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Theoretical and Experimental Study of Hydraulic Impact with Reduced Pressure

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Abstract – The article presents the theoretical and experimental studies results of negative water hammer in the pressure pipeline of a pumping station. At the same time, a completely satisfactory coincidence of the pressure calculating results in a hydraulic shock using the proposed method with experimental data was obtained, which also justifies the demand for accounting for the water outflow from the check valve plate in the first reduced shock pressure phase.

Keywords – Negative Water Hammer, Pumping Station, Pressure Pipeline, Check Valve, Water Hammer Phase, Flow Continuity Rupture, Vacuum, Pressure Increase Over Geodetic.

I. Introduction

In Uzbekistan, more than 2.3 million hectares of land is irrigated using irrigation pumping stations, which they are equipped with long pressure pipelines. As a sudden power outage result in the pumping stations injection pipelines, a water hammer process occurs. Water hammer is the most dangerous in the real pipelines operation of hydraulic systems. Therefore, any scientific information on water hammer is relevant. This work is also devoted to the water hammer study.

The scientific theory of water hammer in pipes with an ideal fluid was developed by N.E. Djukovsky [1].

Water hammer is caused by the sudden valve closing or opening and the sudden pump on and off switching in a pipeline or pipeline network.

In the works [2,3,4,5,6,7] analytical methods for calculating water hammer taking into account friction forces are given. However, they are suitable only for relatively simple schemes and, moreover, are also based on the assumption that the frictional forces nature upon impact remains the same as in the steady state.

In the well-known calculating methods [8,9,10,11,12,13] water hammer in pumping stations pressure pipelines and installations, the shock concept at high heads is adopted, which corresponds to the case when the maximum pressure drop

$$\Delta p_1 = a\rho V_0 < p_0 \qquad (1)$$

or the maximum pressure drop

$$\Delta H_1 = \frac{aV_0}{g} < H_0, \qquad (2)$$

that is, at the pressure pipeline beginning, there is no discontinuity in the flow.

Here a is the propagation speed of the pressure wave, ρ is the water density, p_0 is the static pressure, V_0 is the water speed during steady motion, H_0 is the geodesic (static) head, ΔH_1 is the change in head relative to the geodesic.

This leads to the fact that the subsequent increase in the head at the end of the second phase of oscillations is obtained, $\Delta H_1 = \Delta H_2$, which cannot be recognized as correct.

The research purpose is to obtain dependence for calculating the increase in pressure over the geodetic head during hydraulic shock and to refine it in the unsteady motion process with a decrease in fluid pressure taking into account the shock pressure on the check valve disk.

II. Calculation Method

When the pump is stopped immediately or the valve installed at the beginning of the pipeline is closed, it is usually assumed that the initial flow rate V_0 immediately drops to zero. If the gate valve closes in time T_s, less than the pressure fluctuations phase during the impact τ, then it is assumed that for all time T_s the flow rate is determined by the formula:

$$V = \varphi\sqrt{2gH}, \qquad (3)$$

where φ – is speed ratio.

In other words, it is assumed that at the end of time T_s, when $\varphi = 0$, we have $V = 0$.

Such a drop in speed could be expected only if the moving fluid inertia was neglected, because in this case the water mass in the pipeline would move under the pressure difference influence at the valve inlet and outlet sections. But since water has inertia and during the time T_s it moves under the influence of the pressure drop and its own inertia, the V variation law can sharply differ from the law obtained by (3).

Taking into account the water inertia from the complete moment the valve closure T_s, when the speed $V = V_1$, the column will move only by inertia and will stop after time t_1.

In other words, with a negative impact, the initial velocity V_0 is completely extinguished in the time $t_A = T_s + t_1$.

