Influence of Pressure Stabilizer Perforation Area on Character of Unsteady Fluid Motion in Hydraulic Systems

Fedor V. Rekach, Svetlana L. Shambina, and Evgeny K. Sinichenko
Engineering Academy, Peoples' Friendship University of Russia (RUDN University), Moscow, Russia
Email: rekfedor@yandex.ru, {shambina_sl, eks47}@mail.ru

***Abstract*—One of the main causes of pipeline systems' failure are sharp changes and fluctuations in pressure caused by various reasons. Pressure stabilizer is a modern and effective mean for damping of wave processes. The constructive scheme of the device is a pipeline with uniformly distributed perforation through which liquid can flow from the pipeline into a damping add-on above the perforated part of it. The article discusses the pipeline scheme, in which occurs water hammer. It is investigated the problem of optimal perforation area under the assumed constant parameters of the stabilizer. It was used a numerical method of characteristics.**

***Index Terms*—pressure stabilizer, water hammer, pipelines, unsteady flow, incompressible liquid, method of characteristics.**

I. Introduction

With the development of technical progress the security requirements of the work of hydraulic systems, especially under unsteady motion of the fluid, should be increased.

The practice of pipeline systems operating shows that the pulsations of pressure and discharge, that occurs due to the uneven work of pumping facilities and the actuation of the locking elements, can lead to a significant increase of dynamic loads on the pipeline. A sharp increase (decrease) of pressure can cause accidents and accidents with heavy consequences, human casualties.

The correct choice of the operation mode for the hydraulic system is of great importance, since in some areas the pressure can be increased and in others can be reduced at the same capacity of the pipeline. The sudden change of the cross section of the pipeline (for example, the actuation of a valve), turning on and off of pumping units and other devices that can change discharges in the branches of the pipeline, arise waves of high and low pressure moving along the length of the pipeline.

During unsteady motion of the fluid in certain sections of pipeline, pressure changes can be so large and fast that can cause destruction of pipeline's walls.

In order to protect the system from an emergency situation, it is necessary to have methods and technical means for pressure stabilization in the pipeline. In addition, presence of harmful pressure pulsations significantly reduces the efficiency and shortens the service life of pipeline systems. Therefore, the problem of creation of effective means of damping of wave propagation and water hammers remains relevant for many decades.

Manuscript received March 1, 2017; revised June 14, 2017.

II. Differential Equations of Unsteady Fluid Motion

Fundamentals of the theory of unsteady motion of liquid in a pressure pipeline were laid in the works of N.E. Zhukovsky [1], [2]. He obtained the equations for motion of invissid fluids, formed the basis of further development of the theory of pressure flow of viscous liquid. With the help of this theory, explanation of some physical phenomena called water hammer was received. N.E. Zhukovsky introduced the concept of effective speed of sound, which allowed reducing a problem of compressible fluid in an elastic cylindrical pipe to a problem on motion of a compressible fluid in a rigid pipe, but with a lower modulus of elasticity of the liquid.

Theory of unsteady flow of viscous and compressible fluids in pipes was created by Charny [3], who used the hypothesis of quasi-stationarity fluid motion. The essence of the hypothesis is that the force of fluid friction on the pipe wall in unsteady regime is adopted just the same as in stationary motion (with the speed equal to the instantaneous velocity in the considered steady flow).

The unsteady movement of incompressible liquid $(\rho = const)$ is described by the equations of movement and continuity [4], [5] which have the following type:

$$\frac{\partial}{\partial x}\left(\rho g z + p + \alpha\rho\frac{v^2}{2}\right) + \alpha'\rho\frac{\partial v}{\partial t} + \frac{\rho\lambda}{2D}v|v| = 0, \quad \left[N/м^3\right] \qquad (1)$$

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

where p - absolute hydrodynamic pressure; v - average speed on live section; g - acceleration of gravity; z - geometrical height; ρ - liquid density; t - time; λ - coefficient of hydraulic friction along length; D - pipeline diameter; c - speed of distribution for a wave of

doi: 10.18178/ijmerr.6.4.268-271

pressure; α and α' - Coriolis's coefficient and Businesk's coefficient (it is accepted that $\alpha = \alpha' = 1$).

