Numerical substantiation of the parameters of the air-hydraulic hood by a diaphragm

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Abstract. The article is about calculating the main parameters of air-hydraulic hoods with a diaphragm to reduce the emergency consequences of a water hammer, possible in the pressure pipelines of an irrigation pumping station. Based on the results of numerical studies by the method of finite differences of the proposed hydraulic shock absorber, dependencies were obtained based on a certain air in the absorbers, the total capacity of the cylindrical cap was determined to determine the main dimensions of the absorbers. Based on the results of numerical studies by the method of finite differences of the proposed hydraulic shock absorber, dependencies were obtained based on a certain air in the absorbers, the total capacity of the cylindrical cap was determined to determine the main dimensions of the absorbers. To determine the economic dimensions of the proposed cap design, comparative calculations of numerical experiments with experimental data prove the reliability of the proposed dependencies using the finite difference method.

1 Introduction

In the event of a sudden power outage of pumping stations, hydraulic shocks occur in pressure water lines from a decrease in pressure.

To protect pressure pipelines of irrigation pumping stations from hydraulic shock, various types of air-hydraulic caps (AHC) are used [1-12].

AHC is a steel vessel with a cylindrical shape, installed on a pressure pipeline and filled in the upper part with air.

The advantages of AHC include simplicity of design, trouble-free operation, elimination of water discharge, and the absence of a possible rarefaction in the pressure pipeline. With correctly found geometric dimensions of the cap, a high degree of damping of the maximum heads during hydraulic shock (HS) is guaranteed [8-10].

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In works [13-24] various designs of AHC are described: single, double; with transition pipes; with input resistance; with cylindrical nozzles (connecting pipeline); directional action; with automatic air supply; horizontal, etc.

A.F. Mostovskiy [1] considers HS in horizontal pressure pipelines when installing AHC at the end of the pipeline in front of the valve. Based on the application of the equation of "living forces", the author obtains formulas for calculating the maximum pressure increase $\Delta P$ for a known volume of the bell. In this case, the author considers the elasticity of the pipeline walls and the compressibility of water and air.

L. Bergeron in [2] gives a graphical method for calculating pressure pipelines for hydraulic shock in the presence of an air-hydraulic cap. This calculation method is characterized with high accuracy.

N.E. Jukovskiy [3] proposed calculating the HS in the presence of a AHC installed on the pipeline. At the same time, the author proposes an approximate formula for determining the volume of air in the AHC and accepts the adiabatic law of compression and expansion of air in the AHC, since, according to the author, the process of HSh is fast [3].

I.A. Charny [4] uses linearized HSh equations to calculate AHC. In this case, the author adopts an isothermal law ($n = 1.0$) for the compression and expansion of air in the AHC.

In practice, the most widespread is the calculation method proposed by Evangelisti [5]. Evangelisti's method [5] is based on the use of special graphs compiled to approximate integration of the water hammer wave equations by 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 Evangelisti method is not applicable.

V.S. Dikarevsky in [6], trying to eliminate the drawback of the G. Evangelisti method, constructed diagrams $Z_{\text{max}} = f(\sigma, h_{m\sigma})$ and $Z_{\text{min}} = f(\sigma, \bar{h}_{m\sigma})$ for the isothermal law ($n = 1.0$) in a wide range of variation of the parameters $\sigma$ and $\bar{h}_{m\sigma}$. However, in this case, the author allows inaccuracies in solving the basic equations.

F.M. Darson and A.A. Kaliske [7] developed an analytical method for sizing a bell located at the end of a pressure line in front of a gate valve. In this case, the author accepts the isothermal law ($n = 1.0$), the change in the volume of gas in the AHC and does not consider the effect of pressure losses on friction in the pressure pipeline. This method of calculating the cap is also approximate.

B.F. Lyamaev in work [8], developed a method for calculating AHC on electronic computing machines (ECM). The proposed method is based on the joint solution of the equations of HS, continuity in the node connecting the cap to the pipeline and the state of the gas in the AHC. The calculation is performed by the author [8] by the iteration method.

