Assessment of Non-Stationary Processes in Unstable Operating Modes of Pumping Stations

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ABSTRACT

Assessment of the impact of wave processes during transient and emergency operating conditions of the hydraulic system of reclamation pumping stations, which inevitably lead to a decrease in the strength limits of pipelines, the accumulation of metal fatigue, especially in places that are concentrators of fatigue stresses in pipeline metal, which increases the likelihood of accidents with pipeline ruptures. They justified the need to model probable emergency situations of pump operation in the water supply system in order to establish the possibility of using modern methods for calculating transient processes in pumping stations of reclamation systems. Based on the modeling results, it was established that in the pressure pipeline of reclamation pumping stations, during an emergency shutdown of the pump, there is a high probability of a break in the continuity of the water flow. It was calculated that installing a pressure stabilizer on the pressure pipeline with one damping chamber in direct proximity to the pump, check valves and shut-off valves of water pipelines (sources of disturbance) will reduce the amplitude of pressure fluctuations in the pipeline by 2,5...2,6 times and lead to more rapid attenuation of wave processes due to a change in sign-alternating shock loads to smoother ones, extended over time. It was established that emergency protection of the pipeline system using wave pressure stabilization technology will protect pipelines from ruptures in the event of emergencies; ensure energy savings by reducing the accident rate on pipelines and increase the uninterrupted provision of services to the population and water supply enterprises.

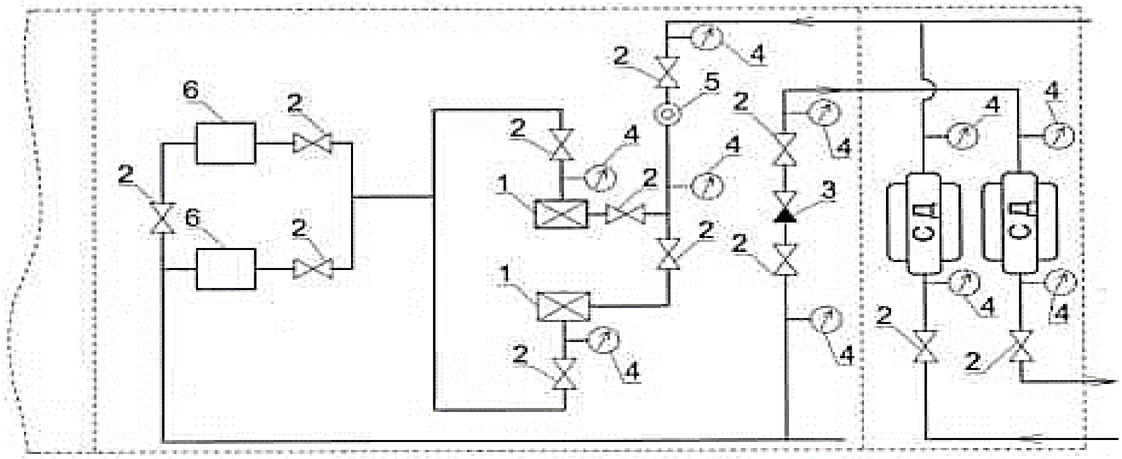
Keywords: reclamation pumping stations, pumping unit, pressure pipeline, pressure stabilizer, transient processes, shock wave propagation speed, water hammer

Based on the operational experience of pumping stations, the causes of pipeline destruction in 70% of cases are: water hammer, pressure drops and vibrations. According to water management data, wear on pressure pipelines and equipment averages 85%, only on pressure pipeline systems for irrigation. During the transient process, the still unsteady movement of the liquid due to a change in the cross-section of the pipeline caused by blocking the cross-section of the pipeline or its opening, stopping and starting the pumping unit and other elements of the pipeline system, releasing pressure, and so on, the speed of movement of the liquid changes, as a result of these processes, waves of high and low pressure arise.

The purpose of the research is to assess the impact of wave processes during transient and emergency modes of pipelines; justification of the need to model probable emergency situations of pump operation in parallel connected common pressure pipes in order to establish the possibility of using modern methods for calculating transient processes in pumping stations of irrigation systems.

