Protection of pipeline systems from water hammer using oscillatory circuits

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Abstract. The issues related to reduction of the amplitude of high pressure waves in long pipes are relevant in connection with the danger of failure of some hydraulic system’s sections. The article deals with the reduction of high pressure by simultaneous separation of fluid flow for long hydraulic systems. Numerical experiments are carried out in order to identify the most cost-effective dimensions of the equipment, as well as the most profitable in terms of energy damping locations of this equipment.

Keywords: hydraulic schemes, pressure fluctuations, water hammer, long pipelines.

1. Introduction

A sharp increase or decrease of pressure in the hydraulic system can lead to serious accidents with great economic consequences, as well as possible human victims. The situation in which there is an extended destruction of pipes with accompanying equipment or the occurrence of plastic deformations [1], which negatively affect the functioning of the pipeline scheme is especially dangerous. To prevent such catastrophes, devices capable of damping excessive (or reduced) pressure are developed tested. Theoretical, numerical and practical research in this area is carried out.

This article focuses on problems of harmful pressure fluctuations’ reduction by means of energy dampers separating the flow. The idea of this device’s functioning is that with a significant increase (or decrease) of the pressure in the hydraulic system, the flow is directed along the path where it meets the hydraulic resistance. The principle of operation of these energy dampers is as follows: when the pressure increases in the pipeline sections where there is a constant or fluctuating flow discharge (and hence the corresponding flow velocity), the flow of liquid is blocked. An oscillating circuit is created. If you block the flow of fluid at the same time at two points of the segment, then there are two waves: high pressure and vacuum. They interact and partially extinguish each other in the process of mutual movement.

The computational part of the numerical program was implemented in C++, the graphical representation of information was made in Marple.

2. Analysis of the stated issue

The founders of hydraulics as a science in Russia were full members of the Russian Academy of Sciences: M.V. Lomonosov (1711-1732), Leonard Euler (1707-1783) and Daniel Bernoulli (1700-1782). Hydraulics received a theoretical basis as a result of their theoretical and practical studies. Russian scientist N.E. Zhukovsky (1847-1907) has made a significant contribution to the development of hydraulics [2, 3]. He was the first one who developed the theory of water hammers in pipes and gave a classical solution to a wide range of technical issues in the field of hydraulic supply and hydraulic engineering.

The theory of unsteady fluid motion was created and developed by I.A. Charny [4] and D.A. Fox [5]. In reference book [6] the values of hydraulic resistances are given. The theory and practical
modeling of the equipment stabilizing pressure in short pipelines is considered in the works of R.F. Ganiev, H.N. Nizamov and E.I. Derbukov [7]. Pressure stabilizers can be used in heat pipes, water supply lines, sewage systems, as well as in any schemes in which the movement of liquid is realized. The equipment serving for this purpose is also considered in [8, 9]. The resonance phenomena were studied in the works of Glikman [10]. The fluctuations in the feed systems of liquid fuel in the rockets are considered in the works [11, 12].

The equations of fluid motion and continuity of fluid flow are shown below:

\[
\partial_t \left( \rho g z + p + \alpha \rho v^2 \right) + \frac{\alpha}{2D} \rho \frac{\partial v}{\partial t} = 0, \quad \left[ N/(M^2 \cdot sec) \right],
\]

\[
\nu \frac{\partial p}{\partial x} + \frac{\partial p}{\partial t} + \rho c^2 \frac{\partial v}{\partial x} = 0, \quad \left[ N/(M^2 \cdot sec) \right],
\]

where \( x \) - coordinate along pipe’s axe; \( \rho \) - mass density of liquid (const); \( g \) - acceleration of free fall; \( z \) - the height of the considered point; \( p \) - pressure in the pipeline; \( \alpha \) - the coefficient of Coriolis (adopted \( \alpha = 1 \)); \( v \) - average flow velocity; \( \alpha' \) - the ratio of Businesc (adopted \( \alpha' = 1 \)); \( t \) - time; \( \lambda \) - hydraulic resistance coefficient; \( D \) - the pipe diameter; \( c \) - propagation velocity of waves of increased pressure.

