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A Hydraulic Impact Theory and Calculation with Breaking Flow Continuity

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ABSTRACT

The article presents the theoretical studies results of hydraulic shock with flow continuity rupture in the pressure the pumping station pipeline. Calculated dependencies are obtained for calculating the shock pressure magnitude and the first period duration of reduced pressure, taking into account the hydraulic resistance along the pipeline length in the discontinuity event in the flow. The calculation results are compared with the Professor D.N. Smirnov's experiments results.

Comparative calculations using the proposed method with D.N. Smirnov experimental data gives a satisfactory agreement and confirms the proposed method reliability.

KEYWORDS: *water hammer, pressure pipeline, water hammer pressure, flow continuity rupture, reduced pressure duration, check valve, vacuum, friction head losses*

1. INTRODUCTION

Currently, in the Republic of Uzbekistan, 1,693 pieces of irrigation pumping stations are used to irrigate more than 2.3 million land hectares. Ensuring the normal operation safety and reliability of the pumping stations used is in current importance. A dangerous process during normal operation of pumping stations pressure pipelines, as you know, are hydraulic shocks, accompanied by the breaks formation in the flow continuity in the injection water supply. The water hammer study, taking into account the continuous flow rupture in pressure systems, has not yet been fully studied [1,2,3,4]. Any scientific information on the water hammer study is relevant. This work is devoted to this issue.

An experimental water hammer study taking into account the flow discontinuity is given in [3,4,5,6,7]. These works [3,4,5,6,7] did not take into account the reduced pressure duration in the first impact phase, no dependences are given to determine the phases number of the water hammer. This data is very important for the impact parameters analysis.

In [8], theoretical studies have been carried out, which are related to the discontinuity formation in the water flow in a pipeline and by determining the maximum pressure magnitude during hydraulic shock in different sections along its length. However, in [8], short pipelines are provided, in which the pressure losses due to friction along the length can be ignored.

The work purpose is to determine the maximum pressure during a hydraulic shock in the first period of reduced pressure in the flow rupture event continuity, taking into account the pressure loss due to friction in a long pressure pipeline.

2. CALCULATION METHOD

Water is supplied by a pump at a speed V_0 to the pressure basin. A non-return valve is installed at the beginning of the discharge pipeline. When the check valve is instantly closed, the water stops and the water pressure instantly decreases by the $\frac{aV_0}{g}$ value, where g is the gravity acceleration, a is the propagation velocity of the shock wave.

With the above hydraulic process, the following condition is met:

$$\frac{aV_0}{g} > H_0 + H_{вак.макс.} + H_{тр} \quad (1)$$

where $H_{вак. max.}$ Is the value of the vacuum in the source of the hydraulic shock;

$H_{тр.}$ is friction head loss up to the considered point of the pressure pipeline cross-sections;

H_0 is geodetic head.

When condition (1) is met, the flow continuity rupture occurs at the check valve, and water continues to move at a certain residual velocity through the pressure pipeline.

The Allievi chain equations connecting the heads H_i and H_i-1 - and the velocities V_i and V_i-1 - in the section of the pipeline at the gate in the i-th and (i-1) - th phases have the form [9,10,11]:

$$H_{i-1} + H_i - 2H_0 = \frac{a}{g}\left(V_i - V_{i-1}\right), \quad (2)$$

for the first phase $H_i = -H_{вак.\ max}$.

Then from (2) we obtain:

$$H_0 - H_{вак.макс.} - 2H_0 = \frac{a}{g}\left(V_1 - V_0\right),$$

from where

$V_1 = V_0 - V_*$, where $V_* = \frac{g}{a}\left(H_0 + H_{вак.макс}\right)$, V_1 – represents the residual speed with which the water mass torn off near the check valve moves in the pipeline towards the pool. This speed decreases from phase to phase (friction forces are not taken into account here) until it reaches zero.

