure increase are of great importance. More accurate calculations allow using pipes without excessive safety margins, and more correctly selecting protective equipment for them [1,2,3,4].

The task of refining existing and developing new methods for calculating hydraulic shock requires new theoretical and experimental studies of hydraulic shock in real (viscous) liquid [5,6,7,8].

The aim of the research in this paper is a theoretical and experimental study of hydraulic shock with an increase in pressure in simple water pipes taking into account friction forces and the development of a method for calculating it that is simple enough for practical application [4,5,6].

At present, it can be considered that the theory of hydraulic shock without breaking the continuity of an ideal flow has been developed quite fully [1,2,3,4]. At present, we do not yet have a sufficiently developed theory of hydraulic shock for a real liquid. The latter is explained by certain mathematical difficulties that arise when solving various problems on hydraulic shock after introducing viscous forces into the initial differential equations of unsteady fluid motion. Such issues

as taking into account energy losses during the □restoration□ of friction pressure in the impact phase, the attenuation of impact oscillations over time, and so on remain unresolved to this day [5,6,7].

Hydraulic shock with a break in the continuity of the flow is one of the most complex problems in the theory of unsteady motion of real liquid in pipes [1,2,3,5]. An analysis of studies of hydraulic shock with a rupture of the flow continuity by A.F. Mostovsky, D.N. Smirnov, L.F. Moshnin and a number of other authors shows that there is still no consensus not only on the magnitude, but even on the possibility of increasing the shock pressure above the value determined by the formula of N.E. Zhukovsky [1,2,3,5,8,9].

Research methodology. In this work, the solution of differential equations for the unsteady motion of a low-viscosity real fluid under a quadratic friction law is used to solve the problem of taking into account energy losses during the □recovery□ of friction pressure in the impact phase [5,8,9]. The issue of the maximum possible pressure during a hydraulic shock with a rupture of the flow continuity is considered [3,4,5]. To assess the accuracy of the obtained solutions, their results are compared with the data of experiments carried out on pressure pipelines.

The paper considers the solution to the problem of taking into account pressure losses due to friction during a direct hydraulic shock, which is caused by the instantaneous closing of the valve, starting with an increase in pressure [3,4,5]. Analysis of the existing solutions shows that they are not mathematically correct enough, and the final results are contradictory [5,6,7].

The initial equations are the hydromechanics equations of a real fluid [1,2,6,9]:

$$\left. \begin{aligned} -\frac{\partial H}{\partial x} &= \frac{1}{g} \left(\frac{\partial \vartheta}{\partial t} + \frac{\lambda}{2d} \vartheta^2 \right) \\ -\frac{\partial H}{\partial x} &= \frac{c^2}{g} \frac{\partial \vartheta}{\partial x} \end{aligned} \right\}, \quad (1)$$

Where H - pressure; ϑ - water speed; λ - coefficient of hydraulic resistance; g - acceleration of gravity; d - pipeline diameter; c - shock wave propagation velocity; χ - longitudinal coordinate; t - time.

Equations (1) are integrated under the initial condition

$$0 < x \leq l \quad \vartheta = \vartheta_0, \quad H = H_0 \quad \text{at } t \leq 0$$

and boundary conditions [2,3]

$$x = 0 \quad H = H_0 = \text{const} \quad \text{at any } t;$$

$$x = |l - ct| \vartheta = \frac{g}{c} h_m \left(\frac{l - x}{l} \right) \quad \text{at } 0 \leq t \leq 2l/c, \quad (2)$$

Where ϑ_0 - initial speed of water movement; H_0 - static pressure; h_m - friction pressure losses along the entire length of the pipeline at the initial water velocity, determined by the Darcy-Weisbach formula.

Boundary condition (2) is obtained from the equality of the live force, which determines the speed of water movement during unsteady motion, and the work that is spent on the deformation of the pipeline and water by the pressure difference that occurs during a hydraulic shock in two adjacent sections of the pipeline due to pressure losses due to friction before the shock [2,3].