D.A. Fox gives in [9] a numerical method for calculating AHC. The author applies the method of characteristics with a regular rectangular grid with constant steps $\Delta x$ and $\Delta t$. The author jointly solves the equations of continuity, the state of air (gas) and the equations of relations on the characteristics. The calculations are carried out on a computer ECM. The author [9] proposed to take the value of the polytropic coefficient equal to $n = 1.20$ in the calculations and take into account the pressure loss along the length according to the hypothesis of quasi-stationarity. To damp the intensity of water hammer in the pressure pipelines of irrigation pumping stations, an air-hydraulic cap with a diaphragm is used (Fig. 1); the dimensions of the cap are determined according to the conditions for starting and stopping the pumping unit [10]. In this work and Fig. 1, we use the notation that we described earlier in detail in [10].
2 Methods

The method for calculating the air-hydraulic hood with a diaphragm installed at the beginning of the pressure pipeline [10] (Fig. 1) is presented.

The proposed method assumes that the pump is turned off instantly, and the time for closing the check valve is zero [10].

To solve the problem of water hammer in the system air - hydraulic cap - pipeline - reservoir, the following wave equations of hyperbolic type are used [6, 8, 10]:

\[ h - 1 = \frac{1}{2\pi} \sqrt{2n\sigma} \frac{d\vartheta}{dt} + (\overline{h_{t_0}} + \overline{h_{d_0}}) \overline{\vartheta} | \overline{\vartheta} | ; \]  

\[ d\overline{W} = 2\pi \sqrt{\frac{2\sigma}{n}} \overline{\vartheta} ; \]  

\[ \overline{W} = \frac{1}{h^n} , \]  

Equations (1), (2) and (3) are solved under the following initial conditions [6,8,10]:

\[ \begin{cases} h_0 = 1 + \overline{h_{t_0}} \\ \overline{\vartheta}_0 = 1 \end{cases} \quad \text{at} \quad t = 0 . \]  

By analogy with Evangelisti, we will solve the system of equations (1) - (3) by the method of finite differences [10].
Following equation (3), we have

\[
\bar{W}_i = \frac{1}{h_i^n} \quad \text{and} \quad \bar{W}_{i+\Delta i} = \frac{1}{h_{i+\Delta i}^n},
\]

where \(\bar{W}_i\) and \(\bar{h}_i\) are values \(\bar{W}\) and \(h\) at the moment of time \(\tilde{t}\); \(\bar{W}_{i+\Delta i}\) and \(\bar{h}_{i+\Delta i}\) are values \(\bar{W}\) and \(h\) at time \(\tilde{t} + \Delta \tilde{t}\); \(\Delta \tilde{t}\) is estimated time interval (step).

Then we get

\[
\Delta \bar{W} = \bar{W}_{i+\Delta i} - \bar{W}_i = \frac{\frac{1}{h_i^n} - \frac{1}{h_{i+\Delta i}^n}}{\frac{1}{h_{i+\Delta i}^n} \cdot \frac{1}{h_i^n}}
\]

(5)

Following equation (2), we have

\[
\Delta \bar{W} = 2\pi \sqrt{\frac{2\sigma}{n}} \bar{g}_i \Delta \tilde{t},
\]

(6)

where \(\bar{g}_i\) is the value \(\bar{g}\) at time \(\tilde{t}\).

Since \(\Delta \bar{W}\) by (5) and \(\Delta \bar{W}\) by (6) are equal, we get

\[
\frac{\frac{1}{h_i^n} - \frac{1}{h_{i+\Delta i}^n}}{\frac{1}{h_{i+\Delta i}^n} \cdot \frac{1}{h_i^n}} = 2\pi \sqrt{\frac{2\sigma}{n}} \bar{g}_i \Delta \tilde{t},
\]

whence follows

\[
h_{i+\Delta i} = \frac{h_i}{\left(1 + 2\pi \ h_i^{1/n} \sqrt{2\sigma} \ \bar{g}_i \Delta \tilde{t}\right)^n},
\]

(7)

or for \(n = 1\) (isotherm)

\[
h_{i+\Delta i} = \frac{h_i}{1 + 2\pi \ h_i \sqrt{2\sigma} \ \bar{g}_i \Delta \tilde{t}}.
\]

(8)