The check valve has a vacuum space filled with air bubbles and steam, the pressure in it will be equal to, i.e. $H = -H_{вак. max.}$, the velocity of the separated water mass of the flow in the subsequent phases according to (2) will accordingly be equal to:

$$\left.\begin{aligned} V_1 &= V_0 - V_* \\ V_2 &= V_0 - 3V_* \\ V_3 &= V_0 - 5V_* \\ &\ldots\ldots\ldots\ldots \\ V_i &= V_0 - (2i-1)V_* \end{aligned}\right\}. \quad (4)$$

We determine the total values of the traversed paths of the water mass for each phase, taking into account that this path first increases to a certain value S, and then decreases to zero. Then, equating to zero the indicated sum, we find the number of vacuum spaces n, i.e.

$$t_\phi \sum_{i=1}^{n} V_1 = 0$$

or

$$\sum_{i=1}^{n} V_1 = n(V_0 - nV_*) = 0, \quad (5)$$

From it

$$n = \frac{V_0}{V_*}. \quad (6)$$

Substituting the value of n in (4), we obtain the velocity of the water mass at the moment of its impact on the check valve, equal to

$V_n = -(V_0 - V_*) = -V_1$. (7)

In this case, the additional pressure of the water hammer in excess of the geodesic pressure will be equal to

$$\Delta H_2 = \Delta H_1 + \Delta H_{доб.} = \frac{aV_0}{g}, \quad (8)$$

where $\Delta H_1 = H_0 + H_{вак.max.}$ the largest drop in shock pressure compared to geodesic;

$$\Delta H_{доб.} = \frac{a}{g} V_1 = \frac{a}{g}(V_0 - V_*). \quad (9)$$

The largest value of the shock pressure will be equal to:

$$H_{макс.} = H_0 + \Delta H_2 = H_0 + \frac{aV_0}{g}. \quad (10)$$

When the water supply through the pump is instantaneously interrupted with the formation of a discontinuity in the flow at the check valve in the pipeline, an increased pressure above the geodetic pressure arises, equal to [8]:

$$\Delta H_2 = \frac{aV_0}{g}.$$

The duration of the first period of reduced pressure without regard to friction forces is

$t_v = n\, t_\phi$. (11)

It is possible to determine over the geodetic pressure and the duration of the first period of reduced pressure, taking into account the head loss due to hydraulic resistance along the length of the discharge pipeline. We use the Darcy-Weisbach formula to determine the head loss

$$H_{тр} = \lambda \frac{L}{d} \frac{V^2}{2g}, \quad (12)$$

where λ – is the coefficient of hydraulic friction resistance, d – is the discharge line diameter.

Then the loss of kinetic energy will be equal to:

$$V_{тр} = \frac{g}{a} H_{тр} = \frac{1}{2} \cdot \frac{L}{a} \cdot \frac{\lambda}{d} V^2. \quad (13)$$

At the moment of rupture of the continuity of the flow through the pipeline from the place of the rupture of propagation, the wave of reduced pressure ($H_0 + H_{вак.max}$), which corresponds to the instantaneous velocity V_*.

This speed, formed due to the deformation of the walls of the pipeline and changes in the density of water in it, propagates through the pipeline.

Calculating the loss in speed by formula (13), through each half-phase we will have

$V^* = V_* - V^*_{тр}$. (14)

where

$$V^*_{тр} = \frac{1}{2} \cdot \frac{L}{a} V_*^2.$$

Obviously, for the entire time that there is a vacuum space (in the case under consideration, at the beginning of the pressure pipeline, at the check valve), there will be $H = -H_{вак.max.}$, and in the last section of the pressure pipeline adjacent to the pressure basin of sufficiently large dimensions positive pressure equal to atmospheric pressure plus the immersion of the last section under the pressure basin horizon. Based on this, in the initial section of the pressure pipeline (at the check valve), the instantaneous velocity during the rupture of the pressure flow changes by the value V_*, and in the last section by the value $V^* = V_* - V^*_{тр}$ (taking into account the speed loss for half phase of water hammer).

Therefore, at the moment of restoring the continuity of the flow, the super geodetic pressure of the hydraulic shock will be equal to

$$\Delta H_2 = \frac{a}{g} V^* + \frac{a}{g} V_n = \frac{a}{g}(V^* + V_n), \quad (15)$$

where $\frac{a}{g} V^*$ the value of the pressure increase, equal to the previous pressure decrease relative to the geodetic, taking into account the loss in speed V^* for half the phase; $\frac{a}{g}V_n$ is the value of the additional shock pressure obtained as a result of a water hammer a mass of water at a speed of V_n about a check valve.