III. Method of Characteristics

Equations (1), (2) describing the unsteady motion of the fluid in pressure pipelines are quasilinear equations of the hyperbolic type of the first order [6]. Such equations do not have analytical solution and can be integrated only by numerical methods [7]-[10]. For the solution of nonlinear differential equations explicit scheme is adopted, which allows to calculate rapidly changing flow (water hammer).

If we accept liquid volume $Q = F \cdot v$ and absolute hydrodynamic pressure $H = p/(\rho g)$ (expressed in meters of water column) as the basic main characteristics of a flow liquid, then we will receive the following equation instead of (1) and (2):
stead of (1) and (2):

$$\frac{\partial}{\partial x}\left(gFz + gFH + \frac{Q^2}{2F}\right) + \frac{\partial Q}{\partial t} + \frac{\lambda}{2DF} Q\,|\,Q\,| = 0, \left[m^3/\sec^2\right], \quad (3)$$

$$\frac{Q}{F}\frac{\partial H}{\partial x} + \frac{\partial H}{\partial t} + \frac{c^2}{gF}\frac{\partial Q}{\partial x} = 0, \quad [m/\sec]. \quad (4)$$

Multiplying (3) on (c/gF) and, adding (subtracting) to the obtained expression (4), we will get for the direct characteristic the following:

$$\frac{dx}{dt} = \frac{Q}{F} + c; \quad (5)$$

$$\frac{\partial H}{\partial t} + \frac{c}{gF}\frac{\partial Q}{\partial t} + c\frac{dz}{dx} + c\frac{\lambda}{2DgF^2} Q\,|\,Q\,| = 0 \quad (6)$$

For the return characteristic:

$$\frac{dx}{dt} = \frac{Q}{F} - c; \quad (7)$$

$$-\frac{\partial H}{\partial t} + \frac{c}{gF}\frac{\partial Q}{\partial t} + c\frac{dz}{dx} + c\frac{\lambda}{2DgF^2} Q\,|\,Q\,| = 0 \quad (8)$$

Let's assume that we know the values of H and Q in the closely located sections x_A and x_B of the pipeline in time points t_A and t_B respectively. Using the method of characteristics we can found values H_C and Q_C in section C $(x_A < x_B < x_C)$ in the time point t_C, taking in mind that both x_C and t_C are unknown and should be determined by calculations. This method is described in details in [3]. This study examines the regular rectangular grid of the characteristics: a step on time Δt and a step on coordinate Δx are constants.

IV. Entry Conditions

As entry conditions parameters of the steady current of a flow (index "y") in hydraulic system are set:

1) Discharges Q_{yi} and heads H_{yi} on everyone i section of system;

2) Parameters of system – the liquid density ρ, diameters of pipes D_i, marks of axes of the pipes laying z_i in calculative sections, resistance coefficients λ_i, etc.

1. Boundary conditions. On each border one boundary condition (H or Q) is set.

2. Node of pressure system in which N branches are connected. Pressure and discharge in each branch number n for a time point ($j+1$) are determined by the conditions of flow continuity $\sum_{n=1}^{n=N} Q_{n,j+1} = 0$ and equality of pressures in sections of the branches adjoining the node $H_{1,j+1} = H_{2,j+1} = \ldots = H_{N,j+1}$, if heads and discharges in a time point j are known.

3. A latch is set in the node of pressure system. Losses of pressure in the latch established in i section of a constructive site of the pipeline are determined by the formula suggested by Veysbakh:

$$h_3 = \xi_3 \frac{v^2}{2g} = \xi_3 \frac{Q^2}{2gF^2} \quad (9)$$

where ξ_3 - coefficient of losses of pressure in a latch which depends on extent of its opening; v - speed in a pipe before (behind) a latch.

4. A hydraulic stabilizer (HS) is established in the node of pressure system. We will consider the hydraulic stabilizer established in i section of a constructive area of the pipeline, $1 \le i < N$ (Fig. 1).

