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CALCULATION OF COMPRESSION OF ENTRAPPED AIR AT THE FLOW SEPARATION POINT

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Abstract

A method for determining the parameters of hydraulic shock in a pressure pipeline has been developed, taking into account the compression of air at the point of violation of the integrity of the liquid and the compressed place of formation of discontinuities in the flow continuity. A mathematical model of resource-saving innovative shock-resistant devices for pumping stations of a pressure pipeline and a scientific justification for their parameters have been developed.

Keywords: Hydraulic shock, pressure pipe, damper, air compression-expansion law, flow continuity, unsteady motion, isothermal process, adiabatic process.

Introduction

РАСЧЕТ СЖАТИЯ ВОЗДУХА, ЗАЩЕМЛЕННОГО В МЕСТЕ ОБРАЗОВАНИЯ РАЗРЫВА СПЛОШНОСТИ ПОТОКА

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Аннотация
Разработана методика определения параметров гидравлического удара в напорном трубопроводе с учетом сжатия воздуха в месте нарушения целостности жидкости и сжатого места образования разрывов сплошности потока, разработана математическая модель ресурсосберегающих инновационных ударопрочных устройств насосных станций напорного трубопровода и научное обоснование их параметров.

Ключевые слова: Гидравлический удар, напорная труба, демпфер, закон сжатия-расширения воздуха, непрерывность потока, неустановившееся движение, изотермический процесс, адиабатический процесс.

Introduction

Hydraulic shock, accompanied by a disruption of the flow integrity, poses a major threat to the normal operation of pressure pipelines. The process of water hammer occurs in the pressure pipelines of the pumping station, causing damage to the pressure pipelines, check valves, the pumping station building and pumping units. When the engine stops, the pump speed, water supply and pressure decrease, and after a while the flow changes direction [1,2].

In pumping station pipelines, hydraulic shocks caused by pump shutdowns and short-term power outages are often accompanied by the formation of discontinuities in the flow, as a result of which spaces filled with water vapor and dissolved air released from the water under vacuum are formed between the separated water columns [1-5]. At the moment of elimination of these gaps, a collision of columns moving at different speeds occurs, which leads to a significant increase in pressure.

To reduce the impact pressure, L.F. Moshnin [6] suggests introducing and trapping air in places where discontinuities in the flow are formed. Trapped air, acting as a buffer, changes the conditions for the formation of reflected waves of pressure increase and decrease at the boundaries of the separated water columns. As the columns approach each other, the air gradually compresses, which prolongs the process of hydraulic shock and, thus, eliminates the possibility of an instantaneous increase in pressure.

In order to avoid the propagation of pressure increase and decrease waves along the entire length of the pipeline, it is recommended to install shut-off check valves and air inlet and outlet valves at points where breaks in the flow continuity occur [2].

Research Methodology

The method for calculating hydraulic shock during air intake and entrapment in places where discontinuities in the flow continuity are formed, based on the application of elastic hydraulic shock equations, is complex and labor-intensive [2-5]. Taking into account the wave nature of the hydraulic shock process does not allow us to directly determine the maximum increase in pressure without intermediate calculations [2].

Let us assume that after the pump is turned off, a discontinuity in the flow occurs at an intermediate point in the pipeline, as a result of which the water columns move apart by a distance l_p. If air is introduced at the site of the rupture, the distance between the separated columns increases. Let us denote this distance as l_0. Let us determine the increase in trapped air pressure when the columns approach each other. For this purpose, we will consider the unsteady motion of water in a simple pipeline with trapped air at the end, shown in Fig. 1 [2].

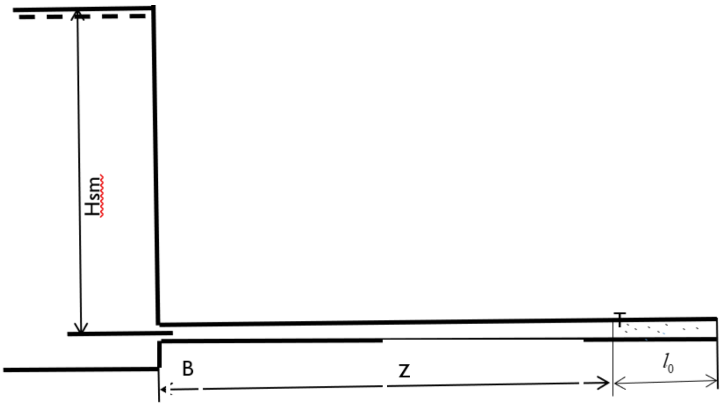

Fig. 1. Unsteady movement of water in a simple pipeline with trapped air at the end of the pipeline.