2. Emergency power outages and operating pumps lead to water hammer in pressure pipelines.

3. When operating pumping stations, the impact of wave processes in transient and



Materials and methods. In the process of analyzing the design and technological features of the hydraulic system of reclamation pumping stations (Fig. 1) as well as consultations with the personnel operating them, it was found that:

1. Increasing the reliability of the hydraulic system and ensuring its trouble-free operation is largely determined by the hydraulic operating modes, as well as the resistance of pipelines to possible sudden disturbances of a wave nature that occur during an emergency stop of pumps.

emergency operating modes of reclamation pumping stations of the hydraulic system inevitably leads to a decrease in the strength limits of pipelines, the accumulation of metal fatigue, especially in places that are concentrators of fatigue stress (welds, scuffing, and so on) metal, which increases the likelihood of accidents with pipeline ruptures. A study of modeling probable emergency situations of pump operation in the water supply system of reclamation pumping stations was carried out in order to establish the possibility of using modern methods for calculating transient processes from a given pumping station.

Figure 1. Diagram of the main elements of the station with installed pressure stabilizers: 1 - circulation pump; 2 - shut-off valve through passage; 3 - check valve through passage; 4 - pressure gauge; 5 - mud filter; 6 - heat exchanger

$$\begin{cases} \frac{\partial P}{\partial x} = \frac{\partial G}{\partial t} \cdot \frac{1}{F} \\ \frac{\partial P}{\partial t} = \frac{\partial G}{\partial t} \cdot \frac{c^2}{F}, \end{cases} \quad (1)$$

where P is pressure, H/m2; F - cross-sectional area, m2; G = ρ· υ·F - mass flow rate of liquid, kg/sec.; ρ - fluid density; υ - speed of fluid movement in the pipeline; x, t - coordinate of the pipeline axis and time, respectively; c is the speed of wave propagation (speed of sound) in the pipeline, m/sec.

The speed of pressure wave propagation is calculated by the formula:

$$c = \sqrt{\frac{E}{\rho}} \cdot \frac{1}{E} = \frac{1-\beta}{K} + \frac{\beta}{P} + \frac{D}{\delta \cdot E_0} \quad (2)$$

where β is the fraction (volume) of undissolved air in water (in this case it was taken to be equal to β = 0); ρ is the density of the water-air mixture (ρ_{water} = 1000 kg/m3); E - Young's modulus for the water-air mixture adjusted for the elasticity of the pipes; K - volumetric compression modulus of water in the absence of undissolved air (K = $2{,}13 \cdot 10^3$ MPa); D - pipe diameter; δ - pipe wall thickness; E0 - Young's modulus of elasticity of the pipe materials ($E_0 = E_{Steel} = 2{,}06 \cdot 10^5$ MPa).

Results and discussion. The solution to system (1) is presented in the form of the d'Alembert integral, valid for motion without damping. We place the origin of coordinates at the open end, and direct the x axis upstream to the source of disturbance. In this case, the sign [2] changes in the system:

$$\begin{cases} -\frac{\partial P}{\partial x} = \frac{\partial}{\partial t}(\rho \cdot \upsilon) \\ \frac{\partial P}{\partial t} = c^2 \frac{\partial}{\partial x}(\rho \cdot \upsilon) \end{cases} \quad (3)$$

Formulas for ρ ·υ and P will take the form:

$$(\rho \cdot \upsilon) = f_1\left(t - \frac{x}{c}\right) + f_2\left(t + \frac{x}{c}\right) \quad (4)$$

$$P = c\left[-f_1\left(t - \frac{x}{c}\right) + f_2\left(t + \frac{x}{c}\right)\right] \quad (5)$$

For *x = 0 и P = 0:* $f_1(t) = f_2(t)$. Let the law of change in mass velocity be known in the section *x = l*, where the source of disturbance is located:

x = l, ρ· υ= φ (t), φ (t) = 0 for *t ≤ 0.*

Let's denote $f_2\left(t + \frac{l}{c}\right) = \varphi(t)$

then in the section $x = l$: $\rho\cdot\upsilon = \varphi(t) = \varphi(t) + \varphi(t - T_0)$,

where $T_0 = \frac{2l}{c}$ – hydraulic shock phase.

The pressure in the section $x = l$ is the difference between the same waves $\varphi(t)$ and $\varphi(t - T_0)$:

$$P = c\,[\varphi(t) - \varphi(t - T0)], \qquad (6)$$

This circumstance makes it possible to analytically or graphically construct the function $\varphi(t)$ and $\varphi(t - T_0)$ from the known value $\rho\cdot\upsilon$ of the disturbance source for subsequent moments of time according to the scheme indicated in the table.

