FIGHTING WATER HAMMER IN THE PRESSURIZED ADDUCTION WORKS OF HYDROTECHNICAL SYSTEMS

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Abstract

This paper presents an experimentally proven mathematical model of determining theoretically the functional characteristics of an overpressure safety valve of open type, with a spring. These were implemented in a computer program that simulates the water hammer in a gravitational adduction, to quantitatively determine the suppressing effect of the valve. For the qualitative and/or quantitative effect of the water hammer, the elasticity of the fluid and of the pipe wall must be taken into consideration. Although the duration of the phenomena, $T_{LB} = t_f - t_0$, is usually relatively small, the study of the water hammer is of paramount importance since, in the absence of constructive solutions and/or adequate usage measures, dangerous overpressures and/or under-pressures may occur, leading to the loss of resistance and/or stability of the hydraulic system with serious economic and safety consequences. The goal of this study is to determine the sections and the moments in which dangerous pressures occur, as well as to find technical solutions to fight water hammers. As far as the values of the parameters are concerned (that is the pressures) and their time variation, respectively the manifestation of the water hammer phenomena, these are specific to each concrete hydraulic plant and, in fact, *we cannot make significant general assessments*. Some apparently insignificant particularities of the general design may be the cause of serious distinctions in the manifestation of the water hammer phenomena. Analytical formulae, graphic-analytical methods and numerical methods can be used to determine the dangerous pressure values.

Keywords: water hammer, safety valve, mathematical modeling, numerical simulation, overpressure suppression.

The "water hammer (hydraulic shock)" phenomenon in pressurized hydraulic systems (particularly a unifilar pipe) consists in a nonpermanent (transitory), quickly variable movement taking the shape of flow and pressure waves that travel with a speed called celerity which is a lot higher than that of water in permanent regime (celerity is limited by the speed of sound in water) (Bartha I., Javgureanu, V., Marcoie N., 2004); in this way, during the manifestation of this phenomena, both hydrodynamic parameters that are considered to be important for the motion, the piezometric charge H and the flow rate Q are dependent on the spatial coordinate x as well as on the temporal one t.

Water hammer is generated by the sudden change of one or both hydrodynamic parameters in any of the adduction sections, a change that may be accidental or controlled – by using a device generically called "control device". The most severe scenarios of occurrence and manifestation of water hammer are: accidental interruption of electric power supply (power outage/failure) - in the case of pumping adduction works, and the sudden closing of a valve downstream – in the case of gravitational adduction works. In these cases the pressure variations have relatively large amplitude that can be several times bigger than the pressure in the permanent regime of design/usage. Thus, depending on the longitudinal profile of the pipeline, in certain moments, in some sections there may be either overpressures or under-pressures that may be dangerous for the resistance and/or the stability of the adduction work.

Consequently, although the duration of the phenomenon, $T_{LB} = t_f - t_0$, is usually relatively small, the study of water hammer is of paramount importance since, the negative effects of water hammer may trigger serious economic and safety consequences.

When the occurrence of these dangerous pressures cannot be totally eliminated only through non-structural exploitation measures, the adduction work must be equipped with adequate safety devices that must limit the overpressures and/or under-pressures to values below the resistance

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capacity of the pipe. The investment and the maintenance costs of the safety devices for water hammer can sometimes be pretty high, even prohibitive, for this reason, the construction-dimensional type of safety device must be established through specialized determinations, sometimes even using computer simulations.

For the qualitative and/or quantitative effect of the water hammer, the elasticity of the fluid and of the pipe wall must be taken into consideration.

This paper presents an experimentally proven mathematical model of determining theoretically the functional characteristics of an overpressure safety valve of open type, with a spring. These functional characteristics were implemented in a computer program that simulates, in various scenarios, water hammer in a gravitational adduction, to quantitatively determine the suppressing effect of the valve.

MATERIAL AND METHOD

From the numerous ways of limiting the overpressures, we selected the method of evacuation of a certain amount of water into the atmosphere (without the possibility of recovery) through anti-shock devices like safety valves with spring (*figure 1*) that open when reaching a certain pressure value.

These devices will be placed in certain (so called “deep”) points of the longitudinal profile of the adduction work, in which the pressure in the pipe axis – both during permanent regimes and during the water hammer – is the highest.