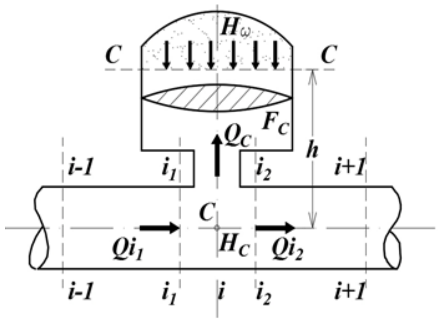

Figure 1. Hydraulic stabilizer in the pipeline

As a first approximation we find the discharge Q_C arriving at *HS* on a temporary step $j: Q_C = Q_{i_1,j} - Q_{i_2,j}$.

In case of the polytrophic law of expansion we will get for air compression the following:

$$H_{C,j+1} w_{j+1}^{\chi} = H_{C,j} w_j^{\chi} \quad (10)$$

where H_C - a head in section $c-c$, w - air amount in HS. It is obvious that: $w_{j+1} = w_j - Q_C \Delta t$.

According to (10), we have:

$$H_{C,j+1} = H_{C,j}\left(\frac{w_j}{w_{j+1}}\right)^{\chi} \quad (11)$$

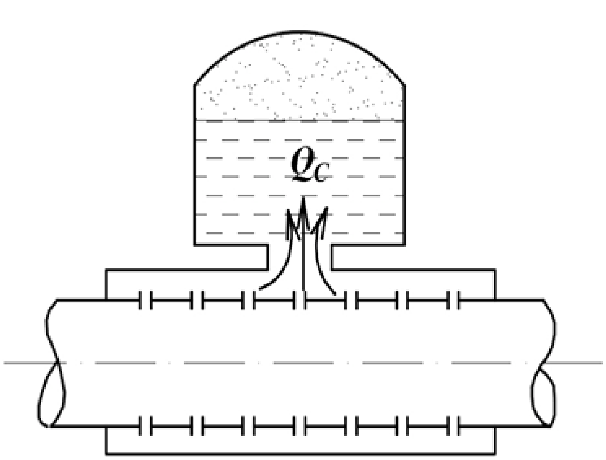

Figure 2. Scheme of pressure stabilizer

When liquid moves through a punched opening (Fig. 2), losses of a pressure are calculated using the following formula:

$$h_{pun} = \xi_{pun} \frac{v_{pun}^2}{2g} \qquad (12)$$

where v_{pun} - the average speed of movement of liquid through an opening, ξ_{pun} - coefficient of losses of a pressure. In case of the long pipeline (when time of movement of liquid in one direction is estimated in tens of seconds) ξ_{pun} can be accepted as a constant [11]. Values of ξ_{pun} for various openings and traffic patterns of liquid are given in the reference book [4] on p. 147.

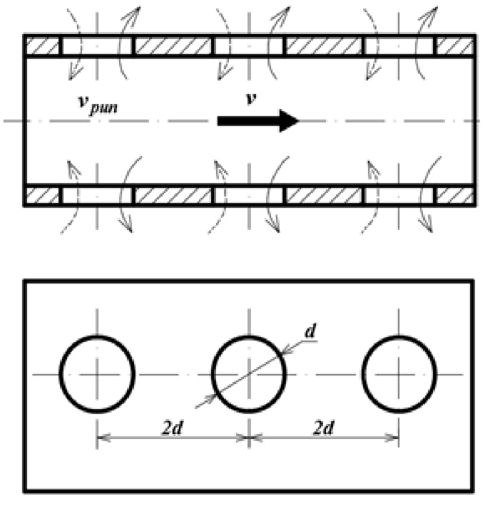

Figure 3. Local resistance of openings

We will consider one of schemes represented in Fig. 3. For an opening in a thin wall (at a pipe thickness $\delta < 3d$), numbers of Reynolds: $\mathrm{Re} = \frac{v_{pun} d}{\mu} \geq 10^4$ and $\frac{v}{v_{pun}} < 0.5$; ξ_{pun} is accepted to be equal to 2,7.

