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IJIEMR Transactions, online available on 24nd Nov 2020. Link :http://www.ijiemr.org/downloads.php?vol=Volume-09&issue=ISSUE-11

**DOI: 10.48047/IJIEMR/V09/I11/19**

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Volume 09, Issue 11, Pages: 94-100

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# THE HYDRAULIC IMPACT WAVE PROPAGATION SPEED STUDY IN A TWO-PHASE FLOW

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**Abstract.** The article is devoted to a shock wave propagation velocity study taking into account the two-phase flow in long pressure pumping stations pipelines. The shock wave velocity is the main water hammer parameter.

Water hammer poses a danger to main stations equipment' normal operation, control and measuring equipment, control devices and pressure pipelines.

When establishing the strength of pressure pipelines indicators, it is necessary to make an accurate shock wave speed calculation, taking into account the undissolved air present in the water.

The classical theory of water hammer is based on a homogeneous model and does not take air into the liquid. This circumstance reduces the calculating of shock wave velocity accuracy.

The article presents the shock wave velocity calculating results by the finite difference method, taking into account the two-phase nature of the pressure flow. The proposed technique results are in good agreement with the experimental data.

**Keyword:** shock wave propagation velocity, water hammer, two-phase flow, real fluid, finite difference method, pressure loss, polytropic exponent, Poisson's ratio.

## INTRODUCTION

The water hammer theory for an ideal fluid in pressure pipelines was first developed by N.E. Djukovsky [1]. In this theory, it is assumed that the fluid moving in the pipeline is a continuous homogeneous (single-phase) fluid. Obviously, real liquids operating in irrigation, drainage, water supply systems, etc., differ to one degree or another from a "pure"' liquid, since they always contain a certain gaseous and solid impurities amount. The impurities presence significantly affects the water hammer nature in pressure pipelines. Therefore, the water hammer calculations of a real fluid based on a homogeneous model do not have

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sufficient accuracy in many cases. To improve the calculations accuracy, it becomes necessary to take into account the real liquids complex structure phase, i.e., to construct calculated dependences based on multiphase media models. Of particular interest is the two-phase (water + air) flow study, since, firstly, liquids in irrigation networks almost always contain undissolved gases. Secondly, it is the gas inclusions presence that has the strongest effect on the shock wave propagation speed in the medium - one of the most important factors determining the entire course of the water hammer process.

Natural and laboratory studies show that water almost always has an insignificant undissolved air amount, which, however, significantly reduces the water hammer $C$ wave propagation speed [2,3].

The shock wave propagation speed in an unlimited gas-liquid flow is determined by the relationship [4,5,6]

$$c=\sqrt{\frac{p}{(1-\varepsilon)\varepsilon\rho_{ж}}}, \quad (1)$$

where $\rho_{ж}$ - fluid density; $\varepsilon$ - volumetric content of undissolved gases in the mixture. Dependence (1), called the low-frequency shock wave velocity approximation [4,5,6], is derived under the incompressibility assumptions of the liquid and the compression isothermal law-the gas expansion. Introducing into consideration the shock wave velocity in an unlimited $c_{ж}=\sqrt{\frac{E_{ж}}{\rho_{ж}}}$ volume "pure" liquid XXX, where $E_{ж}$ is the bulk modulus of liquid elasticity, and generalizing (1) to the gas polytropic behavior case in bubbles, from (1) for ε<<1 we have

$$c=\frac{\sqrt{\frac{E_{ж}}{\rho_{ж}}}}{\sqrt{\varepsilon\frac{E_{ж}}{n\cdot p}}}=\frac{c_{ж}}{\sqrt{\varepsilon\frac{E_{ж}}{n\cdot p}}}, \quad (2)$$

where $n$ - polytropic exponent.

The formulas disadvantage (1), (2) is that they do not take into account the elasticity effect of the liquid and the pipeline walls on the sound speed magnitude and, moreover, become meaningless at zero gas content.

The formula for calculating the sound speed in a two-phase flow taking into account the liquid phase compressibility is given in D.N. Popova work [5]

$$c=\sqrt{\frac{E_{ж}}{\rho(1-\varepsilon)\left(1+\varepsilon\frac{E_{ж}}{n\cdot p}\right)}}. \quad (3)$$

Dependences for determining the shock wave velocity in a gas-liquid flow moving in an elastic pipeline are given in N.A. Kartvelishvili [8], G.I. Melkonyan [9], D.A. Fox [10] and many others works [11,12,13,14,15,16,17]. All these relations have a similar structure, since they are derived under the same assumptions.