A valve is installed at the interface between water and air. The initial absolute air pressure is atmospheric – P_{am}. This diagram corresponds to a pipeline equipped with a shut-off check valve and an air inlet and pinch valve [2].

Let at the moment of time t = 0 the instantaneous opening of the valve cause an unsteady movement of water. Let's determine the speed of water movement and air pressure depending on time. We will assume that during the period of air compression, it does not dissolve in water, as is usually accepted when calculating air caps and pneumatic reservoirs, and the volume of air is negligibly small compared to the volume of water contained in the pipe, that is, $l_0<Z$ [2].

If we neglect pressure losses and dynamic pressure, then the equation of unsteady motion is written in the form [2]:

$$H + \frac{P_{am}}{\gamma} = \frac{P}{\gamma} + \frac{Z}{g}\frac{dv}{dt}, \tag{1}$$

where P_{am}– is the absolute pressure of trapped air.
Equation (1) contains two unknown functions p(t) and v(t).
As the second equation we use the continuity equation, which in this case will be [2,3,4]:

$$\vartheta dt = -dl\,. \tag{2}$$

The relationship between the pressure and volume of air is expressed by the equation of state of the gas.
In the isothermal process of air compression we have [2]:

$$P_{ат} l_0 = Pl\,. \tag{3}$$

Solving equation (1) taking into account equations (2) and (3) with the initial condition t = 0, ϑ = 0 and P = P_{am}, we obtain [2]

$$\frac{\vartheta}{\vartheta_*} = \sqrt{\sigma\left(1 - \frac{P_{am}}{P}\right) - \ln\frac{P}{P_{am}}} \tag{4}$$

where

$$\vartheta_* = \sqrt{2g\frac{P_{am}}{\gamma}\frac{\ell_0}{Z}}; \quad \sigma = \frac{P_{am} + \gamma H_{cm}}{P_{am}}. \tag{5}$$

The adiabatic process of air compression is characterized by the equation [2]

$$P_{am}\ell_0^{\kappa} = P\ell^{\kappa}, \tag{6}$$

where κ - is the adiabatic index, for air κ = 1.4.
The joint solution of equations (1), (2) and (6) taking into account the same initial condition gives [2]:

$$\frac{\vartheta}{\vartheta_*} = \sqrt{\sigma\left(1 - \frac{P_{am}^{1/\kappa}}{P^{1/\kappa}}\right) - \frac{1}{\kappa-1}\left(\frac{P^{\frac{\kappa-1}{\kappa}}}{P_{am}^{\frac{\kappa-1}{\kappa}}} - 1\right.}. \tag{7}$$

The speed ϑ* characterizes the acceleration ability of trapped air. The greater the length of the section of trapped air in the pipe, the greater v*, and therefore the speed of movement.

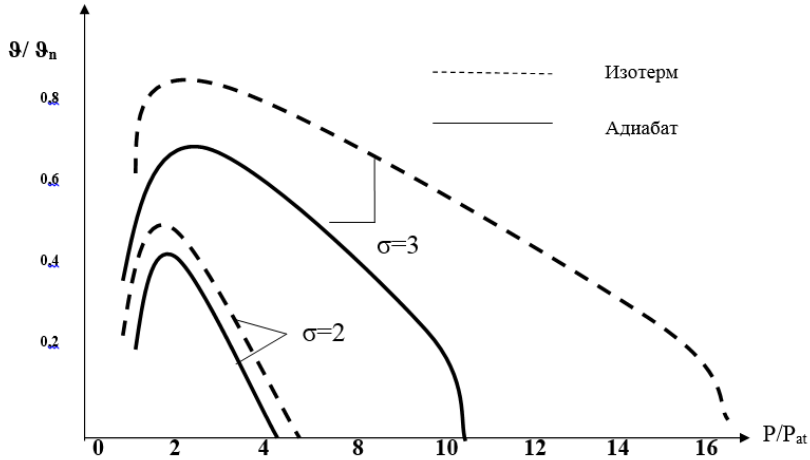

Fig. 2. Graph of the dependence for isothermal and adiabatic air compression processes for parameter values σ = 2 and σ = 3.