In calculations the parameter η is called punching percent, i.e. the total relation of the area of openings to the interior area of the pipe increased by 100% is used.

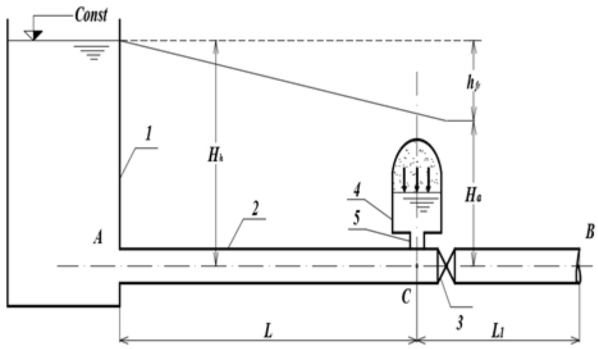

Figure 4. Scheme of the pipeline

We will consider the scheme of the pipeline shown in Fig. 4. Are designated by figures: 1 – the reservoir with fixed head; 2 – pipeline; 3 – latch; 4 – hydraulic stabilizer (HS – pressure stabilizer); 5 – node of the HS connection with the pipeline.

V. Example

Initial data: $L = 3500\,\text{м},\ L_1 = 2670\,\text{м},$ the diameter of the pipe $D = 200\,\text{мм},\ H_H = 74\,\text{м},\ h_{fr} = 42\,\text{м},$ the velocity of a fluid in stationary motion (flow) $v_y = 1.4\,\text{м}/\sec$, coefficient of hydraulic friction $\lambda = 0.0239,$ velocity of propagation of pressure waves $c = 1000\,\text{м}/\sec,$ coefficient of pressure loss at the perforated area $\xi_{pun} = 2.7$.

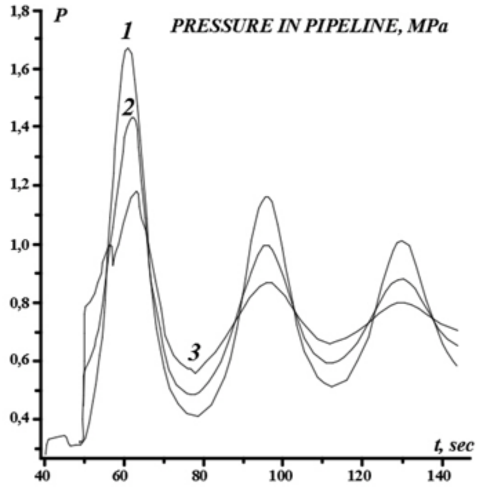

Figure 5. Pressure in pipeline

Fig. 5 shows graphs of pressure change in a point C depending on time: curve 1 – fluctuations in the pressure stabilizer, having an air volume $w_0 = 0.4\,\text{м}^3$ without perforation; curve 2 – the pressure fluctuations with the stabilizer, having a volume of air $w_0 = 0.4\,\text{м}^3$ and the percentage of perforation $\eta = 14\%$; curve 3 – pressure fluctuations with a cap, having a volume of air $w_0 = 0.4\,\text{м}^3$ and the percentage of perforation $\eta = 9\%$. The valve closes in time $t = 50\sec$.

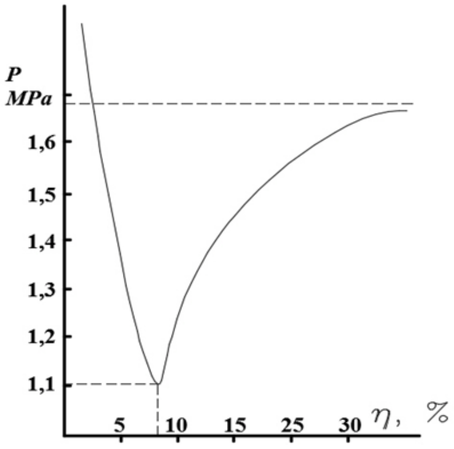

Figure 6. Graph of the maximum pressure

Fig. 6 shows a graph of the maximum pressure depending on percentage of perforation for stabilizer, having a volume of air $w_0 = 0.4 м^3$.