Thus, with a negative impact, due to the inertia of a water column of length l, the change in the flow velocity occurs with some delay in comparison with the change in the valve opening. That is why the use of formula (3) as a boundary condition for calculating a water hammer from a decrease in pressure, as has been accepted so far, can lead to significant errors. The greater the error the greater the pipeline time constant, which characterizes the process of inertial movement of the water column.

$$T = \frac{lV_0}{gH_0}, \qquad (4)$$

D.N. Smirnov in the well-known work [13] for the first time cites the experimental measurements results of the rarefaction value during a hydraulic shock. The author [13] does not compare his experimental data with any calculated data.

III. Studies Results

В данной работе с целью проверки вопроса наличия In this work, in order to check the $\Delta H_2 > \Delta H_1$ и $t_A > T_s$ presence question in the hydraulic laboratory of the KEEI, experiments were carried out. A schematic of the laboratory setup is shown in Fig. 1.

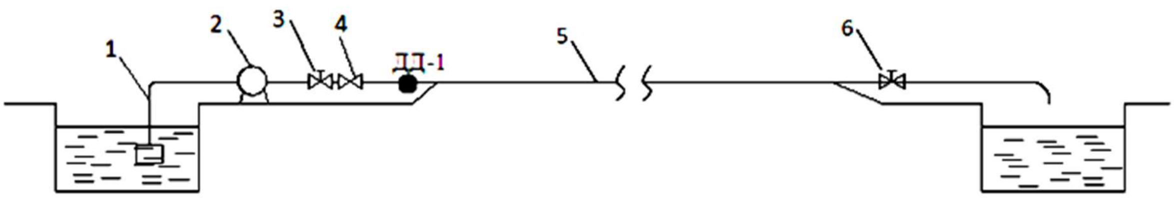

Fig. 1. Experimental setup diagram:
1 – suction line; 2 – pump; 3,6 – crane; 4 – check valve; 5– pressure pipeline.

Pump 2, through suction pipes 1, with 75 mm diameter, picks up water from the supply channel and pumps it through a pressure pipeline 5, 50 mm in diameter, 220 m long, into a pressure well. The water consumption was determined by the volumetric method with a threefold measurement repetition. The geodetic height of the water rise in the pumping unit is 21 m. The waste water is returned by gravity to the supply channel 1. The water hammer was created by quickly closing the plug valve 4, at 20 cm distance from which a PM-10 pressure sensor was installed together with an IG-2I amplifier to record changes in the hydrodynamic pressure at the pressure pipeline beginning.

In the experiments, the closing time of the plug valve varied within T*s* =0.025÷0.14 sec, while in these experiments the shortest duration of the impact phase was τ = 0.22 sec. Table 1 summarizes the research results.

Table 1. Experiments comparisons results with calculations based on the proposed dependence

№ ex.	V_0, m	H_0, m	H_p, m	*l*, m	*a*, m/s	aV_0/g, м	T_s, c	Experiment			Payment		
								ΔH_1, m	ΔH_2,m	t_A, s	ΔH_1,m	ΔH_2,m	t_A, s
1	0,163	21	21,2	220	1300	21,6	0,11	21,6	25,8	0,14	21,6	26,8	0,136
2	0,112	21	21,15	220	1300	14,9	0,037	14,9	23,0	0,075	14,9	24,7	0,094
3	0,095	21	21,15	220	1300	12,6	0,085	12,6	20,0	0,8	12,6	20,8	0,79
4	0,057	21	21,1	220	1300	7,6	0,0315	7,6	9,8	0,04	7,6	10,5	0,048

In table 1, ΔH_1 is the largest drop in head relative to static; ΔH_2 - the greatest increase in pressure relative to static; t_A is the time during which the water velocity at the valve equals 0; T_s is the closing time of the check valve.

As we can see from the table, the increase in the pressure over the geodetic in absolute value is much greater than the decrease, and the time t_A is greater than T_s. In these experiments, due to low initial velocities, the sum of hydraulic losses and velocity head turns out to be negligible in comparison with the geodetic one and can be ignored.

