Hydraulic study on pumping stations equipped with air chamber mounted next to the pump

Claudiu Stefan Nițescu, Anca Constantin, and Mădălina Stănescu

***Abstract*—**Surge tank and air chamber are the most used devices to protect a pumping installation from either cavitation or excessive pressure during water hammer. These devices transform the water rapid variable movement into a slow oscillatory one. The choice of the optimal protection solution should rely not only on hydraulic, but also on technical and economic calculation. Numerical simulation of the water transient movement reveals the most effective protection method from technical view pint, for the water pumping station SRP 4 Seimeni, Constanta county.

***Keywords*—** Air chamber, Asymmetric hydraulic resistance, Head loss, Surge tank.

I. Introduction

Hydraulic systems should be equipped with protective devices in case the pressure oscillation exceeds in amplitude dangerous values during hydraulic shock. These devices may diminish or even eliminate the hydraulic shock in the entire or at least in the vulnerable sections of the hydraulic installation [1], [3], [16], [17].

According to their design, the protection equipment may change the type of the unsteady water movement in installation, which means they may turn the rapid into a slow variable movement or they may modify the hydraulic parameters of the flow. Therefore, the means used for pumping stations protection from water hammer can be divided into two large categories:

-devices that diminish or limit the pressure oscillation amplitude without changing the feature of rapid variable water movement (e.g. check valve by pass ducts, relief valves).

-devices that turn the rapid variable water movement into a slow oscillatory one, in the whole system or at least in sections of the pumping installation (e.g. surge tank, air chamber).

In engineering practices, according to the importance of the pumping station, either one single protection device or a combination of devices may be used. The surge tank is recommended for pumping stations with reduced geodetic head. For economic reasons, the height of a surge tank is limited up to 25 m. No doubt a reduced geodetic head of a pumping station doesn't automatically require a surge tank as a protection device.

The air chamber may be used in pumping installations regardless the values of the discharge or of the pumping head. A pumping installation may be protected by a single one or by a battery of air chambers.

Numerical simulation developed by the use of automate programs make it easy to choose the best protection device combination both from technical and economic view point.

II. Water Hammer Simulation

A. Air Chamber as a Protection Device

In the frame of the irrigation water pumping stations modernization, we are often required to give the best solution for water hammer protection of the discharge ducts. The discharge duct of the old pumping station SRP4 Seimeni, Constanta County is protected by a double air chamber of $10m^3$ each [11].

Aiming to find out the best variant of protection for this installation, we carried out a study based on numerical simulation of the water hammer phenomenon. We took into account cheaper variants, but at least as effective as the double air chamber. A special automate program was used, a program conceived to solve hydraulic transients by the method of characteristics.

Referring to the installation composed of pump, discharge duct, air chamber and reservoir, as it is represented in Fig.1, we used the motion and the continuity equations under the form of finite differences, in order to use the characteristic method, as they are given in [2], [4], [5], [17].

In the intermediate section of the calculus node with air chamber, 5 unknowns occur: the speeds before and after this section, $V'_{j,i+1}$ and respective $V''_{j,i+1}$, water elevation in the air chamber $H_{j,i+1}$, air layer pressure $P_{j,i+1}$ and air layer volume $\tau_{j,i+1}$.

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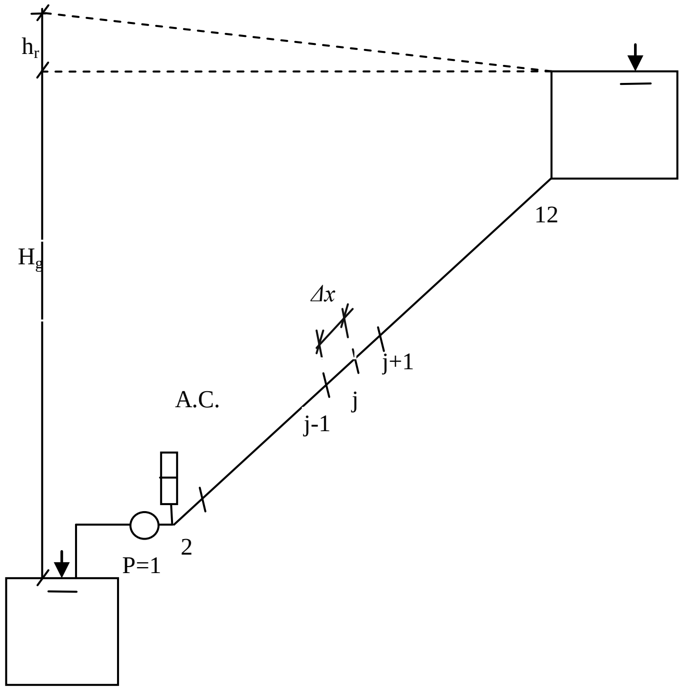

