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Features of Transient Processes in Pumping Stations with Controlled Shut-Off Devices

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Abstract

There are many large and smaller pumping units in various branches of the national economy, for which the following should be considered: influence of hydraulic resistances; peculiarities of hydraulic shock and determination of pressure change wave in the initial point of the water pipeline when installing gates on the pressure lines of pumps; working conditions of pressure pipelines with a complex profile of the route.

The experience of pumping stations operation shows that the main damages and accidents of pump units occur during transient processes, starts, stops, which, according to the operating schedule, can be assigned several times a day, as well as during emergency disconnection of electric motors from power sources. There are significant dynamic loads on elements of structures and hydraulic power equipment: hydraulic shock, abrupt change of force effects on impeller and blade drive systems, accompanied by flow pulsations, vibrations. Therefore, when designing pumping stations, it is necessary to take into account the operation of the pressure path and technological equipment in an integrated manner and assign schemes and composition of structures, based on calculations and analysis of transients, taking into account static and dynamic characteristics of pumps and electric motors. The article is devoted to engineering improved methods for calculating the shutdown mode and emergency shutdown of units from energy carriers.

Pumping station, pump, electric motor, pipeline, gate, shockproof fittings, transients, mathematical models, hydraulic shock, head, flow, shock wave velocity, head loss, hydraulic resistance.

INTRODUCTION

The development of pipeline systems requires high safety of their operation and their work reliability provision, due to their deterioration and insufficient financing of their maintenance and relocation work [1].

During the transient process due to the pipeline section change (because of the pipeline section overlap or its opening), stopping and starting a pump facility and other elements of the pipeline system, pressure relief, etc. the speed of fluid movement changes. As the result of these processes, the waves of high and low pressure arise.

Water hammer, pressure fluctuations and pulsations, increased vibration of pipelines greatly increase the rate of internal corrosion processes, contribute to the accumulation of fatigue microcracks in the metal and are the main factor of emergency situations.

According to operational experience, the causes of pipeline destruction are hydraulic shocks, pressure drops and vibrations in 60% of cases, about 25% occur due to corrosion processes, 15% - due to natural phenomena and unforeseen circumstances [2].

According to the Ministry of Regional Development of the Russian Federation, the level of wear and tear of utilities and equipment makes 65% on average. The pipeline systems of the housing and communal complex of Russia experience 180 accidents per 100 km of heating networks; 70 accidents per 100 km of water pipelines and sewerage networks.

The above confirms the relevance of this work topic.

The purpose of the work is to perform computational and theoretical studies of transient process cases for pressure pipelines during installation of shut-off devices using a computer software complex developed at the Department of Agricultural Water Supply and Wastewater Disposal, Pumps and Pumping station of the RSAU Moscow Agricultural Academy.

MATERIALS AND METHODS

Differential equations of the water hammer process, the general solution of which was first given by N.E. Zhukovsky, can be written in the following form [3, 4]:

$$\frac{\alpha v}{\alpha t} = g\frac{\alpha h}{\alpha x} + g\frac{\alpha z}{\alpha x} + v\frac{\alpha v}{\alpha x} \tag{1}$$

$$\frac{\alpha h}{\alpha t} = \frac{\alpha^2}{g}\frac{\alpha v}{\alpha x} - \frac{\alpha v}{\alpha x} + v\frac{\alpha h}{\alpha x} \tag{2}$$

where h - the pipeline pressure, m; v - the speed of water movement in the pipeline, m/s; z — the pipeline axis elevation, m; t - time (sec) counted from the moment of water hammer occurrence; g - acceleration of gravity, m/s^2; α - propagation velocity of pressure change waves during water hammer, m/s.

At that the axis x is directed along the pipeline axis, and the time t is counted from the moment the water hammer occurs.

Since the speed v of water movement in water pipes is much less than the speed of shock wave propagation, and the value of v/α is usually neglected, and then the equations (1) and (2) are written in the following form:

$$\frac{\alpha v}{\alpha t} = g\left(\frac{\alpha h}{\alpha x} + \frac{\alpha z}{\alpha x}\right), \tag{3}$$

$$\frac{\alpha h}{\alpha t} = \frac{\alpha^2}{g}\,\frac{\alpha v}{\alpha x}. \tag{4}$$

When $h + z = H$ is replaced the value of the head measured from any level of the equations (3) and (4) will be the following:

$$\frac{\alpha v}{\alpha t} = g\,\frac{\alpha H}{\alpha x} \tag{5}$$

$$\frac{\alpha H}{\alpha t} = \frac{\alpha^2}{g}\,\frac{\alpha v}{\alpha x}, \tag{6}$$

since z is independent of time.