Determination of pressure at the source of disturbance

№ of inter-vals	Time intervals from the start	Function values $\varphi(t)$ and $\varphi(t-T_0)$	Pressure at the disturbance source
1	$0\ t< T_0$	$\varphi_1(t) = (\rho\cdot\upsilon)_1$ $\varphi_1(t-T_0) = 0$	$P_1 = c(\rho\cdot\upsilon)_1$
	$T_0 <t< 2T_0$	$\varphi_2(t-T_0) = \varphi_1(t) = (\rho\cdot\upsilon)_1$ $\varphi_2(t) = (\rho\cdot\upsilon)_2 - (\rho\cdot\upsilon)_1$	$P_2 = c\left[(\rho\cdot\upsilon)_2 - 2(\rho\cdot\upsilon)_1\right]$
	$2T_0 <t<3T_0$	$\varphi_3(t-T_0) = \varphi_2(t) = (\rho\cdot\upsilon)_2 - (\rho\cdot\upsilon)_1$ $\varphi_3(t) = (\rho\cdot\upsilon)_2 - (\rho\cdot\upsilon)_1$ $\varphi_3(t) = (\rho\cdot\upsilon)_3 - (\rho\cdot\upsilon)_2 - (\rho\cdot\upsilon)_1$	$P_3 = c\left[(\rho\cdot\upsilon)_3 - 2(\rho\cdot\upsilon)_2 - 2(\rho\cdot\upsilon)_1\right]$
	$(n-1)T_0 <t< nT_0$	$\varphi_n(t-T_0)=\varphi_{n-1}(t)=(\rho\cdot\upsilon)_{n-1}-(\rho\cdot\upsilon)_{n-2}+(\rho\cdot\upsilon)_{n-3...}$; $\varphi_n(t)= (\rho\cdot\upsilon)- (\rho\cdot\upsilon)_{n-1} - (\rho\cdot\upsilon)_{n-2} +(\rho\cdot\upsilon)_{n-3...}$;	$P_n = c\left[(\rho\upsilon)_n - 2(\rho\upsilon)_{n-1} - 2(\rho\upsilon)_{n-2}.....\right]$

Here we denote: $(\rho\cdot\upsilon)_2$,$(\rho\cdot\upsilon)_1$, ...$(\rho\cdot\upsilon)_n$ - values of the mass speed of the pump at time t, $t + T_0$, $t + 2T_0$,... , $t + (n - 1)T_0$; φ_1 φ_2,.,φ_n - values of waves at the same moments; P_1, P_2,..., P_n - pressure values at the same moments [3]. For example, let the flow rate change according to a linear law over time tout, then

$$n = enter\,\frac{t_{out}}{T_0}, \qquad (7)$$

$$P_n = \begin{cases} c\Delta(\rho\cdot\upsilon) \\ 0 \end{cases} \text{при n=2,4,6....}, \qquad (8)$$

where $c\Delta(\rho\cdot\upsilon) = \frac{\rho\cdot\upsilon}{n} \approx \frac{\rho\cdot\upsilon\cdot T_0}{t_{вых}}$ (for large n)

Thus: $P_{\max} = \frac{\bar{c}\,\bar{\rho}\bar{\upsilon}\,2l}{ct_{вых}} \approx \frac{\bar{c}\,\bar{\rho}\bar{\upsilon}T_0}{t_{вых}}$ (also coincides with Michaud's formula).

If $t_{out} \leq T_0$, then $P_{max} = c\rho v$. During an emergency stop of the pumps, a wave of low pressure appears in the pressure pipeline, which spreads throughout the entire pressure pipeline. If there is a water intake, it is reflected from the water intake units with the opposite sign, and the pressure in the reflected wave is also equal to the static one. If, having reached the pumping station, it encounters a closed check valve, it is reflected from it, and the pressure in the hydraulic system increases by the amount of the dip that occurred after stopping the pumping unit, i.e. water hammer occurs. The resulting pressure fluctuations then gradually die out over a certain period of time.

An emergency shutdown of operating pumps and abnormal operation of the valve when starting the pump were considered as a probable abnormal (emergency) situation [4].

The parametric characteristics of the means of damping wave and vibration processes - pressure stabilizers (PS) (Fig. 2), their configuration and installation location are determined on the basis of computational and experimental studies of the hydraulic modes of the hydraulic system and its parametric features, taking into account the peculiarities of the equipment layout and piping hydraulic systems.

