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NUMERICAL CALCULATION OF POSITIVE HYDRAULIC SHOCK IN THE PRESENCE OF A DAMPER

Rajabov Ulug‘bek Mamashoevich
Karshi State Technical University PhD, associate professor
Mamashoyev Umid Ulug‘bek o‘g‘li, assistant
Economy and Pedagogy university

Annotation. The article provides information on the numerical calculation of the main parameters of a hydraulic shock absorber with increased pressure, installed at the end of a pipeline to reduce the emergency consequences of hydraulic shock. Based on the results of numerical studies using the finite difference method of the proposed hydraulic shock absorber, dependencies were obtained based on the specified air in the absorber, the full capacity and the main dimensions of the cylindrical absorber were determined.

To determine the economical dimensions of the proposed damper design, comparative calculations of numerical experiments with experimental data prove the reliability of the proposed dependencies using the finite difference method.

Keywords: water hammer, numerical method, pressure pipeline, water hammer damper, diaphragm damper, polytropic coefficient.

Аннотация. В статье приведена сведений по численному расчету основных параметров гасителя гидравлического удара с повышения давления, установленным в конце трубопровода для снижения аварийных последствий гидравлического удара. На основе результатов численных исследований по методу конечных разностей предложенного гасителя гидравлического удара получены зависимости на основании определенного воздуха в гасители определена польная емкость и основных размеров цилиндрического гасителя.

Для определения экономичных размеров предложенной конструкции гасителя сравнительные расчеты численных экспериментов с опытными данными доказывают достоверности предлагаемых зависимостей по методу конечных разностей.

Ключевые слова: гидравлический удар, численный метод, напорный трубопровод, гаситель гидравлического удара, гаситель с диафрагмой, коэффициента политропы.

Annotatsiya. Maqola bosim ortishi bilan kechadigan gidravlik zarbaning salbiy oqibatlarini kamaytirish uchun bosimli quvurning oxiriga o‘rnatilgan gidravlik zarba so‘ndirgichning asosiy parametrlarining sonli usulda hisoblashlariga bag‘ishlangan. Taklif etilayotgan gidravlik zarba so‘ndirgichning chekli farq usulidan foydalangan holda sonli tadqiqotlar natijalariga ko‘ra, so‘ndirgichdagi

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havo hajmiga asoslangan bog‘lanishlar olingan, silindr shaklidagi so‘ndirgichning to‘la hajmi va asosiy o‘lchamlari aniqlangan.

Taklif etilayotgan so‘ndirgich konstruksiyasining iqtisodiy o‘lchamlarini aniqlash uchun sonli tajribalarning eksperimental ma’lumotlar bilan qiyosiy hisoblari cheklangan farqlar usuli yordamida tavsiya etilgan bog‘lanishlarning ishonchliligini isbotlaydi.

Kalit so‘zlar: gidravlik zarba, sonli usul, bosim quvuri, gidravlik zarba so‘ndirgichi, diafragmali so‘ndirgich, politropa koeffitsiyenti.

1. Introduction

In hydraulic systems, hydraulic shocks often occur due to increased pressure. [1,2,3,4,5,6].

Currently, various types of hydraulic shock absorbers - air-hydraulic caps (AHC) - are used to protect long pressure pipelines from hydraulic shock [7,8,9,10,11,12].

The advantages of the AHC include simplicity of design, failure-free operation, elimination of water discharge, and the absence of possible occurrence of vacuum in the pressure pipeline. If the geometric dimensions of the cap are correctly determined, a high degree of damping of maximum pressures during hydraulic shock (HSH) is guaranteed [7,8,9,10].

In [13,14] various designs of AHC are described: single, double; with transition pipes; with resistance at the inlet; with cylindrical pipes (connecting pipeline); directional action; with automatic air supply; horizontal, and so on.

A.F. Mostovsky [1] considers the GU in horizontal pressure pipelines when installing the AHC at the end of the pipeline in front of the valve. The author, based on the application of the “living forces” equation, obtains formulas for calculating the maximum increase in pressure Δp with a known volume of the cap. In this case, the author takes into account the elasticity of the pipeline walls and the compressibility of water and air [1].