The general integral of these equations is the following:

$$H - H_0 = \varphi\left(t - \frac{x}{\alpha}\right) + \psi\left(t + \frac{x}{\alpha}\right) \tag{7}$$

$$v - v_0 = \frac{g}{\alpha}\,\varphi\left(t - \frac{x}{\alpha}\right) + \frac{g}{\alpha}\,\psi\left(t + \frac{x}{\alpha}\right), \tag{8}$$

where H_0 and v_0 – the initial values of the head and velocity before the water hammer occurs.

The function $\varphi\ (t - \frac{x}{\alpha})$ characterizes the pressure change wave propagating in the direction of the x axis, the function $\psi\ (t + \frac{x}{\alpha})$ characterizes the wave propagating against the direction of the x axis. The direction of the x axis is taken to coincide with the direction of the velocity v_0 of water movement in the pipeline. Then, to reduce the wave of pressure changes, φ and ψ will be denoted. The values of the functions φ and

ψ are determined by the initial and boundary conditions.

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 will be

$H_0 = H(x)$ and $v = v(x)$ at $t \le 0$ $(0 < x < L)$, where L is the pipeline length.

Boundary conditions are determined by the nature of the flow disturbance and in the general case, they are two given functional dependencies connecting the values of the head (pressure), velocity, their first derivatives and time in the initial and final sections of the pipeline [5, 6].

The simplest example of setting boundary conditions is the case of instantaneous cessation of fluid movement at one end of the pipeline v = 0 at

$x = L$ $(t > 0)$ and the constant pressure value at the other end of the pipeline $H = const$ at $x = L$.

Setting the boundary conditions is difficult for the case of water hammer considered in this work, caused by a sudden shutdown of the power supply to the pump motors.

In practice, the change in the head H generated by the pump is set in the form of pump characteristics $H = F_1(Q, n)$. The moment consumed by the pump depends on the amount of water supplied by the pump Q and its turn speed n. $M = F_2(Q, n)$ and is given in the form of characteristic curves.

When installing shut-off devices [7] on the pressure lines of pumps, which are shut off according to a timed program, the peculiarity of the calculation is determined by the fact that the hydraulic resistance of the shut-off device depends on the degree of its shutting. Since the degree of shutting is set in the function of time t, the hydraulic resistance of the shut-off device ξz also turns out to be the function in time $К_3 = \frac{\xi_3}{2g} = f(t)$.

When the shut-off devices are closed, due to a rather sharp change in the hydraulic resistance of the shut-off device during the calculated time interval (especially at the end of shutting off), the amount of water passing through the pump will also be changed sharply, and if we take the value for the previous moment as a zero approximation Q_{curr}^{pum}, the used iterative calculation method may not converge in some cases. Therefore, the zero approximation of the flow rate passing through the pump is determined by the formula that takes into account the value of the hydraulic resistance of the shut-off device at a given time moment t [8]:

$$Q_{pum} = V^{wat}\, w\frac{n}{m} = \left[\pm\frac{\alpha}{2gК_3} \pm \sqrt{\left(\frac{\alpha}{2gК_3}\right)^2 \pm \frac{H^{pum} - H_0^{wat} - 2\psi_1 + \frac{\alpha}{g}V_0}{К_3}}\,\right] w\frac{n}{m}, \qquad (9)$$

where V^{wat} – the speed at the beginning of the water conduit; w – the cross-sectional area of the water conduit; n – the number of water pipelines through which water is supplied; m – the number of simultaneously operating pumps; α – the speed of motion change wave propagation; g – the acceleration of gravity; H^{pum} – the pump head; ψ_1 – the pressure change wave propagating against the direction of the initial velocity; v_0 – the initial value of the speed before the water hammer occurs.

The upper signs "+" are valid for the cases when v > 0, the lower signs "-" are for the cases when v < 0. The value of the head created by the pump H^{pum}, is assumed to be equal to the value at the previous calculated moment of time.

The head at the beginning of the conduit is determined by the dependence [9, 10]:

$$H^{wat} = H^{pum} - K_3 \mid V^{wat} \mid V^{wat} ,$$

where H^{pum} – according to the characteristics of the pump for the argument $\frac{Q}{\beta}$ (β – the relative rotation speed $\frac{n}{n_0}$) the value $\frac{H}{\beta^2}$ is determined (fig.1);

n – rotational speed at a given moment of time, min^{-1}

n_0 – pump rotation speed before turning on the power supply, min^{-1}.

