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Waterhammer protection with air vessels - A comparative study

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Abstract

As pressurized liquid transport systems need to be protected against waterhammer phenomena, different kinds of protection devices can be applied. Each of them has its own characteristics and advantages. In the whole scope of protec-tion installations, air vessels certainly offer the best guarantee for safe pipe line operation under variable conditions. To meet all operational conditions different types of air vessels are commercially available. The most important ones are the classical air vessel with gas bubble, eventually equipped with a rubber balloon and with a single connection to the main pipe; the classical air vessel with double connection which acts as a flow through system. In a more recent ver-sion of an air vessel, the normally isolated air bubble can be connected to the atmospheric pressure, again with a single or a double connection pipe (AARA-vessel). The principles and typical working schemes of all these types of air vessels are identified and briefly discussed. Based on some practical examples the application field of each type is defined and illustrated. Relevant design parameters are put in evidence. It is shown that expertise and thorough understanding of transient flow phenomena are needed to work out economical interesting water hammer protection designs. Thanks to the former and to the great variety of vessels it becomes possible to work out an appropriate solution for each particular transient flow problem.

1.Introduction

Generally spoken, in pressurized liquid transport systems with a length of more than 100 m dangerous waterhammer phenomena might occur. This means that for most pipe systems attention must be paid to the design of an appropriate protection device. The kind and size of the device mainly depend on the nature of the liquid transported and the geometrical and hydraulic characteristics of the system. The pressure variations as a result of a waterhammer can be kept within reasonable limits by making a right choice of pipe diameter and material or by the installation of a bypass, a flywheel, air valves, a surge tank or an air vessel.
Adaption of pipe diameter and material mostly lead to small flow velocities and uneconomical solutions, while a flywheel increases the pumpmotor capacity. This waterhammer protection device, just as a bypass construction, is not able to damp reflected overpressure shock waves. A surge tank can offer an attractive solution when situated in hilly or mountaineous areas, as it mostly has a considerable height. Air inlet valves enter air into the system which needs to be evacuated carefully before pumps can be fully re-started. The big advantage of an air vessel is found in its capacity to deal as well with overpressure as with underpressure waves. It also offers the opportunity to adjust the smoothing of the shock waves. As it is normally installed in the pumping station it's easy attainable for maintenance. The most important air vessel types are the classical one with an isolated gas bubble, eventually equipped with a rubber balloon and connected to the main pipe by a single conduit; the classical air vessel with a double connection, which acts as a flow through system and a more recent version where the normally isolated gas bubble can be connected to atmospheric pressure, again with a single or a double connection pipe.

2 Different types of air vessels

2.1 Classical air vessel

Figures 1a and 1b show the setup and working principle of this device. Once the pressure in the main pipe starts to rise, liquid flows into the tank by this increasing the gas bubble pressure (normally equal to the steady state pressure). The more the gas pressure increases, the more the inflow decreases. Once the waterpressure in the pipe system decreases

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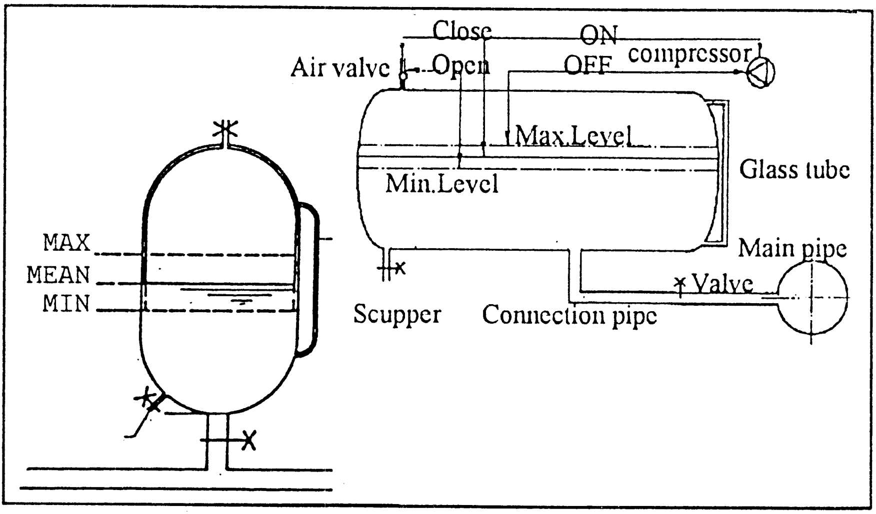

Figure 1. Classical air vessel with and without rubber balloon

again below the gas pressure in the tank, water discharges from the tank into the system. In case of an underpressure wave the action develops in the opposite way. The inflow in the air vessel reduces the discharge in the main pipe and by this the magnitude of the overpressure. By changing the initial gas volume and the connection pipe diameter, the amplitude of the shock waves is kept within preset safety limits.

In order to obtain maximum damping and minimum volume, the connection pipe diameter is smaller than the main pipe.

If the gas is in direct contact with the liquid the latters level is controlled by 3 electrical contacts. The lower one opens a gas release valve if the liquid level becomes to low, while the top contact starts a compressor or opens the valve of a gas container in case the maximum level is exceeded. The middle contact stops the adjustment operation. These control and safety devices are needed as gas may slowly dissolve in the liquid (for example: air and water).

