Modeling the operation of reclamation pumping stations during transition processes

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Abstract. The hydropower and water management complexes include pressure systems with pumping stations that supply the required amounts of water to specified heights. Modern pressure systems are complex and varied. The control elements of these systems, primarily pumping stations, are continually becoming more complex and improved. In this regard, the costs for the construction and operation of pressure systems with pumping stations can be very high, therefore, the issue of choosing the best option when designing these systems becomes especially important. In this case, it is necessary to take into account transient processes, that is, transitions in operational conditions from one stationary mode to another. A significant change in these parameters leads to a violation of the normal operation of pressure systems, premature failure of their individual elements, and sometimes to accidents. Despite the accumulated experience in the construction and operation of pressure water supply systems, there are still no sufficiently general methods for calculating transient processes that ensure an increase in the reliability of structures. The paper presents the mathematical modeling of the calculation of transient processes in pressure water supply systems, the main directions for their further improvement are given.

1. Introduction

In pressure water supply systems, everything is to some extent constantly changing, and the division of processes into stationary and transient is conditional. In stationary modes, some changes in parameters actually occur, but they are relatively small, and therefore they can be ignored.

It is generally accepted that a transient process is a transition from one conditional stationary mode to another with a change in any parameters (pressure, water velocity, unit rotor speed, etc.) that determine these processes in stationary modes. Increases in pressure in pressurized water supply systems occur during transient processes that occur during planned and emergency stops of pumping units, as well as during their start-ups, changes in the speed of rotation of pumping units, closure of valves, filling of pipelines with water.

Water hammer resulting from a change in the degree of opening of shut-off valves can be practically avoided by changing the mode of closing and opening.

For the first time, the equation of non-stationary processes associated with the phenomenon of water hammer was derived by N.E. Zhukovsky. The theory of water hammer was further developed in
the works by V.M. Alyshev, A.G. Jvarsheishvili, V.S. Dikarevsky, K.P. Vishnevsky, L. Aliev and others.

When calculating unsteady processes of fluid movement in pipelines, the following are unknown: pressure \( P \) (head \( H \)), water velocity \( v \) (flow rate \( Q \)), fluid density \( \rho \) and its temperature \( t \). All these quantities are generally functions of coordinates \( X, Y, Z \) and time \( t \). The solution of such a three-dimensional problem is hardly feasible; therefore, the problem should be significantly simplified [1].

To solve the equations describing the unsteady movement of fluid in pipelines, initial conditions must be set that determine the head \( H \) or pressure \( P \) and the speed \( v \) or flow rate \( Q \) before the onset of the transient process and boundary (boundary) conditions that determine the change in functions and their derivatives at the boundaries of the pipelines.

When considering the process of water hammer, it is assumed that until the moment of time \( t = 0 \), the motion was steady or absent, i.e. the values of \( H \) and \( v \) did not depend on time.

Thus, the initial conditions are \( H = H (X) \) and \( v = v (X) \) for \( t \leq 0 \) \((0 < X < L)\), where \( L \) is the length of the pipeline.

The boundary conditions are determined by the nature of the flow disturbance, and in the general case are two given functional dependencies connecting the values of the head (pressure), velocity, their first derivatives and time in the initial and final section of the pipeline.

The simplest example of setting boundary conditions is the case of an instantaneous cessation of fluid movement at one end of the pipeline \( v = 0 \) at \( X = L \) \((t > 0)\) and a constant pressure value at the other end of the pipeline \( H = c \) at \( X = L \).

Despite the accumulated experience in the construction and operation of pressure water supply systems, there are still no sufficiently general methods for calculating transient processes that ensure an increase in the reliability of structures.

The main directions of improving the methodology for calculating transient processes in pressure water supply systems are: supplementing the methodology with cases of transient processes that were not previously envisaged; more accurate accounting of individual factors affecting transient processes; simplification of the preparation of initial data for calculations; improvement of the type of calculation results; more efficient use of the already developed methodology.

The development of the methodology included the following: new blocks in the algorithm and programs that provide calculations in the case of flow continuity cavitation ruptures, a more accurate account of the influence of pipeline hydraulic resistance on friction, and the account of the water level triggers in the reservoirs for water inlet, and the delay in the closure of the check valve plates.