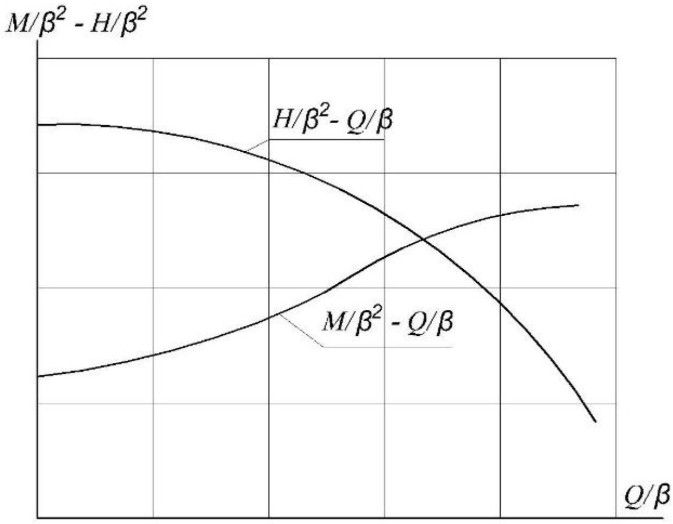

Fig. 1. Pump characteristics in the coordinates *H/β² – Q/ β* and *M/ β² - Q/ β*

Further, according to the obtained value of H^{wat} the pressure change wave is calculated at the beginning of the water conduit φ_{or}^{cur} :

$$\varphi_{or}^{cur} = H^{wat} - H_0^{wat} - \psi_1^{prel} , \qquad (10)$$

where H_0^{wat} – the pressure value at the initial point of the water conduit before the occurrence of a water hammer, m; ψ_1^{prel} – the sum of the pressure change waves that have come from a neighboring point to a given moment of time against the direction of the initial movement of water in the pipeline.

The value of the flow rate Q^{pum}, determined by the formula (9), is compared with the value of the water flow rate passing through the pump, determined at the beginning. If these values do not coincide, their arithmetic mean is calculated and the calculation is repeated.

The calculation sequence described above refers to the time period of the water hammer in which the shut-off device is partially open.

With a fully closed shut-off device, the head created by the pump and the consumed moment will be determined from the condition H_{-0}^{pum} . The values of the pressure change waves φ_{or}^{cur} and the pressure H^{wat} at the beginning of the water conduit will be determined by the following formulas:

$$\varphi_{or}^{cur} = \psi_1^{prel} - \frac{\alpha}{g} v_0^{wat} \tag{11}$$

$$H^{wat} = H_0^{wat} + \varphi_{or}^{cur} + \psi_1^{prel}. \tag{12}$$

RESULTS AND DISCUSSION

Shut-off (gate valves, butterfly valves) and shut-off and safety (check valves) pipeline fittings are usually installed on the pressure lines of pumps. Control valves (pressure regulators) are usually installed at the beginning of pressure pipelines. Safety fittings (the valves for water discharge) can be installed both on the pump pressure lines and on the pipelines.

Taking into account the influence on transient hydraulic processes of valves and shut-off devices with a manual drive is not difficult, since they remain almost in the same position - usually in a fully open position, in which the coordination of hydraulic resistance ξ for valves makes 0.06 ... 0.2, and 0.1 ... 0.5 for shut-off devices [11].

The hydraulic resistances with a known ξ are determined as follows:

$$S_3 = \frac{\xi}{2gw^2}, \tag{13}$$

where w – the cross-sectional area of shut-off devices, m^2;

g– acceleration of gravity, m/s^2.

The degree of electric and hydraulic shut-off valve opening can vary during transient processes. Of course, in a case of an emergency power outage, only the hydraulic actuator valves can work, therefore, to prevent complete emptying of pressure pipelines, it is installed on the pressure lines of large vertical centrifugal pumps. When the shut-off valves are closed, its resistance coefficient ξ increases from the above values to infinity, and this change occurs more smoothly for shut-off devices than for gate valves. This is due to the fact that the flow area of the gate valve is overlapped by a disc (two discs) moving perpendicular to the direction of flow, and the shut-off devices when the disc rotates around a horizontally or vertically located axis. Figure 2 shows the graph of ξ variation for a valve and butterfly valve of the same diameter. In most cases, the closing (opening) of the shut-off valves is provided uniformly, however, as can be seen from the graph (Fig. 2), the increase in hydraulic resistance occurs very unevenly - at first it changes slightly, and very sharply at the end. For a more uniform increase in hydraulic resistance, in some cases, the closing is carried out unevenly, at first quickly, and then slowly. However, in any closing mode, each moment of time will correspond to a certain degree of valve opening and, therefore, a certain hydraulic resistance. Therefore, it is most expedient to set the hydraulic resistance of a closing or opening valve as the function of time Sz = f(t). In practice, the dependence S = f(t) is most conveniently set in tabular form, with an uneven step t, taking into account the nature of the change $S_з$