Fig.1 Pumping station with air chamber on the discharge duct

$$\begin{cases} V'_{j,i+1} - V_{j-1,i} + \frac{g}{c}\left(H_{j,i+1} - H_{j-1,i}\right) + \\ \qquad + \frac{\lambda}{2D} V_{j-1,i} \left|V_{j-1,i}\right| \Delta t = 0 \\ V''_{j,i+1} - V_{j+1,i} + \frac{g}{c}\left(H_{j,i+1} - H_{j+1,i}\right) + \\ \qquad + \frac{\lambda}{2D} V_{j+1,i} \left|V_{j+1,i}\right| \Delta t = 0 \end{cases} \quad (1)$$

where index i accounts for time,
index j accounts for node,
v-velocity, (m/s);
H-head, (m);
c-celerity, (m/s);
Δt -step of time, (s);
D -pipe's diameter, (m);
λ-Darcy's coefficient;
g-gravity acceleration, (m/s^2).

The equation that gives the water pressure as a function of air pressure in the air chamber, [3], [11], is:

$$H_{j,i+1} = Y_{j,i+1} + \frac{P_{j,i+1}}{\gamma} \quad (2)$$

where:

Y – water elevation in the chamber, with respect to a reference horizontal plane, [m];

$P_{j,i+1}$ - pressure at the time $i+1$, deduced from the gas equation of state, [N/m^2].

Assuming a polytropic transformation of the gas, we may write:

$$P_{j,i+1} \cdot \tau^n_{j,i+1} = P_{j,i} \cdot \tau^n_{j,i} \quad (3)$$

where: n - polytropic transformation coefficient *(n=1,0 – 1,4)*.

The air layer volume, at the time $i+1$ can be deduced as a function of the air volume at the time i and of the water velocity in the small duct that connects the air chamber and the protected duct.

$$\tau_{j,i+1} = \tau_{j,i} + \Omega(Y)\left[V_{r,i+1} + V_{r,i}\right]\frac{\Delta t}{2} \quad (4)$$

where:

$\Omega(Y)$ - air chamber horizontal section area, at the elevation Y, [m^2];

V_r - water ascending velocity inside the air chamber.

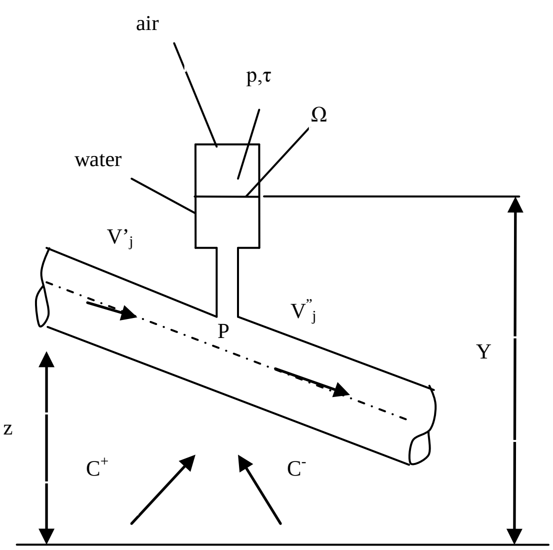

Fig. 2 Calculus node with air chamber

In the calculus nodes with air chamber where the head losses in the connection duct are taken into account, we have one more equation:

$$H_{j,i+1} - H_{d,j+1} = MQ_d\left|Q_d\right| \quad (5)$$

where:

M – hydraulic resistance modulus for the connection duct, [s^2m^{-5}];

H_d – piezometric head in the air chamber, [m];

Q_d –flow rate in and out of the air chamber, [m^3/s].

B. Case study: Seimeni Pumping Station without protection

SRP 4 Seimeni is a lifting pumping station that supplies irrigation water. The station delivers a maximal discharge of 1.3 m^3/s at a geodetic head of 14.5m. The station is equipped with 5 pumps vertically mounted, type MV 303. The pumps technical features are: discharge Q_0= 0,26 m^3/s at a total head of H_0=20m, driven by motors type MIB-2-V with the power N=110 kW and rotational speed n=1485 rot/min. Each individual discharge duct (400mm) is equipped with butterfly type adjusting valve and check valve.

The pumping station's discharge duct has 550 m in length and 800mm in diameter. The discharge duct is concrete made.

Close to the discharge reservoir, the duct is equipped with an air valve DAD-3, which allows air in/ out when the pumps stop/ start to operate.

If the discharge duct were not protected from water hammer, pressure would take dangerous extreme values as the pumps accidentally stop. Cavitation occurs in the along the pipeline. Pressure oscillation and its extreme values may be seen in Fig.3-6.