Changes diagrams in shock pressures for experiments 1 - 3 are shown in Fig. 2, 3 and 4.

Based on the obtained experimental inequality $\Delta H_2 > \Delta H_1$, which is also mentioned in [12], it should be assumed that the difference $\Delta H_2 - \Delta H_1 = \Delta H_s$ is created due to the outflow of water from the gate, which, along with wave phenomena, causes the reverse movement of the column with some the final velocity V_s at the moment of filling the space caused by this outflow.

In order to verify this assumption, the proof of which would be the presence of negative pressure directly behind the check valve (i.e., the presence of a cavitation space with gas bubbles), at a certain positive head in the flow, i.e., when the pressure in the water column decreased by an amount aV_0/g and did not reach atmospheric, we recorded at the installation (in Fig. 1) the pressure changes directly behind the closing valve using a pressure sensor PM-10.

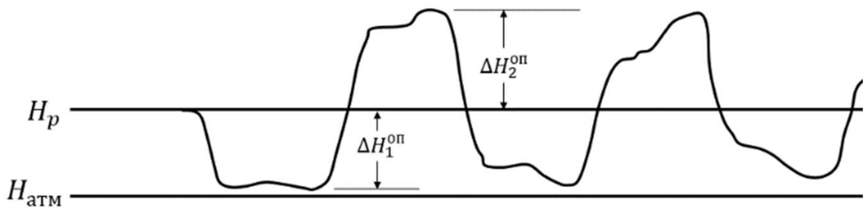

Рис. 2. Change in shock pressure (Experience No. 1: ϑ_0 = 0,163 m/sec; τ = 0,34 sec; ΔH_1^{on} = 21,6 m, ΔH_2^{on} = 25,9 m. Calculated by the proposed method: ΔH_1^{pac} = 21,6 м; ΔH_2^{pac} = 26,8 м).

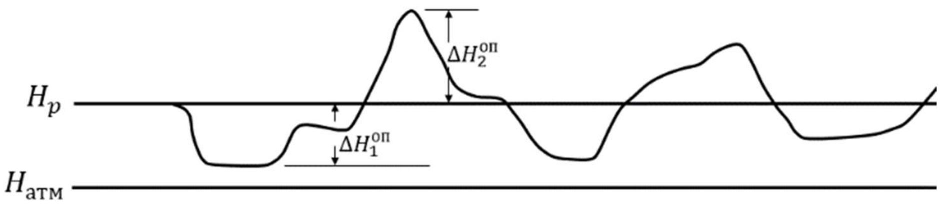

Figure: 3. Change in shock pressure (Experience No. 2: ϑ_0 = 0,112 m/sec; τ = 0,34 sec; ΔH_1^{on} =15,0 m, ΔH_2^{on} =23,2 m. Calculated by the proposed method: ΔH_1^{pac} =14,9 м; ΔH_2^{pac} =24,7 м).

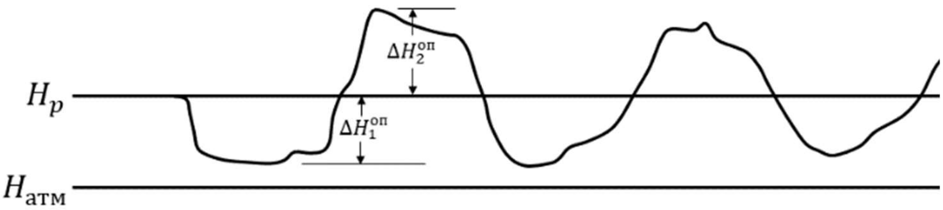

Figure: 4. Change in shock pressure (Experience No. 3: ϑ_0 = 0,0945 m/sec, τ = 0,34 sec; ΔH_1^{on} =12,8 м, ΔH_2^{on} =21,0 m. Calculated by the proposed method: ΔH_1^{pac} =12,6 м; ΔH_2^{pac} =20,8 м).