The paper presents mathematical modeling of the calculation of transient processes in pressure water supply systems. Below are the main directions in which further improvement of transient processes in pressure water supply systems will take place:

- development and inclusion in the algorithm of programs that take into account the calculation of transient processes arising from changes in the operating modes of pumping stations operating in series;
- development of programs that allow for more accurate calculations of transient processes when changing operating modes;
- taking into account the influence of air undissolved in water;
- the possibility of calculating transients with different steps \( \Delta t \) for sections of pipelines of pressure water supply systems, as well as with changing the step \( \Delta t \) for individual periods of the transient process.

The ultimate goal of calculating transient processes is to determine the boundaries of changes in the parameters that determine these processes, and the choice, if necessary, of appropriate protective equipment, indicating all their parameters.

Transient processes caused by a change in the operating mode of pumps, as a rule, should be considered taking into account the pipeline fittings installed on their pressure lines, since its actions can significantly affect these processes [2]. The hydraulic resistance of a closing or opening valve is determined taking into account the time \( S_t = f(t) \).
When calculating the transient process for each estimated time \( t \), the pressure at the beginning of the pressure pipeline downstream of the regulator is determined [3–6].

2. Results

When the pumps are connected in parallel, transient processes are possible: when all pumping units are turned off simultaneously or when one of them is turned off; when starting the pumping unit and when regulating the operation of the pumping station [7].

An additional condition that determines the operation of the pumping station with parallel-connected pumps is:

\[
Q_{ps} = Q_{p}m,
\]

where \( Q_{ps}, Q_{p} \) are water flow rates passing through the pumping station and, accordingly, one pump; \( m \) is the number of pumps connected in parallel.

For the case of simultaneous shutdown of parallel-connected pumps with different characteristics, it is advisable to consider each of them in a separate unit.

When the pumps are connected in series, the distance between them is insignificant, therefore the connecting pipes are short and their length and hydraulic resistance can be neglected. Thus, sequentially operating pumps can be considered located in one node of the design scheme, while it is necessary to take into account the characteristics of pumps of two types [1].

In reclamation pressure systems, a series connection of more than two pumping stations is practically not used [8]. When developing a mathematical model, the cases of transient processes that occur when only the first pumping station is turned off, only the second pumping station is turned off and both stations are turned off simultaneously were considered. The number of parallel-connected pumps at each station can be any and the pumps at the stations are different (within the station, the characteristics of the pumps are identical). The number of parallel-connected pressure pipelines of each station can be any, and accordingly the diameters of the first and second stations are different (the diameters and lengths of the parallel-connected pipelines of each station are the same).

The first pumping station is assumed to be at zero, and the second station is in one of the intermediate nodes of the design scheme. The calculation of transients for the first station is carried out according to the following formulas:

\[
H_{i,j} = H_{p,j} + S_p \cdot Q_{p,j}^2 = H_{p,j} + (S_p - S_{cv} + S_{bl}) \cdot Q_{p,j}^2,
\]

where \( S_{ps} \) is the hydraulic resistance of the check valve, through which the water flow does not pass during the reverse movement; \( S_{bl} \) is the hydraulic resistance of the bypass line, the diameter of which is usually taken equal to 1/3 ... 1/4 of the diameter of the check valve.

\[
\left[M_p j - \text{Sign} (\beta_j) \cdot M_{pipe} \right] / Q_{p,j}^2 = f (\beta_j / Q_{p,j}).
\]

The change in the opening angle of the check valve disc is determined by the average angular velocity:

\[
\alpha_j = \alpha_{j,1} + \frac{w_j + w_{j-1}}{2} \Delta t.
\]

For the second pumping station, the pressure pipelines of the first station will be suction ones; therefore, to calculate the transients in this station, the following formulas are used:

\[
H_{i(l+1),j} - H_{i(l-1),j} = H_{p,j} - S_p / Q_{p,j} / Q_{p,j},
\]

\[
H_{i(l-1),j} = H_{i(l-1),0} + \varphi_{i(l-1),j} + \psi_{lj},
\]
\[ V_{i(i-1),j} = V_{i(i-1),0} + \frac{g}{\alpha} (\psi_{i(i-1),j} - \psi_{ij}), \]

\[ V_{i(i-1),j} = V_{i(i+1),j} = \frac{W_{i+1}}{W_i}, \]