Fig. 2 shows the dependence of $\frac{\vartheta}{\vartheta_*} = f(\frac{P}{P_{am}})$ for isothermal and adiabatic air compression processes for parameter values σ=2 and σ=3.

The graphs are symmetrical about the abscissa axis. The upper branch of the graph corresponds to the movement of water from the reservoir to the trapped air (the air is compressed), while the lower branch corresponds to the reverse movement of water (the air expands). The lower branches of the curves are not shown in the figure [2].

From (2.11) and (2.14) it is easy to see that the speed of water movement reaches its maximum at $\frac{P}{P_{am}} = \sigma$. This means that in the interval {1, σ} the movement is accelerated, and in the interval $\{\sigma, \frac{P_{\max}}{P_{am}}\}$ it is decelerated [2].

For isothermal and adiabatic air compression processes, the maximum speeds will be:

$$\frac{\vartheta_{\max}}{\vartheta_*} = \sqrt{\sigma - 1 - \ln\sigma}\,, \tag{8}$$

$$\frac{\vartheta_{\max}}{\vartheta_*} = \sqrt{\sigma + \frac{1}{K+1} - \frac{K}{K-1}\sigma^{\frac{K-1}{K}}}\,. \tag{9}$$

From formulas (4) and (7) it follows that ϑ=0 either at $P=P_{am}$, which corresponds to the initial condition, or at $P=P_{max}$, which corresponds to the maximally compressed state of air. Therefore, the pressure maxima for isothermal and adiabatic processes are determined respectively from equations [2]:

$$\sigma(1 - \frac{P_{am}}{P_{\max}}) - \ln\frac{P_{\max}}{P_{am}} = 0, \tag{10}$$

$$\sigma(1 - \frac{P_{am}^{1/K}}{P_{\max}^{1/K}}) - \frac{1}{K-1}(\frac{P_{\max}^{\frac{K-1}{K}}}{P_{am}^{\frac{K-1}{K}}} - 1) = 0. \tag{11}$$

From these equations it follows that the maximum pressure depends only on the pressure head H_{cm} and does not `depend at all on the length of the air section l_0, the length of the pipe Z and the diameter of the pipe D. The fact that the maximum pressure does not depend on the volume of air is somewhat paradoxical. This is explained by the fact that a change in l_0 leads to such a change in v that the relative compression of the air remains unchanged. Thus, with an increase in l_0, the speed of water movement increases and the relative shortening of the length of the trapped air section remains unchanged. The cases $l_0 = 0$ and $l_0 \to \infty$ should be excluded, since in the first case v = 0, and in the second v≠ 0 for all values of t> 0 [2].

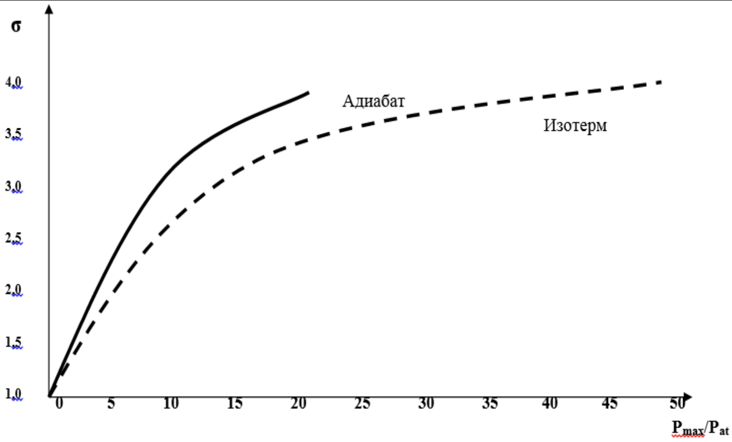

Fig. 3. Dependence curves on the σ values for isothermal and adiabatic processes [2]

Fig. 3 shows the curves of the dependence of $\frac{P_{\max}}{P_{am}}$ on the values of σ for isothermal and adiabatic processes [2].

From these graphs it can be seen that as σ increases, the ratio $\frac{P_{\max}}{P_{am}}$ increases sharply. For an isothermal process, $\frac{P_{\max}}{P_{am}}$ is greater than for an adiabatic one, and the discrepancy increases greatly as σ increases [2].