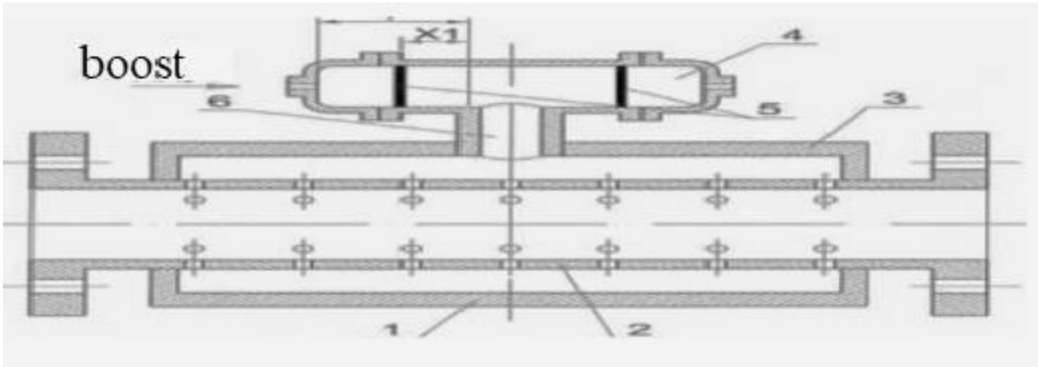


Figure 2. Calculation diagram of a stabilizer with remote cameras:

1 – stabilizer body; 2 – perforated pipeline; 3 – liquid cavity; 4 – gas cavity; 5 – separating elements; 6 – pipe

Based on the modeling results, it was found that in the event of an emergency shutdown of the pump in the pressure pipeline, there is a high probability of a break in the continuity of the water flow. During "collapse", water hammers with an amplitude of 16...17 bar are possible

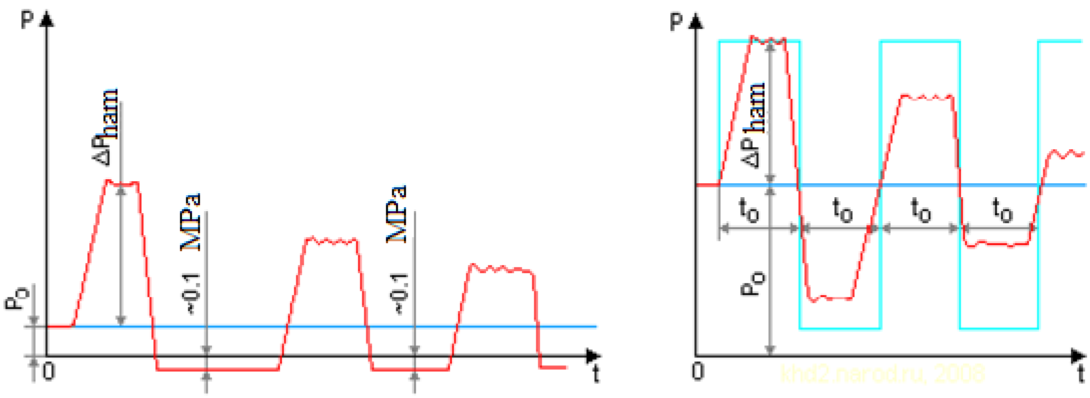


Figure 3. Change in time of pressure near the check valve during water hammer.

On the left is a strong blow (with liquid coming off the plug), on the right is a weak blow (without coming off). The blue line shows the level of initial pressure (before the start of the water hammer), the blue line shows the ideal nature of the pressure change in the absence of energy losses.

P_0 is the pressure of the free medium near the entrance to the pipe; ΔP_{ham} — maximum increase in pressure during water hammer; t_0— duration of the stage with weak water hammer.

Figure 3. Water hammer on the pressure pipeline; emergency shutdown of the pump and rupture of the pressure pipeline

Installing a pressure stabilizer on the pressure pipeline with one damping chamber in direct proximity to the pump, check valves and shut-off valves of water pipelines (sources of disturbance) will reduce the amplitude of pressure fluctuations in the water supply system by 2.5-2.6 times and lead to faster attenuation of wave processes due to changes from alternating shock loads to smoother ones, extended over time.

Conclusions. Emergency protection of the system using wave pressure stabilization technology will allow:

1. Protect pressure pipelines from bursts in the event of emergency situations
2. Ensure energy savings by reducing accident rates on pipelines
3. Increase the uninterrupted supply of water to irrigated areas.

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