F.M. Darson and A.A. Kaliske [2] developed an analytical method for determining the dimensions of a cap located at the end of a pressure pipeline in front of a valve. In this case, the author accepts the isothermal law (n=1.0) of the change in gas volume in AHC and does not take into account the influence of pressure losses on friction in the pressure pipeline. This method of calculating the cap is also approximate [2].

L. Bergeron in [3] provides a graphical method for calculating pressure pipelines for hydraulic shock in the presence of AHC. This calculation method is characterized by high accuracy, but is also very labor-intensive.

N.E. Zhukovsky [4] proposed a method for calculating the HSH in the presence of a AHC installed on the pipeline. In this case, the author proposes an

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approximate formula for determining the volume of air in the AHC and adopts the adiabatic law of compression and expansion of air in the AHC, since, according to the author, the HSH process is fast-flowing [4].

I.A. Charny [5] uses linearized HSH equations to calculate the AHC. In this case, the author adopts the isothermal law (n=1.0) for the compression and expansion of air in the AHC.

In practice, the most widely used calculation method was that proposed by G. Evangelisti [6]. The method of G. Evangelisti [6] is based on the use of special graphs compiled as a result of approximate integration of the wave equations of hydraulic shock using the finite difference method.

The disadvantage of these graphs is the limited range of variation of the initial parameters and therefore in many cases the G.Evangelisti method is not applicable.

V.S. Dikarevsky in his work [7], trying to eliminate the shortcoming of G. Evangelisti's method, constructed diagrams $\overline{Z}_{\max} = f\left(\sigma, \overline{h}_{mp0}\right)$ and $\overline{Z}_{\min} = f\left(\sigma, \overline{h}_{mp0}\right)$ for the isothermal law (n=1.0) in a wide range of changes in the parameters σ and $\overline{h}_{mp0}$ However, the author allows for inaccuracies in solving the basic equations.

B.F. Lyamaev [8] developed a method for calculating the AHC on a computer. The proposed method is based on the combined solution of the HSH equations, the continuity at the cap-to-pipeline connection, and the gas state in the AHC. The calculation is performed by the author [8] using an iterative method.

D.A. Fox presents in [9] a numerical method for calculating the AHC. The author applies the method of characteristics with a regular rectangular grid with constant steps Δx and Δt. The author solves the equations of continuity, the state of air (gas), and the equations of relationships on characteristics simultaneously. The calculations were carried out on a computer. The author [9] proposed to take the value of the polytropic coefficient equal to n=1.20 in calculations, but the value n=1.20 was not substantiated experimentally and takes into account pressure losses along the length according to the quasi-stationarity hypothesis.

To carry out the experimental work, a pilot plant was used, which is designed to study the hydraulic shock absorber in long pressure pipelines both in the phase with decreasing pressure and in the phase with increasing pressure [10].

Experiments conducted [10,14] to determine the value of n confirm that, when calculating HSH in a gas-liquid flow, n=1.20 is very practical and convenient, while the experimental data agree well with the calculated data. Therefore, in this work, all studies and calculations were conducted at n=1.20.

To reduce the intensity of positive hydraulic shock at the end of a pressure pipeline, it is proposed to use a hydraulic shock absorber (HSA) with a diaphragm (Fig. 1). The dimensions of the damper are determined by the conditions for starting

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and stopping the pumping unit [10]. In this work and in Fig. 1, we use the designations that we described in detail earlier in [10,14].

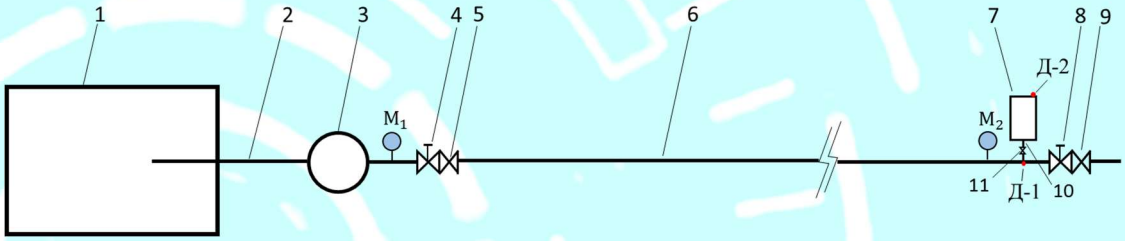


Fig. 1. Diagram of the pumping unit: 1- tank; 2- suction pipeline; 3- pump brand 3K-6; 4,8- valves; 5,9- quick-acting plug valves; 6- pressure pipeline; 7- hydraulic shock absorber; 10- connecting pipeline; 11- diaphragm; $Д_1$, $Д_2$ – pressure sensors; M_1, M_2 - pressure gauges.