As a result of the decision, it was determined, what

$$H = H_0 + \frac{c g_0}{g} - \frac{\alpha^2}{3} h_m, \quad (3)$$

Where $\alpha = h_r g (c g_0)^{-1}$ - the ratio of pressure losses due to friction in a steady flow regime to the magnitude of the pressure increase during an impact according to the formula of N.E. Zhukovsky [1].

In dependence (3), the last term expresses the loss of energy due to friction during the impact phase. From this dependence it is not difficult to establish that for values $0 < \alpha \leq 0.5$ with practically acceptable accuracy the maximum possible pressure upon impact can be determined with some reserve using the formula of N.E. Zhukovsky [1]

$$H = H_0 + \frac{c g_0}{g}.$$

Thus, when calculating a direct hydraulic shock, starting with an increase in pressure, when the relative friction losses (α) do not exceed 0.5, the shock pressure can be determined with practically acceptable accuracy using the formula of N.E. Zhukovsky, that is, energy losses during the "restoration" of friction pressure in the shock phase can be neglected.

It should be noted that the conditions $\alpha \leq 0.5$ are met by many water pipelines of water supply systems. The data of experiments by various authors and those conducted by us (the discrepancy is up to 5%) confirm the correctness of the obtained solution.

The paper also presents the results of a theoretical and experimental study of the issue of the maximum possible pressure during a hydraulic shock with a break in flow continuity.

When solving the problem, the following conditions were initially adopted

$$\begin{aligned} 0 \leq x \leq l & \quad g = g_0 & \quad H = H_0 & \quad \text{at } t \leq 0; \\ x = l & \quad H = H_0 = \text{const} & & \quad \text{at any } t \geq 0, \end{aligned} \quad (4)$$

Where h_b - the vacuum value in a pipeline during a hydraulic shock in the pressure reduction phase.

The physical meaning of condition (4) is that during a hydraulic shock, the speed of water movement in the opposite direction, which is achieved by filling the voids in the rupture zone, at the boundary with this zone can only be equal to or less than the speed of water movement in the forward direction. This limitation follows from the law of conservation of energy and the physical condition that during an impact the pressure in the pipeline cannot fall below a certain limit [2,3].

According to this solution, the maximum possible pressure during a hydraulic shock with a break in the continuity of the flow, measured from atmospheric pressure, is [7].

$$H = H_0 + \frac{c g_0}{g} + \Delta h, \quad (5)$$

Where, $0 \leq \Delta h \leq H_0$ - pressure increase due to the elasticity of water and the pipeline in excess of the value determined by the formula of N.E. Zhukovsky [1].

In real conditions, due to pressure losses due to friction in pipelines, the impact movement is reduced compared to the value calculated according to (5). Taking into account the pressure losses due to friction according to A.F. Mostovsky [2], the boundary condition (4) is represented as

$$x=0 \quad g \leq \left| g_0 \sqrt{\frac{H_0 + h_e}{H_0 + h_m + h_e}} \right|, \quad H \geq h_b = \text{const} \quad \text{at } t > 0. \quad (6)$$

Research results. During operation, the hydraulic characteristics of the water pipeline change, and the water supply mode may also change. Since the pressure during a hydraulic shock is of a pulsating nature and can both increase and decrease with a change in the speed of water movement, in dependence (5) the value of Δh is taken to be the maximum possible and equal to H_0 . In this case, neglecting the energy losses that occur during the restoration of static pressure and during the increase in the reverse velocity in the pipeline above the value determined by (6), from (5) we obtain [4,6]:

$$H = (H_0 - h_e) + \frac{c \mathcal{G}_0}{g} \sqrt{\frac{H_0 + h_e}{H_0 + h_m + h_e}} + (H_0 + h_e) \frac{H_0 + h_e}{H_0 + h_m + h_e}. \quad (7)$$

Dependence (7) takes into account the elasticity of water, pipeline and viscous forces and makes it possible to determine the maximum possible pressure during a hydraulic shock with a break in the continuity of the flow.

The results of calculations according to dependence (7) are compared with experiments [2,3]. The agreement between experimental data and theoretical data has sufficient convergence.