In reality, the air compression process will be polytropic. On the one hand, the space into which the air is admitted is filled with a water-air mixture, and there will be intense heat transfer from the air to the water [2]. Therefore, the air temperature during the compression process will change little and in this respect the process is close to isothermal. On the other hand, the compression process occurs in a short period of time and heat is only partially transferred from the air to the water. In this respect, the compression process is close to adiabatic.

To evaluate the effect obtained by admitting and trapping air at the point where a discontinuity in the flow occurs, we determine the increase in pressure P′ in the absence of air in the discontinuity zone [2].

In this case, in equation (1) instead of p, the saturated vapor pressure $P_{н.п.}$ should be substituted, which is assumed to be constant during the period of air compression. After such a replacement, equation (1) will characterize the uniformly accelerated motion of water. It is obvious that at the moment when the boundary of the water column reaches the closed end of the pipe, the speed of water movement will be maximum and equal to:

$$\vartheta'_{\max} = \sqrt{2g(H + \frac{P_{am}}{\gamma} - \frac{P_{Н.П.}}{\gamma})\frac{\ell_p}{Z}}, \qquad (12)$$

and the maximum increase in pressure according to the well-known formula of N.E. Zhukovsky [7,8,9], will be:

$$p' = \rho a v'_{\max}. \qquad (13)$$

From equation (13) it is evident that the magnitude of the maximum increase in pressure in the absence of air depends on the length of the rupture zone l_p and on the length of the pipeline Z, which was not the case when air was trapped.

Fig. 4 shows a graph of the dependence of $\frac{P'_{\max}}{P_{am}}$ on $\frac{\ell_0}{Z}$ for values σ=3 and a=1000 m/sec.

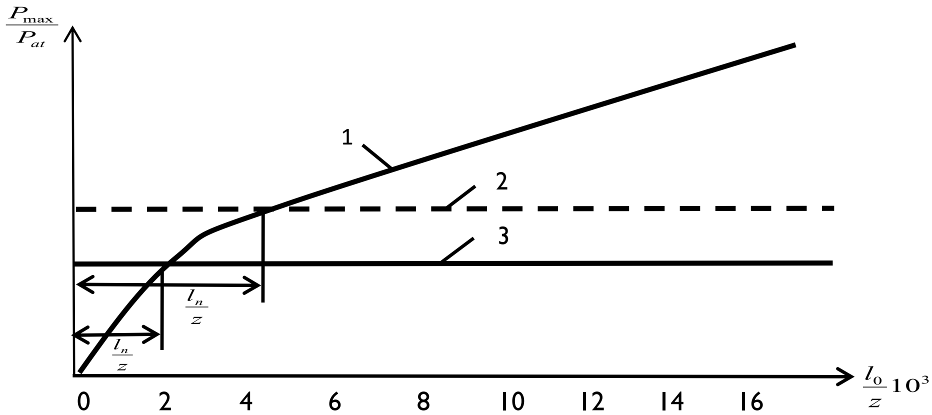

Fig. 4. Graph of dependence on for values σ = 3 and a = 1000 m/sec [2].

According to the graph shown in Fig. 3, the values of $\frac{P'_{\max}}{P_{am}}$ at σ=3 for isothermal and adiabatic processes were determined and plotted in Fig. 2.7 as straight lines parallel to the abscissa axis. We will call the abscissas of the intersection of the lines with the curve $\frac{P'_{\max}}{P_{am}}(\frac{\ell_0}{Z})$ the limit values of the length of the flow discontinuity zone l_n [2].

As can be seen from the graph, the intake and trapping of air at the point where the flow discontinuity is formed reduces the pressure at $l_0 > l_n$. At $l_0 < l_n$, the intake and trapping of air not only does not reduce, but, on the contrary, increases the pressure. The limiting value of the length of the rupture zone for an adiabatic process is less than for an isothermal process [2].

It is obvious that at any value of l0, that is, when air is admitted and trapped at the point of formation of a discontinuity in the flow, any amount should lead to a decrease in the impact pressure. Therefore, the increase in pressure in the case $l_0 < l_n$ is erroneous. This result is obtained due to the failure to take into account the compressibility of water and the elasticity of the pipeline walls. At smaller air volumes, the compressibility of water and the elasticity of the pipe walls in relation to the compressibility of the trapped air cannot be neglected. Therefore, for this problem, the equation of unsteady motion of an incompressible fluid in a rigid pipe can be applied for $l_0 > l_n$ [2].