In this work and in Fig. 1 we will use the notations that we described earlier in detail in [10].

2. RESEARCH METHODOLOGY

This paper presents a numerical calculation method for a hydraulic shock absorber with a diaphragm installed at the end of a pressure pipeline. [10,15] (Fig. 1).

The proposed method assumes that the closing time of a fast-acting plug valve is zero [10].

The proposed damper with a diaphragm is installed at the end of the pressure pipeline 6 in front of the valve 8 (Fig. 1).

The initial conditions in this case are as follows [10]:

$$\left.\begin{aligned} \vartheta &= \vartheta_0 \\ H_a &= H_{0a} \end{aligned}\right\}, \text{ at t=0} \qquad (1)$$

or in dimensionless form

$$\left.\begin{aligned} \bar{\vartheta} &= \bar{\vartheta}_0 = 1; \\ h_0 &= 1 - \bar{h}_{mp0} \end{aligned}\right\}, \text{ at } \bar{t}=0. \qquad (2)$$

The problem is to determine the dimensions of the damper for given H_{amax} and H_{amin} or the inverse problem of determining H_{amax} and H_{amin} in a pressure system in the first period of oscillations [10].

The following assumptions are made: the fast-acting plug valve 9 closes instantly and completely; the problem is solved based on a “rigid” model of unsteady fluid motion; the pressure created by the variable liquid layer in the damper is not taken into account [10].

To solve the problem of hydraulic shock in a pumping unit (Fig. 1), the following hyperbolic wave equations are used [6,7,8,10]:

$$1 - h = \frac{1}{2\pi}\sqrt{2\chi\sigma}\,\frac{d\bar{\vartheta}}{d\bar{t}} + \left(\bar{h}_{mp0} + \bar{h}_{\partial 0}\right)\bar{\vartheta}\left|\bar{\vartheta}\right|; \qquad (3)$$

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$$d\overline{W} = -2\pi\sqrt{\frac{2\sigma}{\chi}}\,\overline{\vartheta}\,d\bar{t}; \qquad (4)$$

$$\overline{W} = \frac{1}{h^{\frac{1}{\chi}}}, \qquad (5)$$

Where $\bar{h}_{\partial 0} = \frac{h_{\partial 0}}{H_{za}}$; $h_{\partial 0}$ - pressure loss at speed $\vartheta 0$ in connecting pipeline 10 (Fig. 1), on which diaphragm 11 is installed. The remaining designations are adopted [10].

The system of equations (3)-(5) can be solved numerically by the finite difference method [7,10].

The solution of system (3)-(5) using the finite difference method was implemented on a computer. Calculations were performed at χ=1.2 and $\Delta\bar{t}$=0.025.

By analogy with G.Evangelisti, we will solve the system of equations (3)-(5) using the finite difference method [10].

Equation (3) can be written in the following form

$$\overline{W}_{\bar{t}} = \frac{1}{h_{\bar{t}}^{1/n}} \text{ и } \overline{W}_{\bar{t}+\Delta\bar{t}} = \frac{1}{h_{\bar{t}+\Delta\bar{t}}^{1/n}}, \qquad (6)$$

Where $\overline{W}_{\bar{t}}$ и $\bar{h}_{\bar{t}}$ - values of $\overline{W}$ and h at time $\bar{t}$; $\overline{W}_{\bar{t}+\Delta\bar{t}}$ and $\bar{h}_{\bar{t}+\Delta\bar{t}}$ - values $\overline{W}$ and h at time $\bar{t}+\Delta\bar{t}$; $\Delta\bar{t}$ - calculated time interval (step).

Then we get

$$\Delta\overline{W} = \overline{W}_{\bar{t}+\Delta\bar{t}} - \overline{W}_{\bar{t}} = \frac{h_{\bar{t}}^{1/n} - h_{\bar{t}+\Delta\bar{t}}^{1/n}}{h_{\bar{t}}^{1/n} \cdot h_{\bar{t}+\Delta\bar{t}}^{1/n}}. \qquad (7)$$

According to equation (2) we have

$$\Delta\overline{W} = 2\pi\sqrt{\frac{2\sigma}{n}}\,\overline{\vartheta}_{\bar{t}}\Delta\bar{t}, \qquad (8)$$

Where $\overline{\vartheta}_{\bar{t}}$ - value $\overline{\vartheta}$ at time t.