In this case, the maximum pressure of the water hammer will be equal

$$H_{макс} = H_0 + \Delta H_2 = H_0 + \frac{a}{g}\left(V^* + V_n\right). \qquad (16)$$

To determine the duration of the first period of reduced pressure and the velocity V_n of the water mass at the moment it hits the check valve, we will write expressions for the column velocity for each subsequent half of the water hammer phase.

Residual speed value, i.e. the velocity of the mass of water at the beginning of the first phase is equal to:
$V_1 = V_0 - V_*$.

For the next half phase, this speed will be:
$V_{1,3} = V_1 - V_* - V_{1\,тр} = V_0 - 2V_* - V_{1\,тр}$,
and at the beginning of the second phase, the speed value will be:
$V_2 = V_{1,5} - V_* - V_{1,5\,тр} = V_0 - 3V_* - (V_{1\,тр} + V_{1,5\,тр})$
and so on.

Thus, the velocities of the mass in the next half of the phase will respectively be equal:

$$\left.\begin{aligned}
&V_1 = V_0 - V_*,\\
&V_{1,5} = V_0 - 2V_* - V_{1mp},\\
&V_2 = V_0 - 3V_* - \left(V_{1mp} + V_{1,5mp}\right)\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&V_n = V_0 - (2n-1)V_* - (V_{1mp} + V_{1,5mp} + \ldots\ldots +\\
&+ V_{(k-0,5)mp} - V_{k\,mp} - \ldots.V_{(n-0,5)mp}
\end{aligned}\right\}, (17)$$

here k – the number of the phase from which the mass of water begins its reverse movement, and the speed calculated by formula $V_{i\,тр}$ (i = 1; 1,5; …; n – 0,5) (13).

Similarly to formula (5), the algebraic sum of all velocities (17) for the first period of reduced pressure is equal to zero:
$(2n - 1)V_0 - n(2n - 1)V_* - (2n - 2)V_{1тр} - (2n - 3)V_{1,5тр} - (2n - 4)V_{2тр} -$
$\ldots. - [2n - 2(k - 0,5)]V_{(k-0,5)тр} + (2n - 2k)V_{k\,тр} + [2n - 2(k + 0,5)]V_{(k+0,5)тр} + \ldots = 0$

or
$2V_* n^2 - (2V_0 + V_* - Q)n + (V_0 - R) = 0$, (18)

where
$Q = 2(V_{1тр} + V_{1,5тр} + \ldots + V_{(k-0,5)тр} - V_{kтр} - V_{(k+0,5)тр} - \ldots)$
$R = 2V_{1тр} + 3V_{1,5тр} + 4\,V_{2тр} + \ldots + 2(k - 0,5)V_{(k-0,5)тр} - 2k\,V_{kтр} -$
$- 2(k + 0,5)V_{(k+0,5)тр} - \ldots$

Solving the quadratic equation (18) with respect to n, we find the number of phases of a water hammer (during which there was a cavitation-vacuum space) equal to

$$n = \frac{1}{4V_*}\left[\left(2V_0 + V_* - Q\right) + \sqrt{\left(2V_0 + V_* - Q\right)^2 - 8V_*\left(V - R\right)}\right]$$

, (19)
here only a positive value of the root is taken by equation (18), since the plus sign satisfies the condition of the problem being solved.

Having found *n*, from (17) we can determine the water mass velocity at the moment of its impact on the check valve.

3. STUDIES RESULTS

Below are calculations to determine the magnitude of the shock pressure and the duration of the first period of reduced pressure, taking into account the hydraulic resistance along the length of the pipeline in the event of a rupture of the flow continuity. The calculation results are compared with the results of the experiments of D.N. Smirnov [6].

As can be seen from Table 1, comparative calculations by the proposed method with the experimental data of D.N. Smirnov give satisfactory results.