The research purpose is, using the numerical method - the finite difference method, to determine the shock wave velocity value in a two-phase flow and to establish the proposed method reliability by comparing the calculated water hammer values wave velocity with the experimental values.

**CALCULATION METHOD**

The propagation speed of a water hammer $C$ wave is the most important parameter when calculating a water hammer. In this work, the propagation water hammer wave speed was determined by the formula [2]:

$$C = \frac{\sqrt{\frac{E_{ж}}{\rho}}}{\sqrt{1+\frac{ДE_{ж}}{eE_T}\left(1-\mu^2\right)+\varepsilon\frac{E_{ж}}{\Delta p}A}},$$

(1)

where $E_{ж}$ and ρ are bulk modulus and density of the fluid, respectively;

D, e, $E_T$ - diameter, wall thickness and bulk modulus of the pipeline wall material, respectively;

μ - Poisson's ratio;

ε - volumetric gas content at pressure before impact $p_0$;

Δp - pressure rise during water hammer,

$$A = \left[1-\left(\frac{p_0}{p_0+\Delta p}\right)^{1/x}\right],$$

(2)

where $x$ is adiabatic degree exponent.

When calculating $C$ in two-phase flows, pressure losses along the length are usually not taken into account, taking the pressure value before $p_0$ impact equal to the pressure at the impact source. In reality, the pressure, and along with $C$ speed, will vary along the length depending on the pressure loss and the geodetic the pipeline axis marks. Taking into account that the pressure changes continuously along the length, the averaged the wave impact velocity propagation in the $Z$ length section is determined by the dependence:

$$C_Z = \frac{Z}{\int_{x=0}^{x=z}\frac{dx}{C}},$$

(3)

where $C$ is velocity in the section spaced from the impact source at a distance $x$.

In this case, applying the finite difference method [2], we obtain:

$$C_Z = \frac{Z}{\sum_{n=1}^{n=k}\frac{l_n}{C_n}} = \frac{K}{\sum_1^k\frac{1}{C_n}},$$

(4)

where $l_n$ is the length of an elementary section where $C_n$ changes insignificantly, $l_n=x_n-x_{n-1}$;

K is sites number.

The velocity $C_n$ is determined by the pressure $p_{оп}$ in section $\frac{x_n+x_{n-1}}{2}$ or $H_{ср.п}$ pressure. (Fig.1).

The $C_z$ values comparison, calculated taking into account the head loss with the experimental $C_{оп}$ values, shows that most of the calculated $C_z$ values exceed the experimental ones (Fig. 2).This is due to the fact that the calculation did not take into account the change in the elasticity of the system (water-air mixture - pipeline). When the shock wave propagates, each section, due to the difference in elasticity (pressure), will create an elementary reflection wave, which will entail a change in the shock pressure, and, accordingly, the $C$ speed. To determine C taking into account the change in pressure along the length and variable elasticity, the method of characteristics is applied [2].

Let us write the system of equations for determining $C$ on the n+1$^{th}$ section (Fig. 1):

$$H_n - H_{n-1} = \frac{C_n}{g}\left(\vartheta_n - \vartheta_{n-1}\right),$$

(5)

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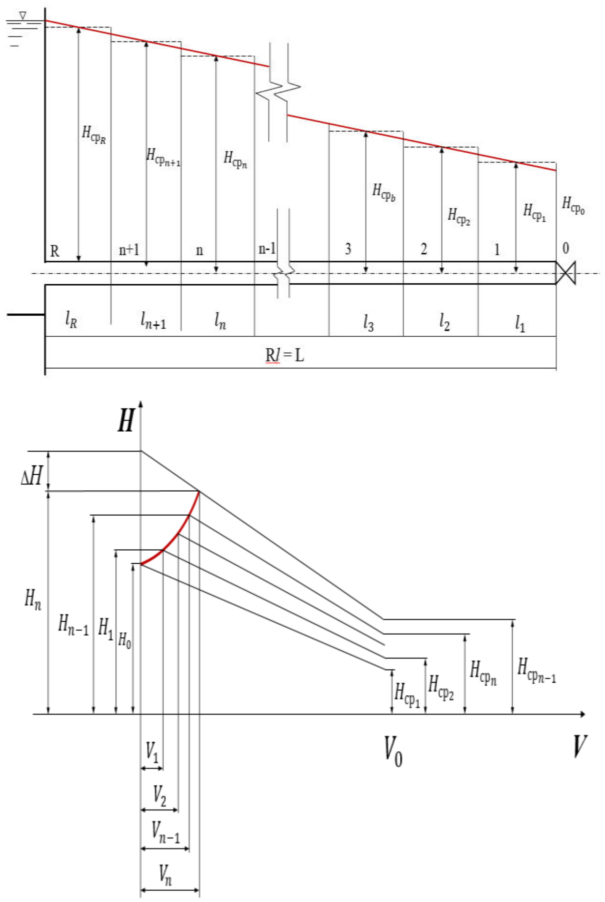