From equation (1), we have
Following equation (3), we have
\[ n_t = \Delta t \]
and
\[ n_{tt} = \Delta t + \Delta \]
where \( t_W \) and \( h \) are values at the moment of time \( t \); \( t_{W+} \) and \( t_{h+} \) are values \( W \) and \( h \) at time \( t+ \); \( \Delta \) is estimated time interval (step). Then we get
\[ n_{tt} \cdot n_t = \Delta t \rightarrow \Delta t \]
Following equation (2), we have
\[ t_W = t_{W+} \]
where \( t \) is the value at time \( t \). Since \( W \) by (5) and \( W \) by (6) are equal, we get
\[ n_{tt} \cdot n_t = \Delta t \rightarrow \Delta t \]
whence follows
\[ \Delta \]
or for \( n = 1 \) (isotherm)
\[ \Delta \]
When deriving the calculated dependencies (7) and (10) by analogy with Evangelisti, the following assumptions were made: when determining \( \Delta W \) according to (5), it was accepted \( \Delta = \Delta \); when determining \( \Delta_{t+} \), it was accepted \( h = h_{t+} \) and \( \Delta = \Delta \).
The dimensionless head \( h' \) in the pipeline at the place where the cap is installed differs from the dimensionless head \( h \) in the cap by the amount of head loss in the "diaphragm", namely [10]
\[ h' = h - h_{\infty} \]
Using dependencies (7), (10) and (12), it is possible to calculate the process of pressure fluctuations in the bell with a diaphragm and the pipeline in time for given \( \sigma, \tilde{h}_{t_{\infty}}, n \) and initial conditions (4) and determine the minimum \( h_{\text{min}} \) and maximum \( h_{\text{max}} \) dimensionless heads in the bell in the first oscillation period.
AHC with a diaphragm is the most promising design, since here, during a transient oscillatory process in the AHC system - pressure pipeline-reservoir (see Fig. 1), independent regulation of the direction of fluid movement is achieved, that is, one of the main disadvantages of AHC of unilateral action is eliminated [5, 6,10].
The main idea in using AHC with a diaphragm is to maximize the use of the effective qualities of AHC both in the phase of decreasing pressure and in the phase of increasing pressure [10].
The problem is posed of determining the minimum absolute head \( H_{\text{min}} \) and the maximum absolute head \( H_{\text{max}} \) in the bell in the first oscillation period.

3 Results and Discussion
When solving the problem, the following assumptions were made: the pump unit turns off instantly; the closing time of the check valve is zero; the problem is solved based on the so-called "rigid" model of unsteady pressure fluid movement, which does not consider the elastic properties of the fluid and the walls of the pipeline [5,10].
Let's write down the main calculated dependences of the AHC with a diaphragm
\[ h_{t+\Delta t} = \left( \frac{h_{i}}{1 + 2\pi \sqrt{\frac{2\sigma \cdot h_{i}^{n}}{n}} \cdot \mathcal{G}_{i} \cdot \Delta t} \right)^{n} \]  \quad (13)

\[ \mathcal{G}_{i+\Delta t} = \mathcal{G}_{i} + \frac{2\pi \Delta t}{\sqrt{2n\sigma}} \left[ h_{i+\Delta t} - 1 - (h_{\text{mp}} + h_{\text{do}}) \mathcal{G}_{i} \right] \]  \quad (14)

Analysis shows that dimensionless heads \( h_{\text{min}} \) and \( h_{\text{max}} \) are functions of the parameters \( \sigma, c, \ h_{\text{do}} \) and \( n \), that is,

\[ h_{\text{min}} = F_{1}(\sigma, h_{\text{mp}}, h_{\text{do}}, n) \]  \quad (15)

\[ h_{\text{max}} = F_{2}(\sigma, h_{\text{mp}}, h_{\text{do}}, n). \]  \quad (16)

If we denote

\[ \overline{Z}_{\text{min}} = 1 - h_{\text{min}} \]  \quad (17)

\[ \overline{Z}_{\text{max}} = h_{\text{max}} - 1 \]  \quad (18)

then we can write

\[ \overline{z}_{\text{min}} = \Phi_{1}(\sigma, h_{\text{mp}}, h_{\text{do}}, n) \]  \quad (19)

\[ \overline{z}_{\text{max}} = \Phi_{2}(\sigma, h_{\text{mp}}, h_{\text{do}}, n) \]  \quad (20)

The problem by definition \( \overline{h}_{\text{min}} \) and \( \overline{h}_{\text{max}} \) or \( \overline{Z}_{\text{min}} \) and \( \overline{Z}_{\text{max}} \) can be solved on a computer. To calculate \( h_{\text{min}}(\overline{Z}_{\text{min}}) \) and \( h_{\text{max}}(\overline{Z}_{\text{max}}) \) using dependencies (13) and (14), a program for solving this problem on ECM was compiled for the given values of \( \sigma, \overline{h}_{\text{mp}}, \overline{h}_{\text{do}} \) and \( n \). The calculations were performed at \( n = 1.0 \) (isotherm), \( n = 1.2 \) (polytropic), and \( n = 1.41 \) (adiabat). For each \( n \), the values of the parameters \( \sigma, \overline{h}_{\text{mp}}, \overline{h}_{\text{do}} \) varied within the following limits:

\[ \sigma = 0.025 \ldots 1.0 \]  \quad (with a step \( \Delta \sigma = 0.025 \));

\[ \overline{h}_{\text{mp}} = 0 \div 1.0; \]  \quad (with a step \( \Delta \overline{h}_{\text{mp}} = 0.1 \));

\[ \overline{h}_{\text{do}} = 0 \div 1.0 \]  \quad (with a step \( \Delta \overline{h}_{\text{do}} = 0.1 \)).