Since $\Delta\overline{W}$ according to (5) and $\Delta\overline{W}$ according to (6) are equal, we get for n=1

$$\frac{h_{\bar{t}}^{1/n} - h_{\bar{t}+\Delta\bar{t}}^{1/n}}{h_{\bar{t}}^{1/n} \cdot h_{\bar{t}+\Delta\bar{t}}^{1/n}} = 2\pi\sqrt{\frac{2\sigma}{n}}\,\overline{\vartheta}_{\bar{t}}\Delta\bar{t},$$

from which it follows

$$h_{\bar{t}+\Delta\bar{t}} = \frac{h_{\bar{t}}}{\left(1 + 2\pi h_{\bar{t}}^{1/n}\sqrt{2\sigma}\,\overline{\vartheta}_{\bar{t}}\Delta\bar{t}\right)^{n}}, \qquad (9)$$

From equation (1) we have

$$d\overline{\vartheta} = \frac{2\pi}{\sqrt{2n\sigma}}h d\bar{t} - \frac{2\pi}{\sqrt{2n\sigma}}d\bar{t} - \frac{2\pi}{\sqrt{2n\sigma}}\left(\bar{h}_{mp0} + \bar{h}_{\partial 0}\right)\overline{\vartheta}\left|\overline{\vartheta}\right|dt, \qquad (10)$$

from where we get

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$$\bar{\vartheta}_{\bar{t}+\Delta\bar{t}} = \bar{\vartheta}_{\bar{t}} + \frac{2\pi\Delta\bar{t}}{\sqrt{2n\sigma}} \cdot \left[\bar{h}_{\bar{t}+\Delta\bar{t}} - 1 - \left(\bar{h}_{mp0} + \bar{h}_{\partial 0}\right)\bar{\vartheta}_{\bar{t}}\left|\bar{\vartheta}_{\bar{t}}\right|\right], \qquad (11)$$

When deriving the calculated dependencies (9) and (11) by analogy with G.Evangelisti, the following assumptions were made: when determining $\Delta\bar{W}$ according to (7), $\bar{\vartheta} = \bar{\vartheta}_t$ was adopted; when determining $\vartheta_{t+\Delta\bar{t}}$, $h = h_{\bar{t}+\Delta\bar{t}}$ and $\bar{\vartheta}\left|\bar{\vartheta}\right| = \bar{\vartheta}_{\bar{t}}\left|\bar{\vartheta}_t\right|$ were adopted.

The dimensionless pressure h' in the pipeline at the location of the cap installation differs from the dimensionless pressure h in the cap by the amount of pressure loss in the "diaphragm", namely [10]

$$h' = h - h_{\partial 0}\bar{\vartheta}\left|\bar{\vartheta}\right|. \qquad (12)$$

Using dependencies (7), (9) and (10), it is possible to calculate the process of pressure fluctuations in the cap with a diaphragm and the pipeline over time for given σ, $\bar{h}_{\text{тро}}$, $\bar{h}_{\partial o}$, n and initial conditions (1), (2) and determine the minimum h_{min} and maximum h_{max} dimensionless pressures in the cap in the first period of oscillations.

A AHC with a diaphragm is the most promising design, since here, during a transient oscillatory process in a pumping unit (Fig. 1), independent regulation of the direction of fluid movement is achieved, that is, one of the main disadvantages of a single-acting AHC is eliminated [5,6,10].

The main idea in using a AHC with a diaphragm is to achieve maximum use of the effective qualities of the AHC both in the pressure reduction phase and in the pressure increase phase [10].

3. RESEARCH RESULTS

The following assumptions were made when solving the problem: the plug valve closing time is zero; The problem is solved on the basis of the so-called "rigid" model of unsteady pressure flow of liquid, which does not take into account the elastic properties of the liquid and the walls of the pipeline [5,10].