VI. Conclusions

1. Decrease of punched holes square area less than 10% should be well checked analytically and experimentally at the stage of system design.

2. Increase of punched holes square area more than 25% does not give a visible effect of reducing of pressure in the hydraulic system.

3. Proper selection of punched holes square area may decrease up to 30% water hammer when a predetermined volume of hydraulic stabilizer is established. This leads to a significant economic effect.

Acknowledgment

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 educational centers in the 2016 – 2020.

References

[1] N. E. Zhukovsky, *About Water Hammer in Water Pipes*, M. L.: Gostekhizdat, 1949, 103 p.

[2] N. E. Zhukovsky, *Collected Works in 7 Volumes*, M. L.: Gostekhizdat, Volume 2: Hydrodynamics–763, Volume 3: Hydraulics, Applied Mechanics, 1949, 700 p.

[3] I. A. Charny, *Unsteady Movement of a Real Liquid in Pipes*, M.: Nedra, 1975, p. 296.

[4] B. F. Lyamayev, G. P. Nebolsin, and V. A. Nelyubov, *Stationary and Transition Processes in Difficult Hydraulic Systems*, Leningrad, Mechanical engineering, 1978, p. 191.

[5] D. A. Fox, *The Hydraulic Analysis of the Unsteady Current in Pipelines (the lane with English)*, M.: Energoizdat, 1981, p. 247.

[6] F. V. Rekach, "Calculation of fluctuations in circular cylindrical covers with pressure stabilizer by method of characteristics," *Structural Mechanics of Building Constructions and Constructions*, no. 1, pp. 60–65, 2010.

[7] I. E. Idelchik, *Reference Book on Hydraulic Resistance*, Moscow, Mechanical Engineering, 1975, p. 559.

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

[9] S. S. Pegler, "The dynamics of confined extensional flows," *J. Fluid Mechanics*, vol. 804, pp. 24–57, 2016.

[10] P. Scandura, C. Faraci, and E. Foti, "A numerical investigation of acceleration-skewed oscillatory flows," *J. Fluid Mechanics*, vol. 808, pp. 576–613, 2016.

[11] R. R. Kerswell, "Energy dissipation rate limits for flow through rough channels and tidal flow across topography," *J. Fluid Mechanics*, vol. 808, pp. 562–575, 2016.

Fedor V. Rekach was born in 1961 in Moscow. In 1984 he graduated from People's Friendship University, specialty "Civil Engineering". In 1989 after completing his postgraduate studies he defended his thesis on structural mechanics on competition of a scientific degree of candidate of technical Sciences (PhD).
1989 up to now he has worked in Peoples' Friendship university of Russia at the Departments of Descriptive geometry and Mathematics and at the Department Strength of Materials as an Associate Professor.
Research interests: differential equations with a small parameter; applications of mathematics to mechanics (structural mechanics, dynamics of pipelines, numerical solution).

Svetlana L. Shambina graduated from Peoples' Friendship university of Russia (Moscow) with a degree in Civil Engineering. She obtained her PhD diploma on Structural Mechanics in 1995. The name of PhD thesis was "Calculation of structures made of anisotropic composite materials". The major fields of study are design and calculations of structures made of anisotropic composites, architecture and calculations of large-span structures of complex geometric shape.
At present she is an Associate professor of the Department Architecture and Civil Engineering in Peoples' Friendship university of Russia.

Evgeny K. Sinichenko graduated from the Moscow Institute of Petrochemical and Gas Industry in 1976. In 1985 he obtained his PhD diploma of candidate of technical sciences.
His work experience in the department of architecture and construction of the Engineering Academy is 46 years. He teaches the following disciplines: Hydraulics, Hydraulics of Structures, Hydromechanics, Hydrology and Water Management and others.
The scientific interests are in the following fields: research of water regime in small rivers, the hydraulics of pressure pipelines, problems of engineering education at the present stage. Sinichenko E.K. Is a member of the expert commission "Association of Engineering Education of Russia".