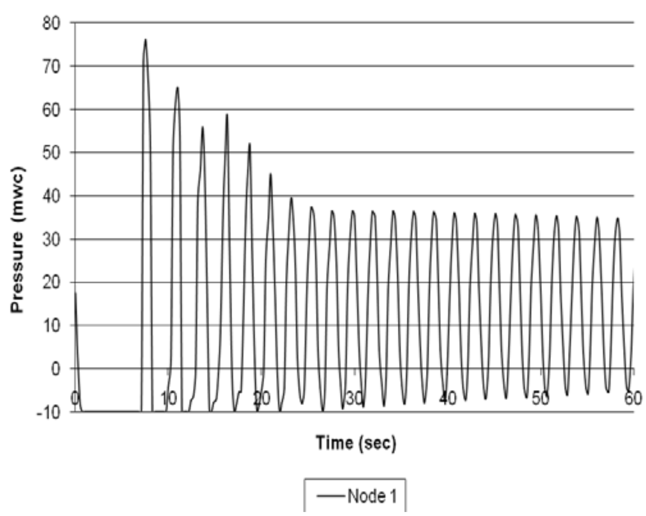

Fig. 3 Pressure in the discharge duct

Considerable negative pressure values occur even in the last part of the discharge duct.

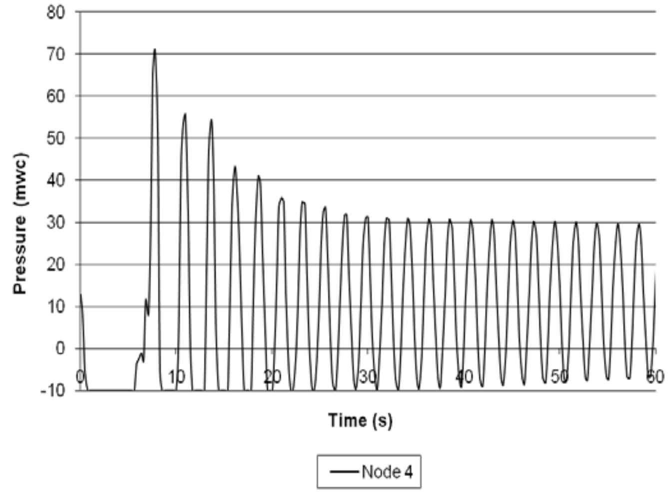

Fig. 4 Pressure in the discharge duct

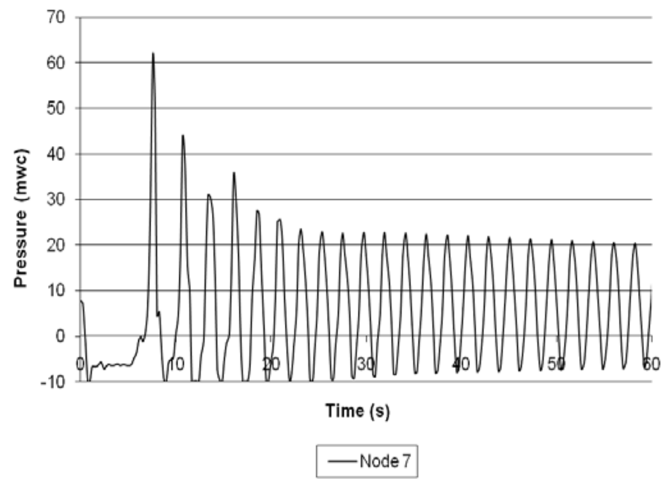

Fig. 5 Pressure in the discharge duct

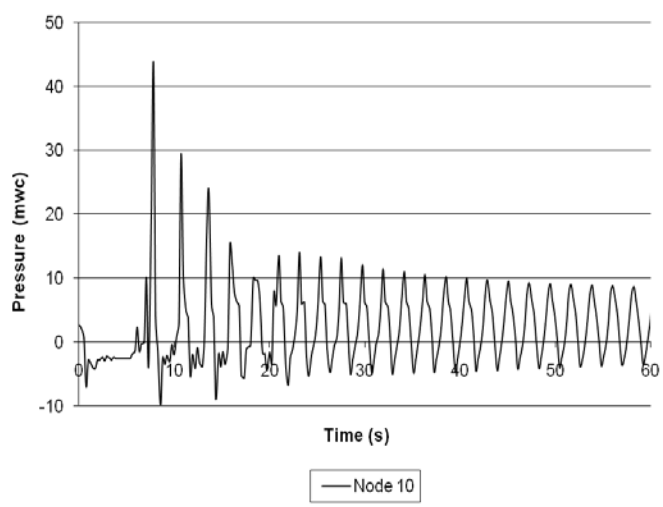

Fig. 6 Pressure in the discharge duct

C. Case study: Seimeni Pumping Station with hydraulic protection

The most reliable among the water hammer protection means is the surge tank. It turns the water rapid variable movement into a mass oscillation. Assuming the same case of a sudden stop of the pumping station due to a power failure, we present below the results regarding pressure evolution inside the duct, in the case it is equipped with a simple surge tank with negligible head loss in the connection duct.