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

Based on the calculation results, tables of values were compiled

\[ \overline{z}_{\text{min}} = \Phi_{1}(\sigma, h_{\text{mp}}, h_{\text{do}}) \]

\[ \overline{z}_{\text{max}} = \Phi_{2}(\sigma, h_{\text{mp}}, h_{\text{do}}). \]
at \( n = 1.0, n = 1.20 \) and \( n = 1.41 \), according to which diagrams were constructed for calculating the AHC with a diaphragm at an instantaneous stop of the pumping unit. Given the large volume of the obtained results of calculations on ECM, as well as taking into account our recommendations on the choice of the value of the polytrope coefficient in this work, the diagrams \( \overline{Z}_{\text{min}} \) and \( \overline{Z}_{\text{max}} \) are given only for \( n = 1.20 \).

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

Calculated

\[
H_{\text{ca}} = H_{c} + 10; \quad \overline{h}_{\text{TPO}} = \frac{h_{\text{TPO}}}{H_{\text{ca}}}; \quad \overline{Z}_{\text{max}} = H_{a_{\text{max}}} - H_{\text{ca}}; \quad \overline{Z}_{\text{max}} = \frac{Z_{\text{max}}}{H_{\text{ca}}}; \\
\overline{h}_{\text{do}} = \frac{h_{\text{do}}}{H_{\text{ca}}}.
\]

Using the diagrams with known \( \overline{h}_{\text{TPO}}, \overline{Z}_{\text{max}} \) and \( h_{\text{do}} \) the values of \( \sigma \) and \( Z_{\text{min}} \), are determined and then

\[
W_{o} = \frac{\omega Z g^{2}}{2g H_{\text{ca}} \sigma}; \quad Z_{\text{min}} = Z_{\text{min}} H_{\text{ca}}; \quad H_{a_{\text{max}}} = H_{\text{ca}} - Z_{\text{min}};
\]

\[
W_{\text{max}} = W_{o} \left( \frac{H_{\text{ca}}}{H_{a_{\text{min}}}} \right)^{1.2}; \quad W_{K} = 1.3 W_{\text{max}} \quad \text{and} \quad h_{K} = \frac{4W_{K}}{\pi D_{K}^{2}},
\]

where \( W_{K} \) is the volume of the AHC, and \( h_{K} \) is its height.

For given \( \sigma, \overline{h}_{\text{TPO}} \) and \( \overline{h}_{\text{do}} \) it is possible to calculate the parameters of the water hammer \( \overline{Z}_{\text{max}}, \overline{Z}_{\text{min}}, H_{a_{\text{max}}} \) and \( H_{a_{\text{min}}} \) for the pressure head system of the AHC - the pressure pipeline-reservoir.

To check the reliability of the above numerical calculations of the AHC with a diaphragm, experimental studies were carried out [10]. A comparison of numerical experiments and experimental data on the study of AHC with a diaphragm is shown in Fig. 2.
4 Conclusions

1. Analysis of existing scientific works shows that in the event of a sudden power failure in the pressure systems of pumping stations, a HSh appears with a discontinuity of the flow, 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 the AHC with a diaphragm.

2. With optimal damping of the maximum pressure of the main unit in the pressure pipelines of pumping stations, it is very important to take into account the changes in the local resistance in the diaphragm of the connecting pipeline and the law of expansion and contraction of the air of the proposed bell design. These factors must be considered when integrating the wave equations of hyperbolic type HSh by the numerical method - the method of finite differences to establish the optimal parameters of the proposed cap design.

3. As a result of the numerical solution of the differential equations of the HSh, dependencies are proposed for calculating the economic dimensions of the proposed design of the HSh damper.

The reliability of the above numerical method is proved by comparing the values of \( \sigma_{\text{number}} \) and with the experimental values of \( \sigma_{\text{op}} \) [10].
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