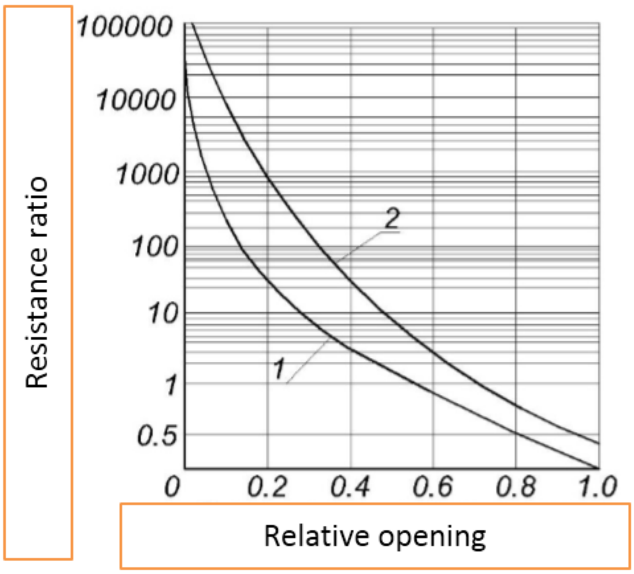

Fig. 2. Dependence ζ of the shut-off device (1) and butterfly valve (2) d = 200 mm from the degree of opening

The check valve, by its purpose, should exclude the possibility of water movement through the pump in the opposite direction, that is, when it is installed, the condition $Q_H \geq 0$ shall be satisfied. This condition is usually accepted in the calculations of transient processes, which simplifies them, but does not always correspond to reality. In fact, the check valve discs are closed with some delay. Two designs of check valves are currently in use: with an overhead disc suspension and with an eccentrically located axle. The degree of opening of the check valve disc when water moves through it depends on the ratio of the moments acting on it: MG - on the disc weight; M_g - on hydrodynamic; M_{tr} - on support friction.

The hydrodynamic moment depends on water movement speed:

$$M_т = К_м \cdot \rho \cdot g \cdot \frac{1+\xi}{2g} \cdot d^3 \cdot |v| \cdot v, \quad (14)$$

where $К_м$ - the coefficient of hydrodynamic moment, depending for a given valve design on the disc opening angle α; ξ - the coefficient of the valve hydraulic resistance, which also depends on α.

The torque from the weight M_G always acts in disc closing direction, and its value depends on α. The hydrodynamic moment M_g in the forward (normal) direction of flow acts to close. The direction of the moment M_{tr} is always opposite to the direction of the algebraic sum of the moments $M_g + M_G$. The angular acceleration of the disc is determined by the following expression:

$$\frac{dw}{dt} J_{ок} = M_г + M_G - \mathrm{Sign}\,(M_г + M_G)\, M_{тр}, \quad (15)$$

where J_{ok} is the moment of the check valve disc inertia, taking into account the added masses of water.

The value of the moment M_{tr} is noted for the state of rest and movement. In the first case, it is usually much larger. The valve disc opening angle ranges from 0° (full opening) to α_{max}, which is always less than 90° (usually from 65° to 85°).

CONCLUSIONS

1. Water hammer in water conduits without protective measures can be accompanied by a significant increase of pressure and necessitate the use of pipes of increased strength.
2. When studying water hammer in water conduits, a number of factors must be taken into account that determine this process: characteristics of pumping equipment, the inertia of rotating masses of pumping units, the length and profile of a water conduit, water velocity, the pressure loss in water conduits.
3. In the design scheme, the travel time of pressure change waves Δt for each of these sections, into which the water conduit is divided, is assumed to be the same, and the calculation is carried out for successive points in time that differ by Δt. The number of sections into which the water conduit is divided is taken depending on the length and profile of the water conduit and the placement of shockproof reinforcement.

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