An experimental study of hydraulic shock with a break in flow continuity by the above-mentioned researchers [2,3] was carried out on installations with horizontal pipelines. To study the impact in question, an experimental setup was installed in an inclined pipeline, which was represented by a steel pipeline with a diameter of 70 mm, a length of 445 m and static pressures of 51.8 meters and 35.9 meters, respectively. At a distance of 2.5 meters from the pump, the glass pipeline was connected to a steel pipeline through a three-way plug valve, which made it possible to switch the water supply from the pump to one of the two pipelines. The initial section of the steel pipeline, 171 meters long, without any obvious breaks, was laid with a steep climb to the +40.6 meter mark, the rest of the section without breaks had a relatively small climb of +11.2 meters. The installation provided the ability to create a hydraulic shock with both a decrease and an increase in pressure. The hydraulic resistance coefficients of the pipelines were determined empirically [4,7].

The studies were conducted at steady-state water flow rates in a steel pipeline ranging from 0.1 m/s to 2.2 m/s, and in a glass pipeline from 0.1 m/s to 2.6 m/s. The hydraulic shock was created by almost instantaneous (0.02 – 0.05 sec.) closing of the plug valve. The pressure fluctuations during the hydraulic shock were recorded using a specially designed device with a signal sent to the computer. During the experiments, discontinuities in the flow continuity in the pipeline were observed visually (in the steel pipeline through transparent inserts at the plug valve and at the fracture). The methodology for conducting experiments and processing experimental data is given in [4,6].

A total of three series of experiments were performed. The experiments reproduced a hydraulic shock starting with an increase in pressure. A hydraulic shock starting with an increase in pressure was studied on the entire steel pipeline and on a glass one.

The excess of the impact pressure over the value according to the solution of A.F. Mostovsky [2] takes place in the entire range of speeds at which a discontinuity of the flow was observed. In this case, the maximum value of this excess on pipelines without breaks is equal to the static pressure, and on pipelines with a break, it is equal to the height of the water column above the place of the upper break, i.e. the difference between the marks of the break point and the water level in the tank. With an increase in the speed of water movement before impact, under the influence of friction forces,

the increase in impact pressure, arising due to the elasticity of water and the pipeline (in formula (5) the value Δh), decreases [4].

The calculated curves according to dependence (7) quite satisfactorily cover the data from experiments on pipelines without fractures from above.

In experiments on pipelines with a fracture, the pressure resulting from the impact of the settling lower column on the closed plug valve was always less than the pressure determined by N.E. Zhukovsky [1]. The maximum pressure fluctuation was always a consequence of the impact of the upper column on the lower one. Therefore, by analogy with dependence (7) for pipelines with a fracture, we obtained [4,6]:

$$H = (H_0 - h_e) + \frac{c g_0}{g} \sqrt{\frac{h + h_e}{h + h'_m + h_e}} + (h + h_e) \frac{h + h_e}{h + h'_m + h_e}, \quad (8)$$

Where h - height of the upper column (difference between the break point and the water level in the tank);

$$h'_m = \frac{\lambda l' g_0^2}{d 2g},$$

l' - length of pipeline from fracture point to end of pipeline.

The calculated curves for dependence (8) satisfactorily cover the data of experiments on pipelines with a fracture. The calculated data for dependences (7) and (8) are in satisfactory agreement with the experimental data of hydraulic shock, beginning with an increase in pressure (Table 1).

Since the upper part of the 265 m long pipeline after the fracture was practically horizontal, i.e. the height of the water column above the upper fracture was 3.4 m, then in the experiments of this series the excess of the shock pressure value according to the solution of A.F. Mostovsky [2] was practically not observed. The experimental points were laid according to the solution of A.F. Mostovsky [2], which follows from the theoretical dependence (8) at $h \rightarrow 0$.