Table 1

№ of Smirnovs experiments	V_0, м/с	H_0	$H_{тр}$	$H_{вак.\,max.}$	L	$\frac{aV_0}{g}$	a, m/sec	ΔH_1	ΔH_2 по опытам Смирного	ΔH_2 по расчетам автора	$t_ф$	t_v according to Smirnov's experiments	t_v according to the author calculations
		M						M				Sec	
1	0,42	36,5	7,0	-	1148	39,4	922	35,0	33,0	33,8	2,49	2,85	2,69
2	1,16	40,0	55,0	7	1148	109,0	922	47,0	86,0	89,3	2,50	5,10	5,10
3	1,32	21,0	70,5	7	1180	105,6	787	28,0	82,0	74,6	3,00	8,10	8,22
4	1,44	17,0	75,0	7	1176	91,2	622	24,0	56,0	61,5	3,80	9,00	9,72
5	1,50	10,0	82,5	8	1170	83,5	545	18,0	49,0	48,9	4,80	11,10	13,92
6	1,69	5,0	87,0	8	1165	71,7	416	13,0	32,0	36,0	5,60	14,70	13,10
7	1,22	36,5	56,0	7	1148	114,7	922	43,5	88,5	89,3	2,49	5,40	5,55
8	0,93	36,5	36,5	6,5	1148	87,8	922	43,0	64,5	71,4	2,49	4,50	4,68
9	0,76	37,0	22,0	6	1148	71,3	922	43,0	61,0	62,0	2,49	3,90	3,96
10	0,58	37,0	14,0	5	1148	54,3	922	42,0	46,0	46,0	2,49	3,45	3,19
11	0,42	37,0	6,5	-	1148	39,4	922	35,0	33,8	2,49	2,49	2,85	2,69

1. For experience II we have data:
$V_0 = 1{,}16$ m/sec; $H_0 = 40{,}0$ m; $H_{тр} = 55{,}0$ м; $H_{вак.max.} = 7{,}0$ m; $a = 922$ m/sec; $t_ф = 2{,}50$ sec; d = 50 mm.

According to the initial data of the second experiment, we calculate:
$\frac{aV_0}{g} = 109{,}0$ м; $\frac{1}{2}\frac{\lambda}{d}\cdot\frac{L}{a} = 0{,}44$ sec/м; $V_* = 0{,}50$ m/sec; $V_{тр} = 0{,}44 \cdot 0{,}50^2 = 0{,}11$ m/sec;

$V^* = V_* - V^*_{1тр} = 0{,}50 - 0{,}11 = 39$ m/sec; $V_1 = V_0 - V_* = 1{,}16 - 0{,}50 = 0{,}66$ m/sec;

$V_{1тр} = 0{,}44 \cdot 0{,}66^2 = 0{,}19$ m/sec; $V_{1,5} = V_1 - V_* - V_{1тр} = 0{,}66 - 0{,}50 - 0{,}19 = 0{,}03$ m/sec;

$V_{1,5тр} = 0{,}44 \cdot 0{,}03^2 = 0{,}00$; $V_2 = V_{1,5} - V_* + V_{1,5тр} = 0{,}03 - 0{,}50 + 0{,}00 = 0{,}53$ m/sec;

$V_{2тр} = 0{,}44 \cdot 0{,}53^2 = 0{,}12$ m/sec; $V_{2,5} = V_2 - V_* + V_{2тр} = - 0{,}53 - 0{,}50 + 0{,}12 = 0{,}91$ m/sec.

Taking into account the condition $(V_n) < V_1$ and taking into account the friction forces, to determine n using formula (18), we will first calculate:

$Q = 2(V_{1тр} - V_{1,5тр}) = 2 \cdot 0,19 = 0,38$ m/sec;

$R = 2V_{1тр} - 3V_{1,5тр} = 2 \cdot 0,19 = 0,38$ m/sec;

$2V_0 + V_* - Q = 2,32 + 0,50 - 0,38 = 2,44$ m/sec;

$22V_0 + V_* - Q = 2,44^2 = 5,8536$ м²/sec²;

$4V_* = 4 \cdot 0,50 = 2,00$ m/sec;

$8V_*(V_0 - R) = 4,00(1,16 - 0,38) = 4 \cdot 0,78 = 3,12$ m²/sec²;

$$\sqrt{(2V_0 + V_* - Q)^2 - 8V_*(V_0 - R)} = \sqrt{2{,}733} = 1{,}65 \text{ m/sec.}$$

Based on the above calculated calculations, we determine the n value:

$$n = \frac{2{,}44 + 1{,}65}{2{,}00} = \frac{4{,}09}{2{,}00} = 2{,}04, \text{ n = 2, 04;}$$

$t_v = n \cdot t_ф = 2{,}04 \cdot 2{,}50 = 5{,}10$ sec; from experience $t_v = 5{,}10$ sec;

$V_{2,04} = - 0,56$ m/sec;

$\Delta H_2 = 93,98(0,39 + 0,56) = 89,28$ м;

from experience $\Delta H_2 = 86{,}0$ м.