The system (1) - (2) consists of two hyperbolic partial differential equations. All variable parameters are changed according to the marching scheme, that is, they are developing with the change of time. These equations require the dependence \( H = H(Q) \) or one constant condition \( (Q \text{ or } H) \) at the boundaries.

The method of characteristics is used as a numerical method, which is discussed in details in [13]. The absolute hydrodynamic head \( H \) expressed in \( m \) and mass flow rate \( Q \) [\( m^3/sec \)] are taken as the main characteristics. The computational part of the numerical program is implemented in C++, the graphical representation of information is made in Marple.

The paper deals with kinetic energy of the liquid flow [14, 15]. The problem is how to reduce it with the use dampers. The idea is as follows: when the pressure at point A rises to a certain value, the signal of the long flow closing by the valves is transmitted almost instantly (the velocity of the electromagnetic field propagation reaches 300 000 km/sec). The best location of the points of the flow stop and graphics of the obtained values of pressure are investigated. The question of further elimination of the threat of a significant increase in pressure is studied. The problems associated with transient fluid motion are discusses in [16, 17]. Some ideas have been gathered from these works.

The investigated hydraulic scheme is shown in figure 1. It consists of 18 nodes and 21 pipes.

Figure 1. The hydraulic scheme.
The pumping station is installed in node 1, the dependence \( H = H(Q) \) is given. The boundary condition in nodes 18 and 17 is a constant head. All the numerical experiments had one goal: to create braking areas in elements 19, 20 and 21 for ensuring that the pressure in the system was significantly less than the pressure without braking areas. The valves are installed in nodes 5, 9 and 15 (points \( D, C \) and \( B \)), these valves receive a signal of operation when the pressure in node 15 (point \( F \)) rises above the pressure specified in the task condition.

3. Numerical calculations and the main results
Now we’ll consider the hydraulic scheme shown in figure 2 in details.

![Figure 2. Pressure at node 15 without energy dissipation with the water head \( H_{18} = 60 \text{ m} \).](image)

![Figure 3. Water discharge at node 15 without energy dissipation with the water head \( H_{18} = 60 \text{ m} \).](image)

![Figure 4. Pressure to the right from the valve \((t_{cl} = 0)\) in node 7 when the signal from node 15.](image)

![Figure 5. Pressure to the left from the valve \((t_{cl} = 0)\) in node 7 when the signal from node 15.](image)

Test problem 1:
Initial data: \( L_1 = 200 \text{ m}, L_2 = 10000 \text{ m}, L_3 = 2700 \text{ m}, L_4 = 300 \text{ m}, L_5 = L_6 = 200 \text{ m}, L_7 = 2700 \text{ m}, L_8 = 300 \text{ m}, L_9 = L_{10} = 200 \text{ m}, L_{11} = 2700 \text{ m}, L_{12} = 300 \text{ m}, L_{13} = L_{14} = 200 \text{ m}, L_{15} = 200 \text{ m}, L_{16} = 200 \text{ m}, L_{17} = 20000 \text{ m}, L_{18} = 12000 \text{ m}, L_{19} = 300 \text{ m}, L_{20} = 300 \text{ m}, L_{21} = 300 \text{ m} \). The diameter of elements 1 - 18 are \( D_{1-17} = 1.0 \text{ m} \), \( D_{18} = 0.5 \text{ m} \), the diameters of tubes 19 - 21 are variable. Water heads in nodes 0, 17 and 18 are \( H_0 = 10, H_{17} = 50, H_{18} = 60 \) respectively. The speed of steady motion of the liquid in the elements 3 - 17 is 0.93 m/sec, the coefficient of hydraulic resistance of pipes (except pipes 19 - 21) is equal to \( \lambda = 0.023 \). The velocity of high pressure waves \( c = 1020 \text{ m/sec} \). The parameters of the pump unit \( H = H(Q) \) are given by three points: \( H_1 = 96, H_2 = 80, H_3 = 42 \text{ [m]}, Q_1 = 0.08, Q_2 = 2.24, Q_3 = 4.0 \text{ [m}^3/\text{sec}] \).