The investigation referred to a surge tank diameter between 1 and 2m. A surge tank with a diameter of 1 m or 1,5 m leads to a large maximal water jump inside the device. The total height of the surge tank:

$$H_{ST}=H_g+Z_{max}+H_s+H_{SS} \tag{6}$$

will exceed the limit of 25 m, imposed by economic reasons. Notations in the relationship (6) are:

H_{ST} – total height of the surge tank, [m];
H_g – geodetic head, [m];
Z_{max} – water level inside the surge tank over the water level in the discharge reservoir, [m];
H_{SS} – additional safety height, [m].

We obtained reduced (acceptable) values for the water jump in case the surge tank diameter is too large, D_{ST}=2.00m.

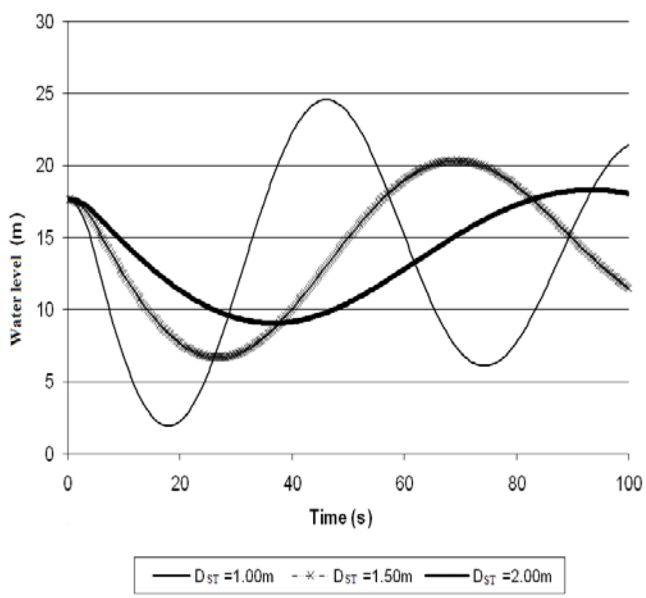

Fig. 7 Water level in the surge tank

Using the graphical method for sizing the surge tank as in [8],[9], for a water maximal jump of 3.50m and a total height of the surge tank of 20m (economic height), we obtained a device of 2.15m in diameter. For this value of the surge tank diameter, D_{ST}=2.15m, the ratio D_{ST} /D exceeds the recommended value:

$$\frac{D_{ST}}{D} \leq 2 . \tag{7}$$

The result is an expensive cost for building such a surge tank. In order to lower the construction cost of the protection device, a hydraulic resistance should be used [11], [14], [15]. The hydraulic resistance is in fact a throttling placed on the connection duct between the surge tank and the discharge duct.

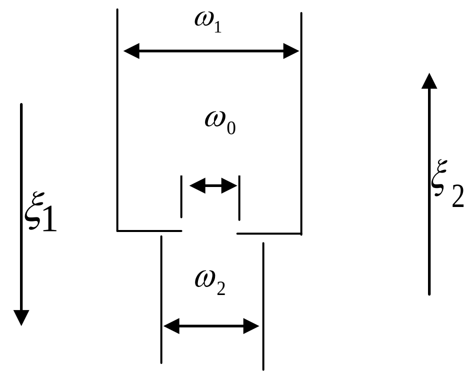

Fig. 8 The hydraulic resistance placed on the connection duct between the surge tank and the discharge duct

ω_1 - cross-section area of the surge tank, [m^2];
ω_2 - cross-section area of the discharge duct, [m^2];
ω_0 - throttle area, [m^2];
D_0- throttling section diameter, [m];
$\xi_{1,2}$ - local head loss coefficients for the two ways of water movement: out/ in the surge tank [6], [7].

These coefficients may be calculated with the relationship:

$$\xi_i = \left(\frac{1}{n\kappa} - \frac{1}{m} \right)^2 \tag{8}$$

where $$m = \frac{\omega_{2,1}}{\omega_{1,2}} \tag{9}$$

$$n = \frac{\omega_0}{\omega_{1,2}} \tag{10}$$

$$\kappa = 0.57 + \frac{0.043}{1.1 - n} \tag{11}$$

Assuming a surge tank diameter D_{ST}= 1.00m, we calculated its height for a few values of the throttling section area.