Let's write down the main calculation dependencies for calculating a damper with a diaphragm

$$h_{\bar{t}+\Delta\bar{t}} = \frac{h_{\bar{t}}}{\left(1 + 2\pi\sqrt{\frac{2\sigma}{n} \cdot h_t^{\frac{1}{n}} \cdot \bar{\vartheta}_{\bar{t}} \cdot \Delta\bar{t}}\right)^n}; \qquad (13)$$

$$\bar{\vartheta}_{\bar{t}+\Delta\bar{t}} = \bar{\vartheta}_{\bar{t}} + \frac{2\pi\Delta\bar{t}}{\sqrt{2n\sigma}}\left[h_{\bar{t}+\Delta\bar{t}} - 1 - (\bar{h}_{\text{тро}} + \bar{h}_{\partial o})\bar{\vartheta}_{\bar{t}}\left|\bar{\vartheta}_{\bar{t}}\right|\right] \qquad (14)$$

The analysis shows that the dimensionless heads h_{min} and h_{max} are functions of the parameters σ, $\bar{h}_{\text{тро}}$, $\bar{h}_{\partial}$ and n, that is

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$$h_{\min} = F_1\left(\sigma, \bar{h}_{mp}, \bar{h}_{\partial 0}, n\right) \quad (15)$$

$$h_{\max} = F_2\left(\sigma, \bar{h}_{mp}, \bar{h}_{\partial 0}, n\right). \quad (16)$$

If we designate

$$\bar{Z}_{\min} = 1 - h_{\min}; \quad (17)$$

$$\bar{Z}_{\max} = h_{\max} - 1, \quad (18)$$

then you can write

$$\bar{z}_{\min} = \Phi_1\left(\sigma, \bar{h}_{mp}, \bar{h}_{\partial 0}, n\right) \quad (19)$$

$$\bar{z}_{\max} = \Phi_2\left(\sigma, \bar{h}_{mp}, \bar{h}_{\partial 0}, n\right) \quad (20)$$

The problem of determining $\bar{h}_{\min}$ and $\bar{h}_{\max}$ or $\bar{Z}_{\min}$ and $\bar{Z}_{\max}$ can be solved on a computer. To calculate $h_{\min}(\bar{Z}_{\min})$ and $h_{\max}(\bar{Z}_{\max})$ using dependencies (15) and (16), a program was compiled to solve this problem on a computer for the given values of σ, $\bar{h}_{mp0}$, n and $\bar{h}_{\partial 0}$. The calculations were performed for n=1.2. For n=1.2, the values of the parameters σ, $\bar{h}_{mp0}$ and $\bar{h}_{\partial 0}$ varied within the following limits:

$\sigma = 0{,}025 \ldots 1{,}0$ (in increments of $\Delta\sigma = 0{,}025$);

$\bar{h}_{mp0} = 0 \div 1{,}0$; (in increments of $\Delta\bar{h}_{mp0} = 0{,}1$);

$\bar{h}_{\partial 0} = 0 \div 1{,}0$ (in increments of $\Delta\bar{h}_{\partial 0} = 0{,}1$).

In all calculations, the time step $\Delta\bar{t}$ was taken to be the same and equal to $\Delta\bar{t}$ =0.01.

Based on the calculation results, tables of values were compiled

$$\bar{z}_{\min} = \Phi_1\left(\sigma, \bar{h}_{mp}, \bar{h}_{\partial 0}\right)$$

$$\bar{z}_{\max} = \Phi_2\left(\sigma, \bar{h}_{mp}, \bar{h}_{\partial 0}\right),$$

at n=1.20, according to which diagrams were constructed for calculating the AHC with a diaphragm during an instantaneous stop of the pumping unit. Due to the large volume of results obtained from computer calculations, and also taking into account our recommendations on the selection of the value of the polytropic coefficient, in this work, diagrams $\bar{Z}_{\min}$ and $\bar{Z}_{\max}$ were obtained only for n=1.20 [14].