To find the function p(t), we use equations (2), (3) and (4).

After simple transformations for the isothermal process we obtain [2]

$$d(\frac{t}{\tau_*}) = \frac{d(\frac{P}{P_{am}})}{\frac{P^2}{P_{am}^2}\sqrt{\sigma(1-\frac{P_{am}}{P}) - \ln\frac{P}{P_{am}}}}, \quad (14)$$

where τ* is some time parameter equal to

$$\tau_* = \frac{\ell_0}{\vartheta_*} = \sqrt{\frac{\gamma\ell_0 Z}{2gP_{am}}}. \quad (15)$$

Let us denote $\frac{t}{\tau_*} = y$ и $\frac{P}{P_{am}} = x$.

From (14) we determine the unknown function y = y(x) by quadrature

$$y = \int_1^x \frac{d\xi}{\xi^2\sqrt{\sigma(1-\frac{1}{\xi}) - \ln\xi}}. \quad (16)$$

Due to the impossibility of accurately calculating the resulting integral, it is necessary to resort to approximate calculation methods. Since the integrand has a singularity at one end (x=1) of the integration interval, calculation on a computer is associated with certain difficulties. To avoid this inconvenience, first introduce a new variable $Z = 1 - \frac{1}{x}$, we transform the integral to the form

$$y = \int_0^{\frac{1-x}{x}} \frac{dz}{\sqrt{\sigma z + \ln(1-z)}}. \quad (17)$$

and then we represent the last integral as the sum of two integrals

$$y = \int_0^{\alpha} \frac{dz}{\sqrt{\sigma z + \ln(1-z)}} + \int_{\alpha}^{\frac{1-x}{x}} \frac{dz}{\sqrt{\sigma z + \ln(1-z)}}, \quad (18)$$

where

$$0 < \alpha < \frac{1-x}{x}.$$

The number α for each value of σ is chosen as follows [2]:

a) We expand the integrand in a series of powers of $Z^{m-\frac{1}{2}}$ (m is a natural number) and limit ourselves to a finite number of terms (n = 6);

b) We estimate the remainder term of the series $R_n(\alpha)$, and choose α so that the error when replacing the series with its segment does not exceed the predetermined accuracy.

Thus, after choosing the value of α, the first integral of expression (13) is calculated approximately, without the help of a computer, and the second integral is calculated on a computer, since the integrand in the integration domain {α, x} is bounded and continuous.

From equations (2), (6) and (7) for the adiabatic process of air compression we obtain [2]

$$dy = \frac{dx}{\sqrt{\sigma x - \frac{1}{K-1}\left[(1-x)^{1-K} - 1\right]}}. \quad (19)$$

From (14) we determine the unknown function y = y(x) by quadrature

$$y = \int_0^x \frac{d\xi}{\sqrt{\sigma\xi - \frac{1}{K-1}\left[(1-x)^{1-K} - 1\right]}}. \tag{20}$$

The integrand at x = 0 has a singularity, therefore, as in the previous case, we represent the resulting integral as the sum of two integrals

$$y = \int_0^\alpha \frac{d\xi}{\sqrt{\sigma\xi - \frac{1}{K-1}\left[(1-x)^{1-K} - 1\right]}} + \int_\alpha^x \frac{d\xi}{\sqrt{\sigma\xi - \frac{1}{K-1}\left[(1-x)^{1-K} - 1\right]}}. \tag{21}$$

As in the previous case, we calculate the first integral approximately, without the help of a computer, and the second integral on a computer [2].

Based on these calculations, Fig. 5 shows the curves of the dependence of $\frac{P}{P_{am}}$ on $\frac{t}{t_*}$ for isothermal and adiabatic air compression processes for parameter values σ = 2, σ = 3.

From the graphs in Fig. 5 it follows that the time interval during which the pressure reaches its maximum depends on the parameters σ and τ_*. From equalities (5) and (15) it follows that this time interval depends on the pressure H_{cm}, the length of the pipe Z and the length of the section of trapped air l_0 [2].