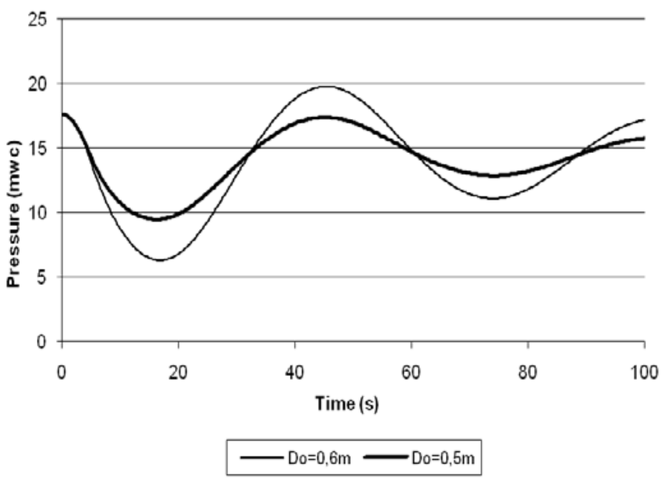

Fig. 9 Water level (pressure) in the surge tank with throttled connection duct

In the case the throttle area is ω_0 =0.196m^{2,} (for a diameter D_0=0.5m) we obtained proper values for both maximal and minimal jumps, the total surge tank height (approximately 19m) being influenced only by the additional safety height and the geodetic head. This is a good solution from technical view point, therefore only economic calculation regarding the investment cost and the payback time will show if it can be adopted.

A. Case study: Seimeni Pumping Station. Existing Solution

The existing Seimeni Pumping Station discharge duct is protected from water hammer damage by the help of an assembly composed by two air chambers.

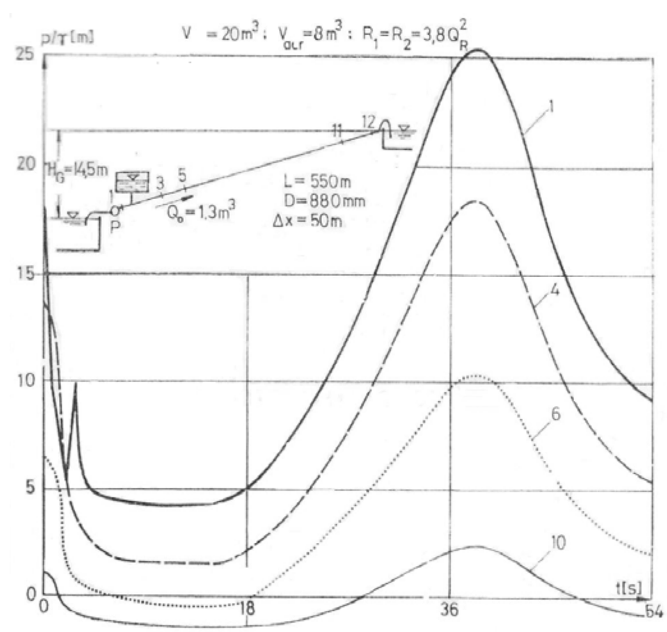

Fig. 10 Old pumping station SRP 4 Seimeni. Pressure values in the discharge duct [11]

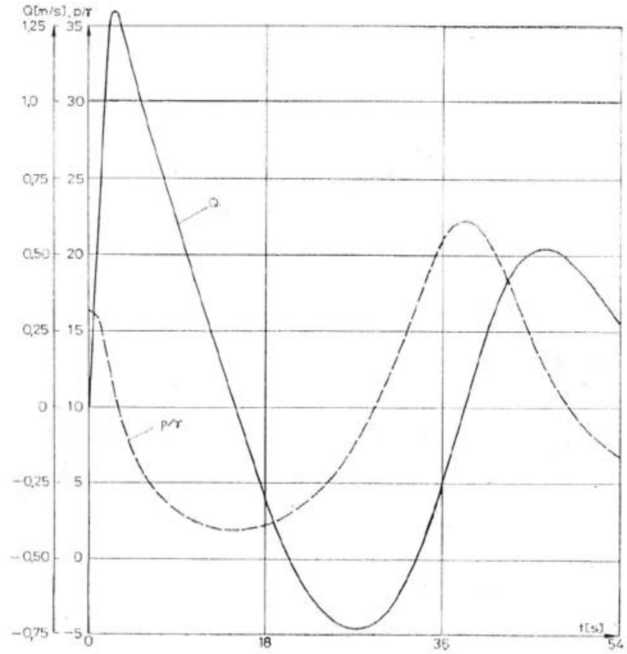

Fig. 11 Air layer pressure (p/γ) and the water flow rate between air chamber and the discharge duct (Q) [11]

The double air chamber is mounted nearby the station building. The features of this assembly are:

-the volume of one reservoir: 10 m^3;

-the volume of the air layer in a reservoir, at the regime water pressure: 4 m^3;

-the diameter of the connection duct of one reservoir: d=350 mm.