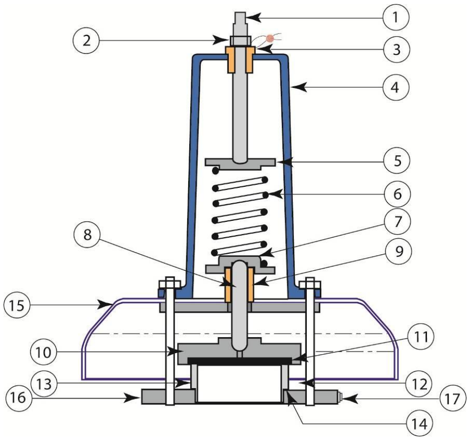
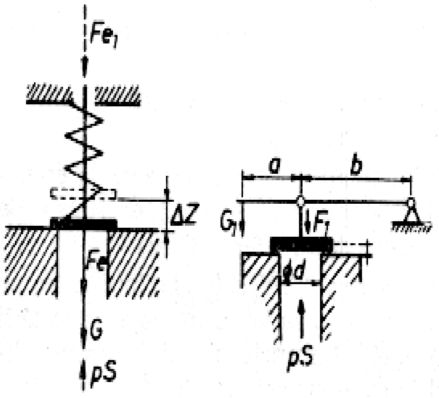


Figure 1 **Safety valves of the open type with spring; 1-Adjusting screw, 2,3-Nut, 4 - Cap, 5- Spring holder, 6- Spring, 7- Spring holder,8- Pin,9- Bearing,10 - Clapper ,11- Clapper gasket, 12- Upper stem, 13- Seat, 14- O’ring, 15- Skirt,16- Flange, 17- Pressure ¼’gas**

The anti-shock devices in are always placed in concrete chambers, while the one of the NEYRPIK type can be placed directly in the atmosphere.

The operating principle design of the safety valves with spring and counter-weight is shown in (*figure 2)* (Alexandrescu Ovidiu, 2002). The valve of the diameter *d* has the surface of the area *S*; a hydrostatic force $F_h=p.S$,oriented upwards, caused by the hydrostatic pressure p, acts on the valve, together with the proper gravity of the valve *G* and the elastic force F_e of the pre-compressed spring (*figure 2a*) or the gravity force F_1 (*figure 2b*), all oriented downwards.



a. **b.**

Figure 2 **The operating principle design of safety valves: (a) with spring; (b) with counter-weight.**

Depending on the ratio of these forces, the valve has one of the following positions:

Closed valve for:

$$p\cdot S\le F_e(0)+G \text{ sau } p\cdot S\le F_1(0)+G \qquad (1)$$

open valve, at the height Δz

$$(p+\Delta p)\cdot S\ge F_e(\Delta z)+G \text{ sau } (p+\Delta p)\cdot S\ge F_1(\Delta z)+G \qquad (2)$$

whereΔp > 0– is the pressure increase comparing to the pressure in the initial permanent regime.

In the case of the valve with spring, the dependency of the elastic force of the opening Δ*z* is given by the expression (Popescu Şt., 1999):

$$F_e(\Delta z)=F_e(0)+k\cdot\Delta z \text{, for } 0\le\Delta z\le(\Delta z)_{\max}, \qquad (3)$$

where *k* – the elastic constant of the spring; $(\Delta z)_{\max}$- maximum opening of the valve, set due to constructive-functional reasons. $F_e(0)$= the pre-compression force of the spring, adjusted in relation to the sealing pressure p_e, which has to be set at a higher or at least equal value to the maximum pressure in permanent (stationary) regimes, $p_{s\,max}$:

$$F_e(0)=p_e\cdot S-G, \text{ for } p_e\ge p_{s\max} \qquad (4)$$

We wish to calculate the equation of the functional characteristic of the valve which expresses analytically the relation between the evacuated flow *Q* and the piezometric charge *H* from the section where the valve is; to this end, the following expressions must also be considered:

-The pressure $p+\Delta p$ in relation to the charge H:

$$p+\Delta p=\rho\cdot g\cdot H \qquad (5)$$

- The velocity equation c for the vent:

$$c=\varphi_v\cdot\sqrt{2\cdot g\cdot H} \qquad (6)$$

where φ_v is the velocity coefficient of the vent.

Through the lateral side of the cylinder of diameter d, height Δz and area $\pi\cdot d\cdot\Delta z$, the flow rateis evacuatedwith the velocity c (*eq. 5*):

$$Q=\varphi_c\cdot\pi\cdot d\cdot\Delta z\cdot c \qquad (7)$$

where φ_c is the contraction coefficient.