2. According to V experience, we have data:
$V_0 = 1,50$ m/sec; $H_0 = 10{,}0$ м; $H_{тр} = 82{,}5$ м; $H_{вак.max.} = 8,0$ м; $a = 545$ m/sec; $t_ф = 4,80$ sec; d = 50 mm.

Next, we calculate:

$V_* = 0,32$ m/sec; $\frac{1}{2}\frac{\lambda}{d}\frac{L}{a} = 0{,}66$ m/sec; $\frac{a}{g} = 55{,}56$ sec;

$V_{тр} = 0,66 \cdot 0{,}32^2 = 0,07$ m/sec; $V^* = V_* - V^*_{тр} = 0,25$ m/sec;

$V_1 = V_0 - V_* = 1,50 - 0,32 = 1,18$ m/sec;

$V_{1тр} = 0,66 \cdot 1{,}18^2 = 0,78$ m/sec;

$V_{1,5} = V_1 - V_* - V_{1тр} = 1{,}18 - 0{,}32 - 0{,}78 = 0{,}08$ m/sec;

$V_{1,5тр} = 0,66 \cdot 0{,}08^2 = 0,00$

$V_2 = V_{1,5} - V_* - V_{1,5тр} = 0,08 - 0,32 - 0,00 = - 0,24$ m/sec;

$V_{2тр} = 0,66 \cdot 0{,}24^2 = 0,04$ m/sec;
$V_{2,5} = V_2 - V_* + V_{2тр} = - 0{,}247 - 0{,}32 + 0{,}04 = 0{,}52$ m/sec;

$V_{2,5тр} = 0{,}66 \cdot 0{,}52^2 = 0{,}18$ m/sec;

$V_3 = V_{2,5} - V_* + V_{2,5тр} = - 0{,}52 - 0{,}32 + 0{,}18 = - 0{,}66$ m/sec.

Taking into account $\sum V_1 = 0$, we can write:
$Q = 2(0,78 + 0,00 - 0,04 - 0,18) = 2 \cdot 0,56 = 1,12$ m/sec;

$R = 2V_{1тр} + 3V_{1,5тр} - 4V_{2тр} - 5V_{2,5тр} = 1,56 - 0,16 - 0,90 = 0,50$ m/sec;

$V_0 - R = 1,50 - 0,50 = 1,00$ m/sec;

$2V_0 + V_* - Q = 3,00 + 0,32 - 1,12 = 2,20$ m/sec; $2{,}20^2 = 4,84$;

$4V_* = 4 \cdot 0,32 = 1,28$ m/sec; $8V_*(V_0 - R) = 2,56 \cdot 1,00 = 2,56$ м²/sec²;

$$\sqrt{(2V_0 + V_* - Q)^2 - 8V_*(V_0 - R)} = \sqrt{2{,}28} = 1{,}51 \text{ m/sec}$$

$$n = \frac{2{,}20 + 1{,}51}{1{,}28} = \frac{3{,}71}{1{,}28} = 2{,}90 \quad n = 2{,}90;$$

$t_v = n \cdot t_ф = 2{,}90 \cdot 4{,}80 = 13{,}92$ sec; по опыту $t_v = 11{,}10$ sec;

$V_{2,90} = V_{2,5} - 0{,}40/0{,}50(V_3 - V_{2,5}) = - 0{,}52 - 0{,}11 = - 0{,}63$ m/sec;

$\Delta H_2 = 55,56 \cdot 0,88 = 48,9$ м; по опыту $\Delta H_2 = 49,0$ м.

4. CONCLUSIONS

Taking into account the above, in conclusion, we can draw conclusions.

1. The dependence is obtained for calculating the maximum pressure during a hydraulic shock in the first period of reduced pressure in the event of a rupture of the continuity of the flow, taking into account the pressure loss due to friction in a long pressure pipeline.
2. The ratio for determining the number of phases during the impact process is obtained.
3. The obtained ratios are very important for the analysis of technical parameters of water hammer.

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