The scheme with a constant water intake in the node 18 \( Q = 0.19 \text{ m}^3/\text{sec} \) was tested. However, this boundary condition (which is the only one in node 18) is too strict to obtain good results. After the introduction of a constant head in the node 18 (\( H_{18} = 60 \text{ m} \)), the pressure and flow in node 15 (point \( F \)
have the following form as shown in figure 2 and 3. The maximum pressure of 1.85 MPa is in good agreement with the theory.

Let’s consider the case when the electrical signal is instantly transmitted to node 7 from node 15. Figure 4 shows the pressure to the right of node 7 when the valve \( (t_{cl}=0) \) in node 7 is actuated after the head exceeds 85 m in node 15. The formula \( t_{cl}=0 \) means that the valve closes instantly. The electrical signal (from node 15) spreads with a speed of about 300,000 km/sec. The vacuum wave goes from node 7 to node 16. A wave of increased pressure simultaneously moves from node 16 to node 7. In the Fig. 4 it is seen that the period of pressure fluctuation between nodes 7 and 16 after the addition of these waves is about 9 sec. This is much less than the oscillation period of the entire system (about 64 sec.) from nodes 1, 18 to node 7 (Figure 5).

**Problem 2.** The initial data are changed (compared to the test problem 1): \( \lambda_{20}=0.04, d_{20}=0.1 \) m. The valve in node 9 closes instantly when the head in node 15 reaches 85 m. In this problem, gate valves in nodes 16 and 9 close almost simultaneously. As a result of the addition of waves, the oscillation period in node 15 (and throughout from node 9 to node 16) is two times less than if the boundary condition of the constant head \( H_9=\text{const} \) (Figure 6). The second positive result is that the peaks of the maximum pressures decreased. An interesting fact is that with a decrease in the friction coefficient in the pipe 20 (or an increase in the diameter of the pipe 20) the pressure even rises with time. This is probably due to the influence of flow to the left of node 8.

![Figure 6. Pressure in node 15 when the gate in node 9 \( (t_{cl}=0) \) closes from a signal of node 15.](image)

![Figure 7. Pressure in node 15 when the valve in node 9 is actuated \( (t_{cl}=0) \) from the head increase in node 9 up to 85 m.](image)

![Figure 8. Pressure in node 15 when the valves in nodes 5, 9,13 close \( (t_{cl}=0) \) from pressure increase in node 15 over 85 m.](image)

![Figure 9. Pressure in node 3 when the valves in nodes 5, 9,13 close \( (t_{cl}=0) \) from pressure increase in node 15 over 85 m.](image)
Problem 3. It differs from problem 2 that the valve in node 9 closes when the pressure in node 9 exceeds 85 m (Figure 7). It is interesting that there is no vacuum wave from node 9 and therefore the average pressure is much higher than in problem 2. In addition, high pressure peaks are wider. All this suggests that it is more difficult to extinguish the overpressure in this case than in the example of problem 2.

Problem 4. It differs from the problem 2 is that the valves in the nodes 5, 9, 13 close when the pressure in the node 15 exceeds 85 m (Figure 8 and 9). In the problem the oscillation frequency is high in node 15 (Figure 8), because the distance between node 13 and 16 is not large (600 m). This creates good conditions for breaking the flow. It should be noted that the pipeline from node 1 to node 5 is poorly protected, but the period of pressure fluctuations in node 3 is less than without electrical devices.