These experiments showed that the pressure directly on the valve disc surface always dropped below atmospheric, while at 0.5 m distance and from it the pressure was positive.

To determine the water outflow length path from the valve, we use the formula [14]:

$$V = V_0\, tg\left(\frac{\pi}{4} - \frac{t}{T}\right) \tag{5}$$

which expresses the change law in the flow rate over time.

If we assume that the check valve closes instantly, then we can suggest that from the moment it closes, the water column moves away from it by inertia and only stops after a while.

$$t_A = \frac{\pi}{4} \cdot T \tag{6}$$

In this case, the path traversed by the column can be expressed as a definite integral [14]:

$$S = V_0 \int_0^{t_A} tg\left(\frac{\pi}{4} - \frac{t}{T}\right) dt \tag{7}$$

The solution to integral (7) has the form:

$$S = V_0 T \ln\sqrt{2} = 0{,}345 V_0 T\,. \tag{8}$$

Calculations according to (8) give somewhat overestimated results, since it is almost impossible to instantly close the valve. Knowing the time T_s, it is possible to approximately (taking the change in speed during the valve closing time to be linear) determine the length of the pipe by which it will be filled in time T_s, i.e.

$$S' = \frac{V_0 T_s}{2}\,. \tag{9}$$

So we get that during the time t_A the water column passes the path *S* from the valve disc. However, since the latter does not immediately block the path to the flow, then during the reverse movement it passes the path S-S$'$.

If tA<τ, then the water column will start its reverse movement only from the beginning of the second phase, and if tA>τ then from the moment tA.

Since there is a certain negative head H_b directly at the valve, the water column will move in the opposite direction under the head $H_o \rightarrow H_b$. If the return path were infinitely long, then the flow rate would increase to a value.

$$V_k = \sqrt{\frac{H_0 + H_b}{K}}\,, \tag{10}$$

where K is pipeline resistance coefficient, determined by dependence

$$K = \frac{h_T}{V_0^2}, \qquad (11)$$

here h_r is the sum of losses and velocity head at steady state. The variation law of this speed is determined by the formula (7):

$$V = V_k \frac{\sqrt[\tau]{l^t} - 1}{\sqrt[\tau]{l^t} + 1}, \qquad (12)$$

where l is the movement path length of the water column by inertia.

Since in reality the column of water must pass some final path, and then during the time necessary for this, equal to the time filling t_s the cavitations space, it acquires a certain velocity V_s, determined by formula (12), and the time

$$t_s = \sqrt{\frac{2S}{d}}, \qquad (13)$$

where $d = \frac{\Delta V}{\Delta t}$ is flow acceleration over a period of time.

In this case, we assume that the water flow moves unsteadily. Determining t_s by formula (13), we can also determine the speed V_s, i.e. the speed with which the water column will hit the valve disc and create an increase in pressure equal to:

$$\Delta H_s = \frac{aV_s}{g}. \qquad (14)$$

This head, adding up with the reflection head from the $\Delta H_1 = \frac{aV_0}{g}$ valve, gives a general increase in head over the geodesic:

$$\Delta H_2 = \Delta H_1 + \Delta H_s = \frac{a}{g}\left(V_0 + V_s\right). \qquad (15)$$

The pressure increase at the valve will begin from the moment $\tau + t_s$, if $t_A < \tau$, or from the moment $t_A + t_s$, if $t_A > \tau$ and acquires a maximum value after the time $\tau/2$.

Table 1 shows the calculation results.

As an example, the four experiments results in table 1, performed according to the proposed method, are in good agreement with our experiments data.

IV. Conclusions

Taking into account the above, conclusions can be drawn.

1. Dependence is obtained for calculating the increase in pressure over the geodetic head during hydraulic shock.

2. In the water hammer process, it is necessary to take into account the shock pressure against the check valve disc.

3. The resulting dependence (15) is very important for calculating the water pressure flow in pipelines for a water hammer with a decrease in pressure.

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