The calculation of the dimensions of the AHC with a diaphragm using the obtained diagrams is performed in the following order. The following are calculated

$$H_{za} = H_z + 10;\ \bar{h}_{\text{тро}} = \frac{\bar{h}_{\text{тро}}}{H_{za}};\ \bar{Z}_{\max} = H_{a\max} - H_{za};\ \bar{Z}_{\max} = \frac{Z_{\max}}{H_{za}};\ \bar{h}_{\partial 0} = \frac{h_{\partial 0}}{H_{za}}.$$

Using the obtained diagrams with known $\bar{h}_{mp0}$, $\bar{Z}_{\max}$ and $h_{\partial o}$, the values of σ and $\bar{Z}_{\min}$ are determined, and then calculated

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$$W_o = \frac{\omega Z \vartheta_o^2}{2gH_{za}\sigma};\ Z_{\min} = Z_{\min} H_{za};\ H_{a\max} = H_{za} - Z_{\min};$$

$$W_{\max} = W_o \left(\frac{H_{za}}{H_{a\min}} \right)^{\frac{1}{1,2}};\ W_K = 1,3 W_{\max} \text{ и } h_K = \frac{4W_K}{\pi D_K^2},$$

Where W_K - volume of the AHC, and h_K -is its height.

For given σ, $\bar{h}_{mp0}$ and $\bar{h}_{\partial o}$, it is possible to calculate the hydraulic shock parameters $\bar{Z}_{\max}$, $\bar{Z}_{\min}$, $H_{a\max}$ and $H_{a\min}$ for a pressure system (Fig. 1).

To verify the reliability of the above numerical calculations of the AHC with a diaphragm, experimental studies were carried out [10,14]. The results of comparison of numerical experiments and experimental data on the study of a AHC with a diaphragm installed at the end of a pressure pipeline [10,14] are shown in Fig. 2.

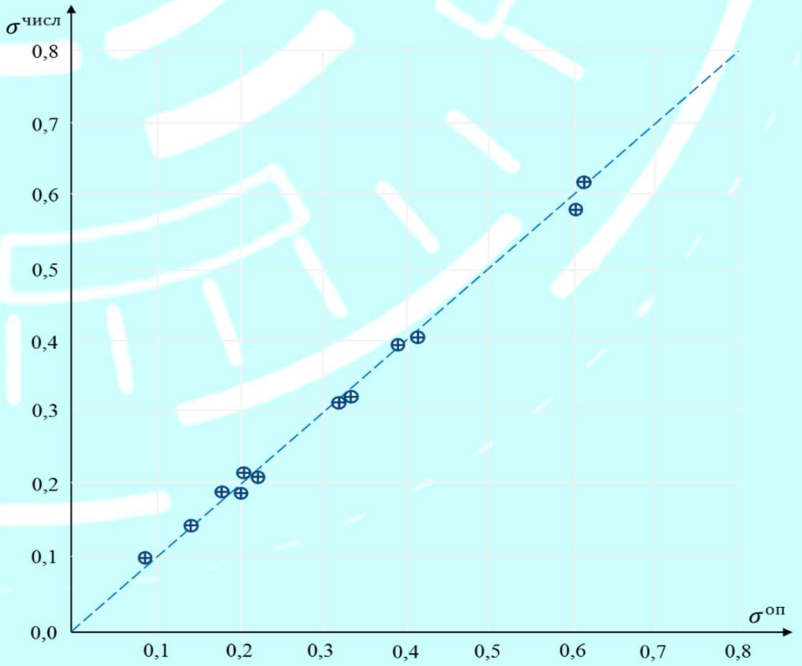


Fig. 2. Comparison of the results of numerical calculations of σ^{num} VGK with a diaphragm with experimental data of σ^{exp}.

4. CONCLUSION

1. An analysis of existing scientific works shows that a sudden power outage in the pressure systems of pumping stations causes a positive HSH, which negatively affects the normal operation of the pumping unit. To prevent this phenomenon, it is very important to develop a new method for calculating the optimal dimensions of a pressure regulator with a diaphragm located at the end of a pressure pipeline.

2. When optimally damping the maximum pressure HSH in the pressure pipelines of pumping stations, it is very important to take into account the changes in local resistance in the diaphragm of the connecting pipeline and the law of

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expansion and compression of air of the proposed design of the cap. These factors must be taken into account when integrating the wave equations of the HSH hyperbolic type using a numerical method - the finite difference method - to establish the optimal parameters of the proposed cap design.

3. As a result of the numerical solution of differential equations HSH, dependencies are proposed for calculating the economical dimensions of the proposed design of damper HSH, installed at the end of the pressure pipeline.

4. The reliability of the above numerical method for calculating the damper is proven by comparing the numerical values σ^{num} with the experimental values σ^{exp} [10].

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