4. Conclusions
1) Introduction of valves, which close almost simultaneously create a wave of vacuum. It adds up with a wave of high pressure. As a result, the pressure at the gate valve in node 15 is significantly less than without them (Figure 2, 4). The period of pressure fluctuations is two times less, so it is much easier to extinguish such oscillations than the oscillations of all systems (Figure 7).
2) Valves, closing simultaneously divide the flow into shorter sections. Here the mileage of high pressure and vacuum waves is correspondingly less. This greatly facilitates the fight against the increased pressure. Comparing figure 5 and figure 2 we see that the periods of pressure fluctuations are different (64 sec. and 82 sec.)
3) Introduction of self-actuating valves when pressure increase (Figure 7) have a higher average pressure and wider pulses of increased pressure, which makes it difficult to stabilize (equalize) the pressure.
4) Figure 9 shows that the introduction of three breaking circuits effectively dissipates high pressure.
5) Creating of short circuits well dissipates energy, due to frequent fluctuations of water discharge.
6) Pressure waves with a short period can be well extinguished by means of pressure stabilizers.

References
[1] Rynkovskaya M 2018 Plastic deformations occurring in shells with developable middle surfaces during bending IOP Conf. Series: Materials Science and Engineering 371 012054
[2] Zhukovsky N E 1949 Collected works in 7 volumes Volume 2: Hydrodynamics Volume 3: Hydraulics. Applied mechanics (Publishing House Gostekhizdat, Moscow) p 487
[3] Zhukovsky N E 1949 On Water Hammer in Water Pipes (Publishing House Gostehizdat, Moscow) p 106
[4] Charny I A 1951 Unsteady movement of a real liquid in pipes (Publishing House Nedra, Moscow) p 224
[5] Fox D A 1981 The hydraulic analysis of the unsteady current in pipelines (Publishing House Energoizdat, Moscow) p 248
[6] Idelchik I E 1992 Reference book on hydraulic resistance (Publishing House Mashinostroenie, Moscow) p 672
[7] Ganiev R F, Nizamov H N and Derbukov E I 1996 Wave Stabilization and Prevention of Accidents in Pipe-Lines (Publishing House MGTU, Moscow) p 260
[8] Rekach F V, Shambina S L and Sinchenko E K 2017 Influence of pressure stabilizer perforation area on character of unsteady fluid motion in hydraulic systems. Int. J. of Mech. Eng. and Robotics Res. 6(4) pp 268-71
[9] Svintsov A P, Kharun M I and Mukarzel S A 2015 Valve head for water fittings with high regulatory capacity Mag. of Civ. Engin. 58(6) pp 8-18
[10] Glikman B F 1986 Mathematical models of pneumohydraulic systems (Moscow: Nauka) p 368
[11] Kolesnikov K S 1971 Longitudinal oscillations of a liquid-propellant rocket engine (Publishing House Mashinostroenie, Moscow) p 259
[12] Natanzon M S 1977 *Longitudinal self-oscillations of a liquid rocket* (Publishing House Mashinostroenie, Moscow) p 208

[13] Rekach F V 2010 Calculation of fluctuations in circular cylindrical shells with pressure stabilizer by method of characteristics *J. Struct. Mechan. of Engin. Constr. and Build*. 1 pp 60-65

[14] Samuel S Pegler 2016 The dynamics of confined extensional flows *J. Fluid Mech*. 804 pp 24-57

[15] Pietro Scandura, Carla Faraci, Enrico Foti 2016 A numerical investigation of acceleration-skewed oscillatory flows *J. Fluid Mech*. 808 pp 576-613

[16] Young W R and Wolfe C L 2014 Generation of surface waves by shear-flow instability *J. Fluid Mechanics* 739 pp 276-307

[17] Kerswell R R 2016 Energy dissipation rate limits for flow through rough channels and tidal flow across topography *J. Fluid Mechanics* 808 pp 562-75

**Acknowledgements**

This paper was financially supported by the Ministry of Education and Science of the Russian Federation on the program to improve the competitiveness of Peoples’ Friendship University of Russia (RUDN University) among the world’s leading research and education centres in the 2016-2020. This publication was prepared with the support of the “RUDN University Program 5-100”.