Downstream, right before the discharge basin, the duct is equipped with an air valve type DAD-3, which allows air in when the pumps stop and air out when the pumps start to operate.

Fig.10 and 11 show the results of the numeric simulation of the transients caused by a sudden stop of the pumping installation, while operating at maximal discharge. The adopted protection solution is effective, because the presence of the air chambers determines a slowly variable water movement, with admissible maximal and minimal pressure values.

This protection solution from water hammer was adopted by the designers due to the fact it was economically superior to the variant with surge tank. [11].

B. Case study: Seimeni Pumping Station protected from water hammer by air chamber with asymmetrical hydraulic resistance

The hydraulic resistance of the connection duct between the air chamber and the protected discharge duct has an enhanced role in extreme pressure limitation. Such a local hydraulic resistance duct may be a symmetrical one, opposing the same resistance despite the way the water flows or an asymmetrical one, opposing different hydraulic resistance, according to the way of flow. The asymmetrical hydraulic resistance devices are of great technical interest, due to their possibility of differential pressure adjusting. Consequently, they allow optimal sizes of the hydraulic system.

The sketch of such a device is represented in Fig.12, where the ways of flowing are A and respective B.

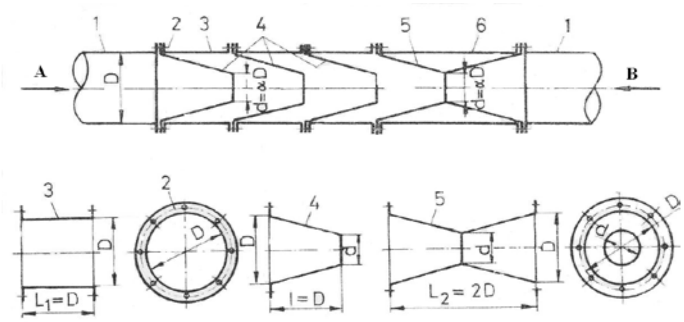

Fig.12 The device with asymmetrical hydraulic resistance, type I.C.H: 1,3-duct; 2- flange; 4- conical nozzle; 5- bi-conical nozzle; 6-duct, [13].

The ratio between the inner diameter of the conical nozzle and the duct diameter is:

$$\alpha = {}^{d}/_{D} = 0{,}4 \div 0{,}6$$

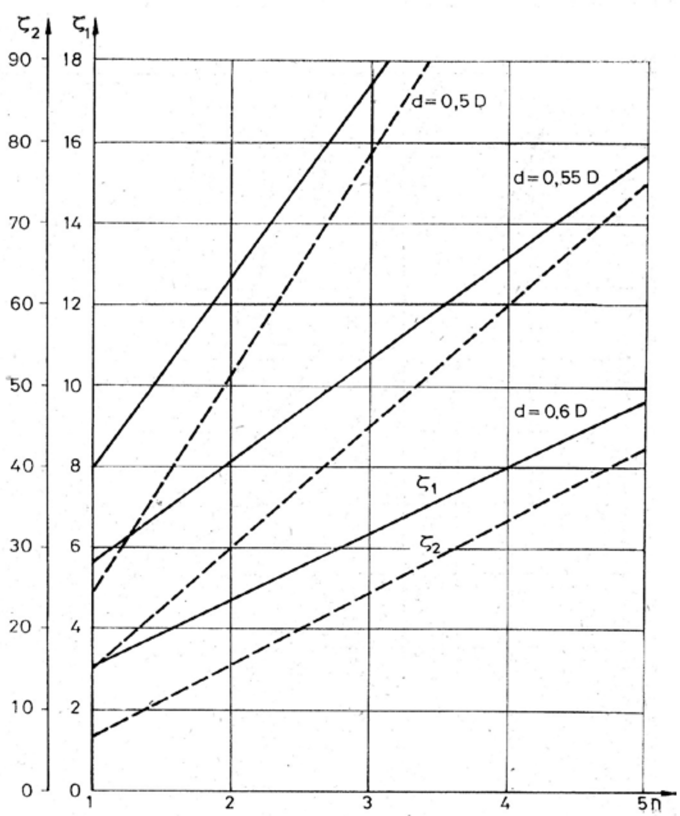

Fig. 13 Coefficients of local hydraulic resistance ζ_1 and ζ_2 as functions of the number of conical nozzles in an asymmetrical resistance device [12], [13]