\[ \psi_{ij} = \frac{H_{ij} + H_{i(i-1),j} - H_{i(i+1),j} + 2\psi_{i(i-1),j} - (1-\alpha)\psi_{i(i+1),j} - S_p / Q_{ip} / Q_{ip}^2}{1 + \alpha}, \]

\[ \psi_{ij} = \alpha (\psi_{i(i+1),j} - \phi_{ij}), \]

where \( \alpha = \frac{w_{i+1} \cdot \alpha_i \cdot m_2}{w_i \cdot \alpha_i \cdot m_1} \), i.e. it is envisaged that the wave propagation velocities for the calculated sections \( i \) and \( i + 1 \) are different, since the diameters of the suction and pressure lines are usually different; \( m_1 \) and \( m_2 \) are the number of lines of pressure pipelines of the first and second pumping stations.

When the check valves on the pressure lines of the pumps of the second station are closed, the values of \( \phi_{ij} \) and \( \psi_{ij} \) are determined by the following formulas:

\[ \phi_{ij} = \psi_{i(i+1),j} - \frac{\alpha_i \cdot V_{i(i+1),j}}{g}, \]

\[ \psi_{ij} = \frac{\psi_{i(i-1),j} + \frac{\alpha_i \cdot V_{i(i+1),j}}{g}}{\alpha_i \cdot V_{i(i-1),j}}. \]

The shutdown of the first pumping station leads to the propagation of pressure decrease waves, which reduces the pressure at the inlet to the pumps of the second station, which can lead to disruption of their operation. Therefore, measures are needed to slow down the decrease in pressure. This is usually done by installing water columns at the second pumping station. When the second pumping station is turned off, the pressure increase waves occurring at the entrance to it propagate to the first pumping station, which leads to an increase in the pressure at its station. Therefore, the mathematical model provides for automatic shutdown of the first and second pumping stations when \( P_{\text{max}} \) and \( H_{\text{min}} \) are set, respectively [9].

The water supply of the pumping station is determined by the water consumption of the pressure system. To simulate automatic shutdowns and starts of pumps, the design scheme provides for a unit for checking the flow rates and pressures, by changing of which these shutdowns and starts are controlled. The position of this node in the design diagram corresponds to the actual place of measurement of flow or pressure in the pressure system. For example, flow measurement with an induction meter is usually done at the beginning of the flow line. The conditions for automatic shutdown and start-up will be as follows:

\[ V_{ij} \cdot W_i < Q_{\text{set}}^{\text{shut}}. \]

\[ V_{ij} \cdot W_i > Q_{\text{set}}^{\text{start}}. \]

where \( Q_{\text{set}}^{\text{shut}} \) and \( Q_{\text{set}}^{\text{start}} \) are set values of water consumption at decrease and increase, below and respectively above which automatic shutdowns and starts of pumps occur.

With automation by pressure, the conditions for pump shutdown and start are as follows:

\[ \rho g (H_{ij} - Z_i) > P_{\text{set}}^{\text{shut}}, \]

\[ \rho g (H_{ij} - Z_i) < P_{\text{set}}^{\text{start}}, \]

where \( P_{\text{set}}^{\text{shut}} \) and \( P_{\text{set}}^{\text{start}} \) are set values of pressure at decrease and increase, below and respectively above which automatic shutdowns and starts of pumps occur.
3. Conclusion
The dependencies that determine the boundary conditions for pumping stations during transient processes in pressure systems are quite diverse and complex, therefore, the following classification was proposed:

1. By the method of accounting for the pumping station in the design diagram of the pressure head system.
2. By the nature of the process after shutting down the pump or pumps.
3. By the conditions of starting the pump unit.
4. By the length of the suction pipeline.
5. By changing the hydraulic resistance of the pressure line of the pump.
6. By the ratio between the flow rates of water through the pump at the beginning of the pressure pipeline.

It can be seen from the material presented that the possibility of using different models for calculating the same cases of transient processes can be checked by comparing the results of the solution using these models.

It is obvious that the best way to check the results of calculations of transient processes according to any accepted mathematical model is to compare the results of calculations with the data of the corresponding field experiments.

The result of the introduction of this methodology can be the saving of energy resources, which is what the development programs of territories in Russia and many EU countries are aimed at (the EU Framework Program for Research and Innovation Horizon Europe for 2021-2027).

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