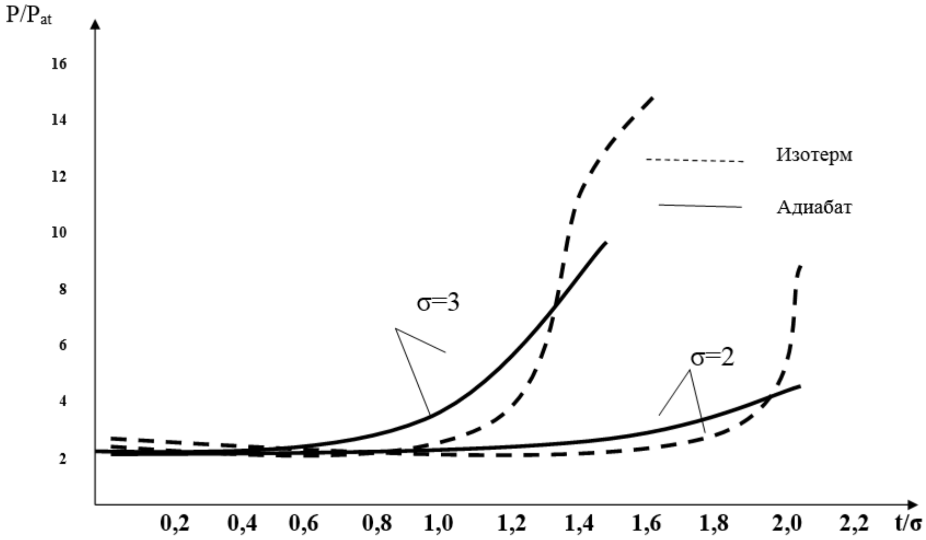

Fig. 5. Dependence curves for isothermal and adiabatic air compression processes for parameter values σ=2, σ = 3.

Using the dependencies $\frac{P}{P_{am}}(\frac{t}{\tau_*})$ and formulas (4) and (7), the curves of the dependence of $\frac{\vartheta}{\vartheta_n}$ on $\frac{t}{\tau_*}$ were constructed, which are presented in Fig. 6.

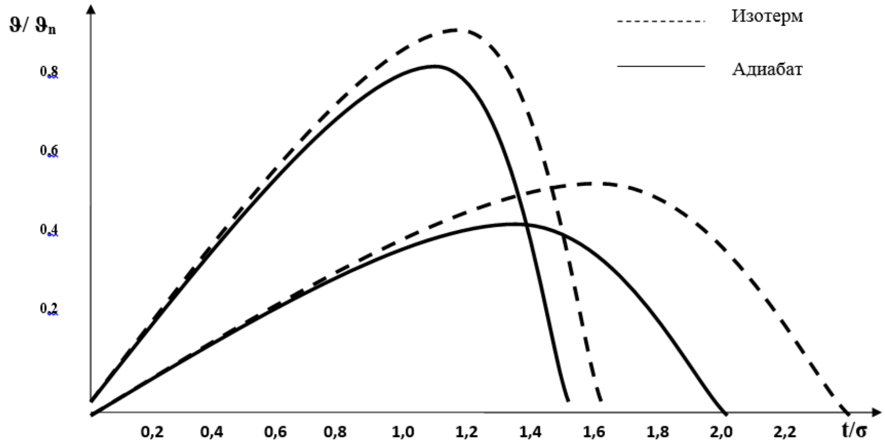

Fig. 6. Dependence curves for isothermal and adiabatic air compression processes for parameter values σ=2, σ=3.

From these graphs it is evident that the effect of flow braking by trapped air increases after the speed of water movement from the reservoir to the air reaches its maximum [2,9-14].

Conclusion.

When the pumps are turned off, a flow break occurs at some intermediate sections along the length of the pipe, where a gap appears, and if air is introduced into this area, the distance between the protruding columns increases. As the columns approach each other, an increase in compressed air pressure is observed. As a result, the unsteady motion of water in a simple pipe with compressed air collected at the end is considered. The gap into which the air enters is filled with a water-air mixture, and heat is intensely released from the air to the water. Therefore, during the compression process, the air temperature changes little, and in this respect the process is close to an isothermal process. On the other hand, the compression process occurs in a short time, and the heat from the air to the water is released only partially. In this respect, the compression process is close to an adiabatic process [2].

It follows from the graphs that the time interval for the pressure to reach its maximum value depends on the parameters σ and τ*. From equations (5) and (15) it follows that this time interval depends on the pressure H, the length of the pipeline L and the length of the compressed air zone l0 [2].

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