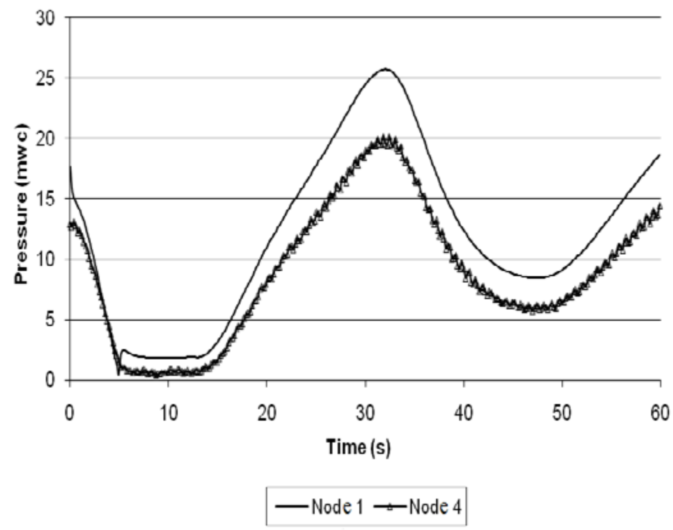

Fig.14 Pressure variation in the case of one air chamber with asymmetrical hydraulic resistance

The asymmetrical hydraulic resistance devices are recommended in pumping installation protection from water hammer because the pumping stations are subjected to asymmetric loads that lead to large variation of pressure. For instance, a sudden stop of the pumping station may occur in the case of power failure, but the start is slowly and deliberately made.

An asymmetrical resistance device mounted on a connection duct reduces the number of additional necessary protection devices and furthermore, improves their technical features.

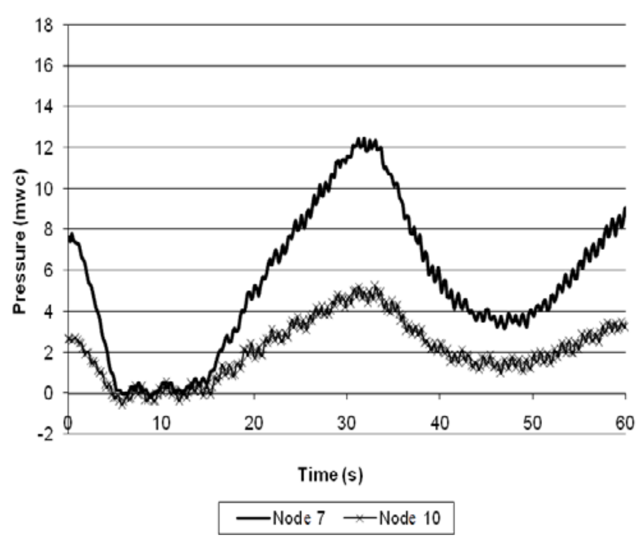

Fig.15 Pressure variation in the case of one air chamber with asymmetrical hydraulic resistance

We considered a more simple solution for the protection of the SRP4 Seimeni pumping station discharge duct by the use of a single air chamber connected to the protected duct through an asymmetrical hydraulic resistance type ICH. The total volume of the air chamber is 10 m^3 and the volume of air layer is 5 m^3. The asymmetrical resistance device is 1.40 m in length and consists of two conical nozzles and one bi-conical nozzle. The connection duct is 350 mm in diameter, with the ratio α=0.6.