**Fig.1. Calculation scheme for determining *C* taking into account the changing pressure along the length and variable elasticity**

$$H_n - H_{cp_{n+1}} = \frac{C_{n+1}}{g}(\vartheta_0 - \vartheta_n), \qquad (6)$$

$$C_{n+1} = \frac{\sqrt{\dfrac{E_{ж}}{\rho}}}{\sqrt{1 + \dfrac{ДE_{ж}}{eE_T}(1-\mu^2) + \varepsilon\dfrac{E_{ж}}{(H_n - H_{cp_{n+1}})}\left[1 - \dfrac{H_{cp_{n+1}}}{H_n}\right]^{1/x}}}, \qquad (7)$$

where $H_n$ - the shock pressure magnitude on the (n+1) site;

$\vartheta_0$ - steady flow rate.

The unknown quantities in the system are $H_n$, $\vartheta_n$, $C_{n+1}$, the remaining quantities are determined when calculating *C* in the previous sections. The propagation velocity impact wave along the entire length is determined by the formula (4).

## STUDIES AND DISCUSSION RESULTS

The pressures obtained by solving equations (5) - (7) will be less than the pressures found without taking reflection into account by the value ΔH (see Figure 1). Therefore, the speed $C_z$, calculated from these dependencies, will be less than the speed obtained only taking into account the head losses. In this case, the calculated $C_z$ values are closer to the experimental data (see Figure 2.). According to the described method, several experiments series were processed on a computer (120 total experiments with gas content reduced to atmospheric φ=0,5÷3,0% by volume). Figure 2 shows two experiments series, the calculations results using data at φ = 1,0 % and φ=1,5%.

In water hammer studies, it is assumed that water hammer propagation speed wave is equal to the sound speed, and the wave profile does not change in length and time.

This solution accurately describes the propagation case of weak acoustic waves due to the fact that the change in density and pressure in the liquid is small.

However, with a hydraulic shock with a sufficiently large value of excess pressure $p/p_0$ and a significant change in density, the nature of the motion becomes much more complicated (this is especially manifested in a two-phase mixture). A finite perturbation propagates at a speed *U*±*C* depending on the propagation direction. Since *U and C* are density functions ($U = \int \frac{C}{\rho} dp$ is the material drift rate that appears when a disturbance occurs $C = \sqrt{\frac{dp}{d\rho}}$),

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then in the general plane wave case with an arbitrary amplitude there is no definite constant "wave velocity" $U \pm C$.

The shock wave for all normal liquids has a concavity directed to the abscissa axis. As a result, $\frac{dp}{d\rho}$ and $C = \sqrt{\frac{dp}{d\rho}}$ increase with increasing compression, the speed $U$ also increases with ρ.

Due to this, at subsequent moments in time, the high wave pressures region, since it causes a higher ρ, will approach the low pressures region. This effect increases with increasing pressure difference.