In some experiments on pipelines with small hydraulic resistances, the fact of an increase in shock oscillation in the subsequent phase of pressure increase compared to the previous one is interesting, which can be explained by the pulsating nature of the pressure increase due to the elasticity of the pipeline and water during a hydraulic shock with a break in the continuity of the flow [4]. Since the hydraulic resistance is relatively small, the pressure losses due to friction during the impact phase are also small. The decrease in the speed of water movement in the opposite direction due to friction in the subsequent phase in some cases leads to an increase in the pressure increase due to the elasticity of the pipeline and water. As a result of the increase in this increase, not only the energy loss due to friction is covered, but also the impact oscillation increases. Visual observation and analysis of experimental data made it possible to establish some provisions that characterize from the qualitative side the complex process of formation and development of a cavitation cavity in a pipeline during a hydraulic shock [4,6].

Table 1

Comparison of calculated data with typical experiments of hydraulic shock, starting with an increase in pressure and accompanied by a rupture of the flow continuity

Water speed, m/sec.	Static pressure, m	Difference between the elevations of the end of the pipeline and its break point, m	Friction pressure loss, m	Head according to N.E.Zhukovsky's formula, m	Pressure in the second phase of pressure increase		
					Experiment, m	by dependence (7), m	by dependence (8), m
Inclined pipeline without fractures							
0,40	35,9	-	0,3	80,7	111,0	116,0	-
0,69	35,9	-	0,8	113,3	152,0	147,4	-
1,05	35,9	-	1,7	153,7	186,0	185,8	-
1,30	35,9	-	2,7	181,5	205,0	210,0	-
1,54	35,9	-	3,8	208,7	226,0	233,7	-
Inclined pipeline with a bend							
0,30	51,8	11,2	0,6	84,1	94,0	-	94,2
0,53	51,8	11,2	1,9	109,1	123,0	-	117,4
0,80	51,8	11,2	4,3	138,2	146,0	-	141,3
1,0	51,8	11,2	6,7	159,8	157,0	-	157,2
1,70	51,8	11,2	19,3	235,6	202,0	-	199,6

Thus, in the case of a hydraulic shock with a break in the continuity of the flow both in a horizontal pipeline and in an inclined one without fractures, the highest total pressure can be determined using dependence (7) [4,6].

In an inclined pipeline with a fracture during the rupture of a water column impact at the fracture point, the total pressure from the collision of the upper column of liquid with the lower one, which is at rest, can be determined using dependence (8) [4,6].

The magnitude of the pressure increase that occurs due to the elasticity of the pipeline and water during a hydraulic shock with a rupture of the liquid column, all other things being equal, depends on the geometric and hydraulic parameters of the pipeline [6].

Conclusion. Based on the above, the following conclusions can be drawn:

1. As a result of the theoretical solution, the boundary condition (2) was obtained and the solution of the differential equations of the unsteady motion of a real low-viscosity liquid under the quadratic law of friction yielded the calculated dependence (3). The latter allows one to take into account the loss of energy, which is caused by additional local movements of water during the "restoration" of the friction pressure in the impact phase.

2. By studying the solution (3) and comparing it with experimental data, it was established that when calculating a direct hydraulic shock, starting with an increase in pressure and proceeding

without breaking the continuity of the flow, the shock pressure can be determined with practically acceptable accuracy using the formula of N.E. Zhukovsky, when the relative friction losses do not exceed 0.5. Many pipelines of pressure systems meet this condition.

3. Based on the energy balance, the boundary condition is proposed: without taking into account the viscous forces (4); with taking into account the viscous forces (6). Using the general solution of differential equations of unsteady motion by N.E. Zhukovsky based on conditions (4) and (6) to determine the maximum possible pressure during a direct hydraulic shock with a break in flow continuity, the following dependencies are obtained: without taking into account the viscous forces (5); with taking into account the viscous forces in pipelines without breaks (7) and in pipelines with a break (8).

4. As a result of the conducted theoretical and experimental studies, the limits and nature of the change in the value of the pressure addition, arising due to the elasticity of the pipeline and liquid, during a hydraulic shock with a break in the continuity of the flow, depending on the change in the velocity of the liquid before the shock, the geometric and hydraulic parameters of the pipeline were established. A comparison of the calculated data according to dependencies (7) and (8) and the experimental maximum values of shock pressures shows their good agreement.

5. The obtained calculation dependencies allow for a fairly accurate engineering calculation of possible impact pressure and, therefore, the correct selection of means of protecting water pipelines from hydraulic shock.

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