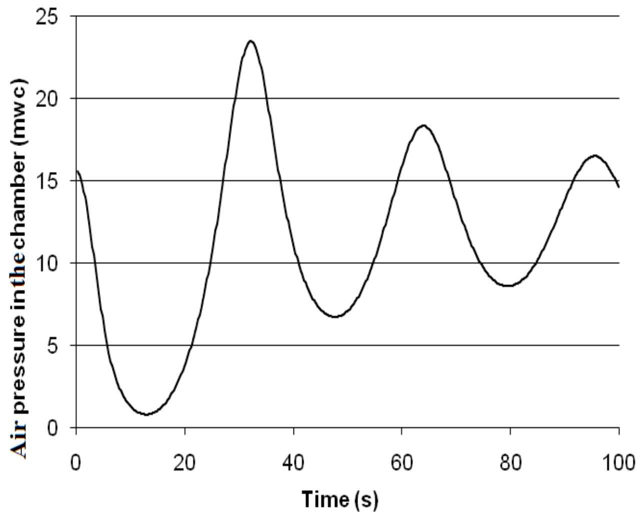

Fig.16 Air pressure variation in air chamber

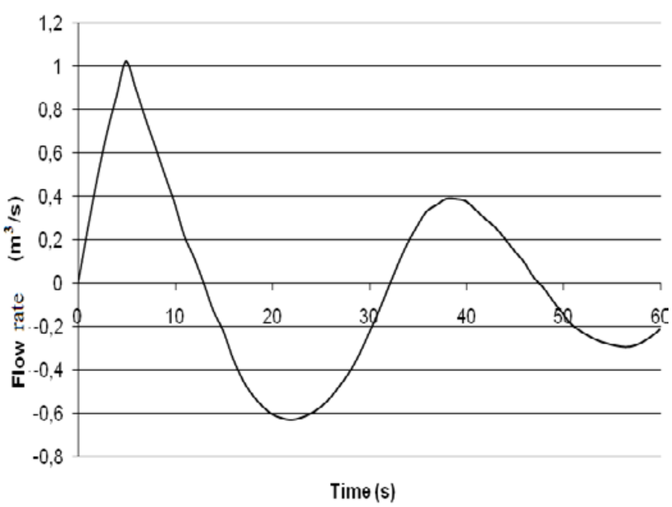

Fig.17 Flow rate for the water change between air chamber and duct

According to the diagram presented in Fig. 13 the coefficients of local head loss for the above depicted asymmetrical hydraulic resistance device are: ζ_1 =4.75 for *A* flow way and ζ_2= 15.85 for *B* flow way.

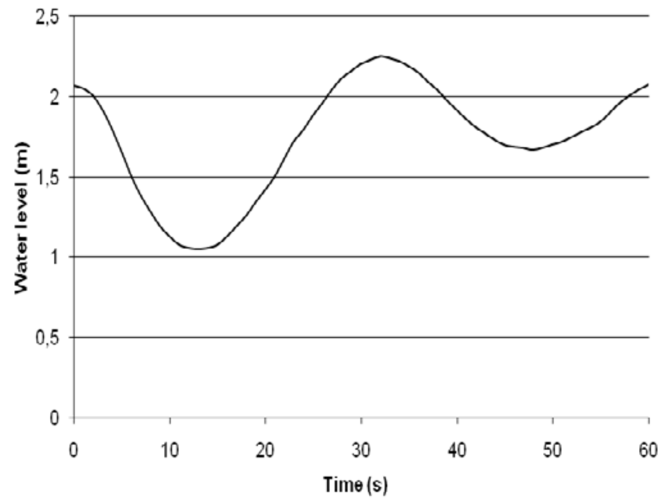

Fig.18 Water level variation inside the air chamber

Pressure variation obtained for the proposed variant is represented in Fig.14, 15. Comparing the graphs in Fig. 10, for the existing solution to the graphs in Fig.14, 15, for the proposed solution we may notice that they are very similar. Extreme pressures in node 1 are the same in both variants. That means the proposed solution is as effective as the existing one, from technical view point, but cheaper. Slight differences between graphs occur in the second half of the discharge duct. In this section, maximal pressure values rise with up to 10%, but the values aren't dangerous. The minimal pressures increase. They become positive in the most of the nodes. In the nodes 7 and 10 minimal pressures are still negative but they have greater values. For instance the minimal pressure is -0.259mwc instead of -0.528mwc in node 7 and -0.671mwc instead of -1.46mwc in node 10.

Comparing the two variants of protection from water hammer:

-with two air chambers, each of 10 m^3 volume ;

-with one single air chamber, of 10 m^3 volume, with asymmetrical hydraulic resistance

we may notice in the second case a greater amplitude of the first oscillation of the air pressure in the chamber. The air maximal pressure in Fig.16, is with about 1m higher than in Fig.11 and the minimal pressure with about 1m lower. But, in the second case the oscillation decays faster, as it may be seen in Fig.16.

The protection efficiency of the asymmetric hydraulic resistance is proved not only by the harmless pressure in the installation during the water hammer, but also by the reduced water change flow rate between the chamber and the discharge duct. This reduction is about 10÷15%. We may say that the combined protection solution provides safety and stability to the hydraulic system.

III. Conclusion

Numerical simulation is a helpful tool for the engineers in charge to decide among different technical and economic solutions regarding water hammer protection.

Referring to the modernization of the SRP4 Seimeni pumping station we may say that the study led to two variants that provide stability and safety to the installation:

- -with surge tank connected to the discharge duct through a hydraulic resistance (D_{ST}=1m, D_0=0.5m); both the total height and the diameter of the surge tank meet the economic requirements;
- -with air chamber (of 10m^3 total volume and 5m^3 volume of the air layer) equipped with an asymmetric hydraulic resistance.

The optimal variant must be chosen according to a rigorous economic analysis.

Taking into account the performance of the existing solution (with two air chambers), we consider the solution with one air chamber and asymmetric hydraulic resistance to be superior from technical point of view. This variant is simpler and the amplitude of the pressure oscillation during water hammer is smaller than in the case of the double air chamber.

As the protection installation is simpler it is easier to watch and maintain it.

In the case of accidental decrease of the air layer volume, the system is protected by the asymmetrical hydraulic resistance device either at high or small pressures.

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