From the system of (*eq. 1*)÷(*eq. 5*) we got:

- the opening Δz of the valve, corresponding to the piezometric charge H, $H\geq H_e$ is:

$$\Delta z=0\text{, for } H\leq H_e \qquad (8)$$

$$\Delta z=\frac{\pi}{4}\cdot\frac{\rho\cdot g}{k}\cdot d^2\cdot\left(H-H_e\right)\text{,for } H_e<H<H_{sat} \qquad (9)$$

$$\Delta z=\left(\Delta z\right)_{\max}\text{, for } H\geq H_{sat} \qquad (10)$$

where:

$H_e=p_e/\left(g\cdot\rho\right)$ is the sealing charge;

H_{sat} = the saturation charge (the minimum value for which the opening of the valve is $\left(\Delta z\right)_{\max}$),.

The equation of the functional characteristic of the valve are:

$$Q=0\text{, for } H\leq H_e \qquad (11)$$

$$Q=\frac{\sqrt{2}}{4}\cdot\pi^2\cdot\sqrt{g^3}\cdot d^3\cdot\rho\cdot\frac{\mu_v}{k}\cdot\left(H-H_e\right)\cdot\sqrt{H}\text{, for } H_e<H<H_{sat} \qquad (12)$$

$$Q=\pi\cdot\sqrt{2\cdot g}\cdot\varphi_v\cdot\varphi_c\cdot d\cdot\left(\Delta z\right)_{\max}\cdot\sqrt{H}\text{, for } H\geq H_{sat} \qquad (13)$$

Considering the actual numerical values for the general constants g and π, the material constant ρ and the velocity φ_v and contraction φ_c coefficients, g = 9.80655 m/s^2, π = 3.1416, ρ= 999.4 kg/m^3 and φ_v =0.97, φ_c=0.607,

The expressions (10)÷(13) are written in this way:

$$\Delta z=\begin{cases}0,\ \text{for } H\leq H_e\\ 7697.4\cdot\dfrac{d^2}{k}\cdot\left(H-H_e\right),\ \text{for } H_e<H<H_{sat}\\ \left(\Delta z\right)_{\max},\ \text{for } H\geq H_{sat}\end{cases} \qquad (14)$$

$$Q_{\sup}=\begin{cases}0,\ \text{for } H\leq H_e\\ 63056\cdot\dfrac{d^3}{\text{k}}\cdot\left(H-H_e\right)\cdot\sqrt{H},\text{for } H_e<H<H_{sat}\\ 8.1919\cdot d\cdot\left(\Delta z\right)_{\max}\cdot\sqrt{H},\ \text{for } H\geq H_{sat}\end{cases} \qquad (15)$$

where $k=7697.4\cdot d^2\cdot\left(H_{sat}-H_e\right)/\left(\Delta z\right)_{\max}$

Introducing the expression of the constant k in the above equations, we got: (*eq. 16*), and (*eq. 17*).

$$\Delta z=\begin{cases}0,\ \text{for } H\leq H_e\\ \left(\Delta z\right)_{\max}\cdot\dfrac{H-H_e}{H_{sat}-H_e},\ \text{for } H_e<H<H_{sat}\\ \left(\Delta z\right)_{\max},\ \text{for } H\geq H_{sat}\end{cases} \qquad (16)$$

$$Q_{\sup}=\begin{cases}0,\ \text{for } H\leq H_e\\ 8.1919\cdot d\cdot\left(\Delta z\right)_{\max}\cdot\dfrac{H-H_e}{H_{sat}-H_e}\cdot\sqrt{H},\ \text{for } H_e<H<H_{sat}\\ 8.1919\cdot d\cdot\left(\Delta z\right)_{\max}\cdot\sqrt{H},\ \text{for } H\geq H_{sat}\end{cases} \qquad (17)$$

RESULTS AND DISCUSSION

For a valve with the constructive parameters d=100 mm and $\left(\Delta z\right)_{\max}$=40 mm, tuned for H_e=140 m.c.a. and H_{sat}=150 m.c.a. (k=19244 N/m), the functional features – of control (*eq.16*) and flow (*eq. 17*) – display the following particularized shapes:

$$\Delta z=\begin{cases}0,\ \text{for } H\leq 140\\ 0.0040\cdot\left(H-140\right),\ \text{for } 140<H<150\\ 0.040,\ \text{for } H\geq 150\end{cases} \qquad (18)$$

$$Q=\begin{cases}0,\ \text{for } H\leq 140\\ 0.0033\cdot\left(H-140\right)\cdot\sqrt{H},\ \text{for } 140<H<150\\ 0.0328\cdot\sqrt{H},\ \text{for } H\geq 150\end{cases} \qquad (19)$$

and are a depicted in (*fig. 3)* and (*fig. 4*).