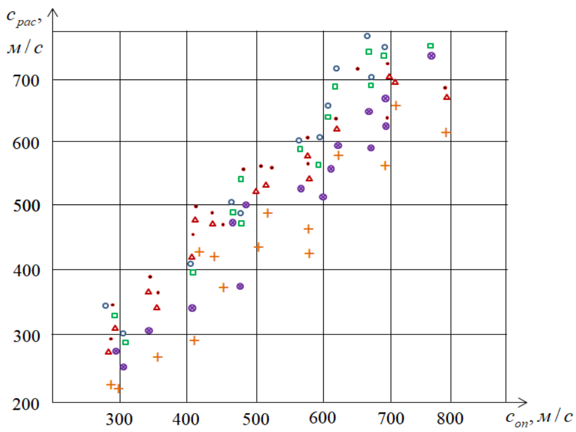



**Fig. 2. Calculation results comparison:**

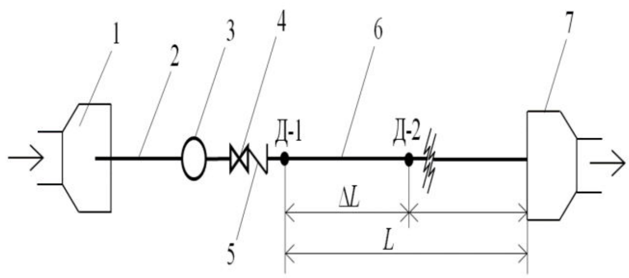
**⊗, + - C speed calculated from the pressure at the valve, respectively φ = 1,0 % and φ = 1,5 %;**

**○, ● - C speed, calculated taking into account the head loss, respectively at φ = 1,0 % and φ = 1,5 %;**

**□, △ - C speed, calculated taking into account the pressure and stiffness loss, respectively at φ = 1,0 % and φ = 1,5 %.**

The end result of such wave profile points movement at different speeds will be the very steep front formation. The wave profile can bend so much that the ρ(*x*) curve turns out to be ambiguous, that is, three different ρ values will correspond to a certain *x* value., Of course, physically such a phenomenon is impossible. Therefore, in ambiguity places, discontinuities will appear, while ρ everywhere, except for the discontinuity points, will be unique, that is, a shock wave will appear in the liquid [2, 18, 19]. On the other hand, when the rarefaction wave propagates, the shock wave formation is not observed, since the compression points of the wave profile will move forward, and the rarefaction points will lag behind, that is, the wave will expand during propagation.

a

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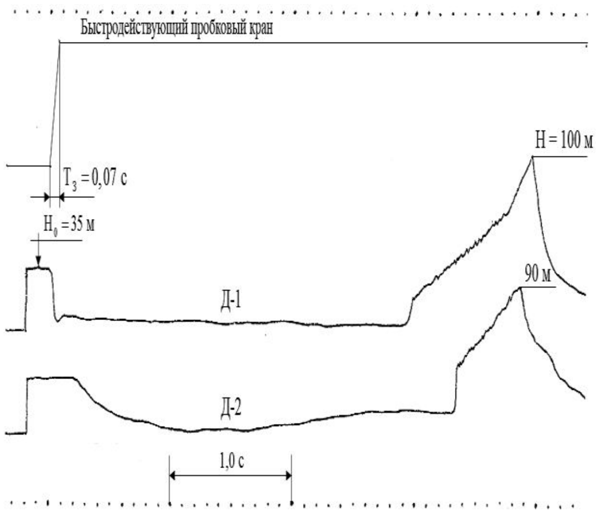


**Fig. 3. Diagrams of the experimental setup (a) and water hammer oscillograms in a two-phase flow (b):**

***a*** **- experimental setup [2]: 1-water source; 2-suction pipeline; 3-pump; 4-valve; 5-check valve; 6-pressure head pipeline; 7-head pool.**

**б - water hammer oscillograms, starting with a decrease in pressure at φ=1,0%, $p_0$ = 350,0 kPa, $\vartheta_0$ = 1,36 m/s [2].**

It should be noted that a steep wave formation front will lead to a sharp pressure gradient in two adjacent wave layers. In this case, the liquid energy when passing through the fracture surface will increase, that is, a fracture surface presence will lead to a significant increase in energy dissipation. As an example, Fig. 3 (a, b) shows two oscillograms schemes obtained by us in the experimental water hammer study in a two-phase flow [2]. Two lines on the oscillograms correspond to the pressure records at two points (pressure sensors $D_1$, $D_2$) along the pipeline length (see Figure 3 c). The obtained oscillograms analysis confirms the conclusion about shock waves occurrence in the pressure pipeline in the case of a water hammer in a two-phase flow [2, 20].

## CONCLUSIONS

1. When a homogeneous liquid moves, there is always a small amount of undissolved air in the pressure pipes. Based on this, any liquid in nature (for example, water) must be considered as a two-phase flow. These factors must be taken into account when calculating pressure pipelines for water hammer with two-phase flow. The main parameter of water hammer is the propagation speed of the shock wave.

2. As the application result of the finite difference method, dependence is proposed for calculating the shock wave velocity in a two-phase flow.

3. The proposed dependence reliability is proved by comparing the calculated values of the shock wave velocity with the experimental values.

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