The control and flow characteristics of the overpressure safety valve of open type, with a spring, were implemented in a computer program that simulates, in various scenarios, water hammer in a gravitational adduction.

In the considered study case for a gravitational adduction with the diameter Dn=400 mm, the length *L*=14 Km, geodetic altitude difference ΔZ=97 m, for the flow *Q* = 0.200 c.m./s, water hammer was generated by closing the downstream valve of a gravitational adduction in Tm= 10'.

Water hammer was simulated in two scenarios: 1°- without the overpressure valve and 2° - with the overpressure valve *d*=100 mm.

In the first scenario the overpressure was $p_{\max}^{\max} = 162.82$ m (*fig. 3*).

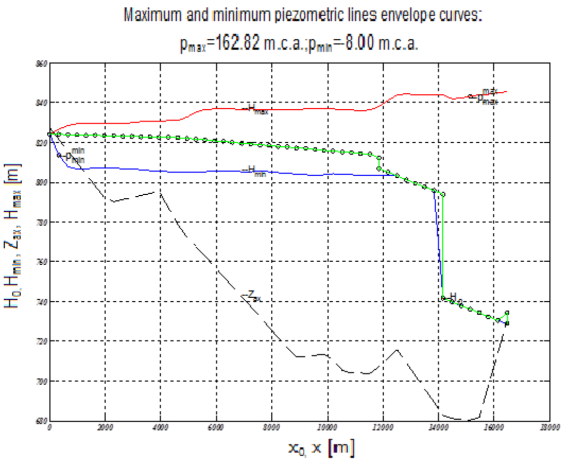


Figure 3 **Hypothesis 4A.Closing the downstream valve, Tm= 10'.Piezometric lines envelope curves**

In the second scenario, with the overpressure valve the overpressure was $p_{\max}^{\max} = 149.19$ m (*figure 4*).

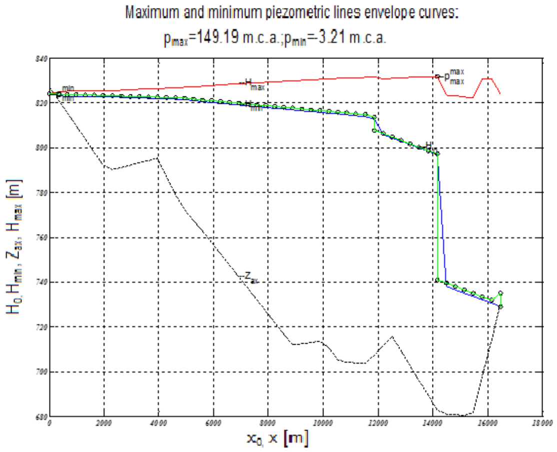


Figure 4 **Hypothesis 4B.Closing the downstream valve,with the overpressure valve, Tm= 10'**

The suppressing effect of the valve was: $\Delta p_{\max}^{\max}$ = 162.82 -149.19=13.63 m.

CONCLUSION

The analysis of the variation of the hydrodynamic parameters of the pressurized water adduction works during the water hammer manifestation is of paramount importance since both overpressures and under-pressures may lead to negative effects like jeopardizing the resistance and/or the stability of the system with important economic and safety consequences.

The determination of the adduction at the moment of the water hammer is done at first for the hypothesis of the absence of the specialized safety devices and then, only in case of dangerous overpressures and/or under-pressures, there follows a second calculus stage in which the pressurized hydraulic system in question is considered to be equipped with safety devices.

One of the most common devices of controlling the overpressures is the safety valve that can be of various constructive-functional types; this paper analyzing the open valve with spring.

Based on general equations of the solid body mechanics and hydraulics, concrete analytical expressions were determined for the control and flow characteristics of the open valve with spring.

The mathematical model elaborated in section 4 was applied, using an adequate computer software program for the open valve with spring Dn 100 and the control and flow characteristics of this valve were graphically presented.

The aforementioned mathematical model and computer program were implemented into a complex computer software package of calculus at water hammer; thus, applying it for an actual pressurized adduction, the suppressing effect of the safety valve was emphasis.

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