If both gas and liquid are separated by a rubber balloon, the control devices are no longer needed which makes the whole installation a lot simpler. Anyhow some control device (glass tube) to verify the water and gas volume should be put on the tank. For both kinds of vessels the operational effect is the same.

This type of air vessel is particulary interesting for large transport systems with high steady state pressure conditions and substantial pipe lengths (>2000 m).

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2.2 The flow through air vessel (figure 2a and 2b).

With this type of vessel the whole main flow passes through the vessel. Increase of pressure causes the liquid level to rise and reduces the outflow and by this the pressure. A lowering of the pressure in the main pipe keeps the outflow going on and reduces the pressure drop. Again the damping efficiency of this vessel can be adjusted by changing the gas bubble volume and the in- and outflow diameter.
When compared to the previous system, this vessel cannot be disconnected from the main pipe during operation as all flow passes through the tank.
Although the overall damping effeciency of this system is smaller when compared to the previous one, the device offers nice opportunities in case of rather high pressure systems where larger pressure fluctuations should be allowed.

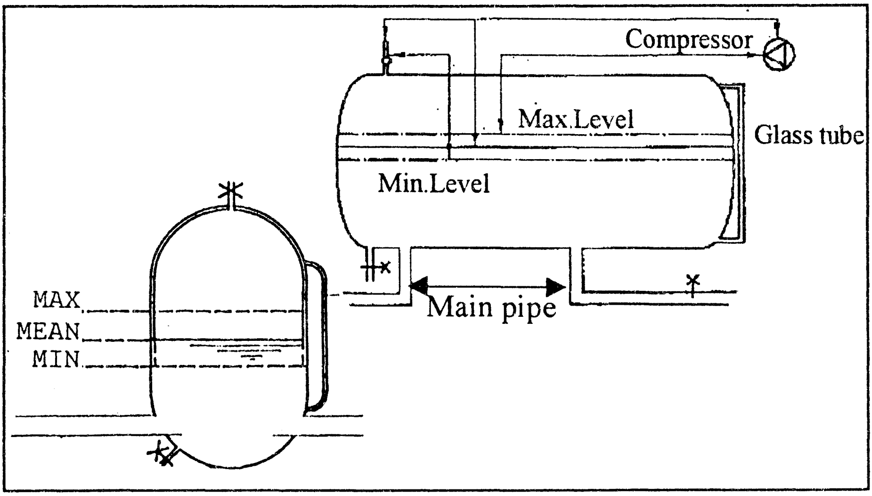

Figure 2. Flow through air vessel

2.3 The AARA (Automatic Air Regulation Anti-Waterhammer) Vessel (figure 3a and 3b)

The AARA tank is in fact a combination of a classical air vessel and a surge tank. The air content is defined by the position of the dip pipe. As long as the water in the tank is higher than the lower dip pipe end, the reservoir acts as an classical air vessel. Once air can enter into the tank, it starts to work as a surge tank (with the air volume under atmospheric pressure) or an air inlet valve, when completely empty. As this device operates automatically, it is a very attractive tool for the protection of small to medium size systems (200 to 2.000 m).

The tank is well suited for application in low pressure waste water transport systems. If well designed, it is completely self-controlling and doesn't need much maintenance thanks to its simplicity. As the lower pressure is limited to atmospheric pressure, the solution is not advised for application in systems with an outflow lower than or close to the lower tank level as in this case air may enter into the pipe system. In this case the vessel acts as a simple air inlet valve and doesn't guarantee safe restart without careful air evacuation.

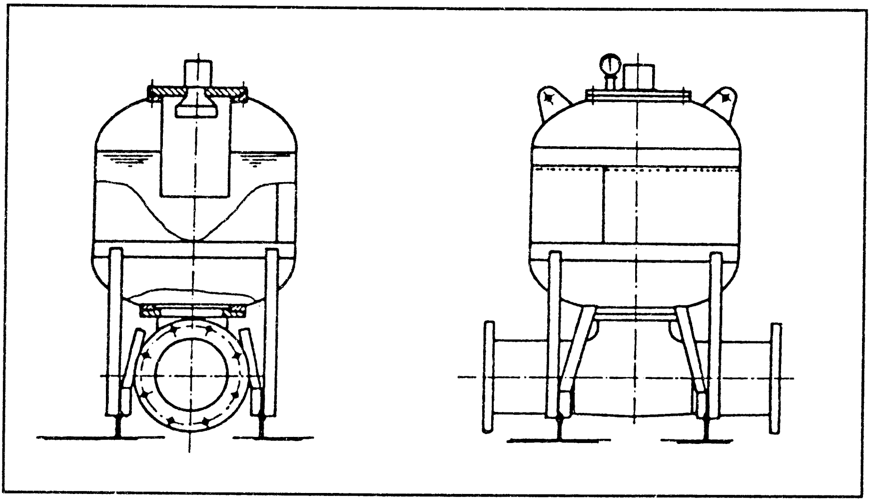

Figure 3. AARA-vessel

3 Numerical simulation

The unsteady flow equations for circular pressurized pipes are:

$$\text{Momentum} : g\frac{\partial H}{\partial x} + U\frac{\partial U}{\partial x} + \frac{\partial U}{\partial t} + \frac{f\,U|U|}{2D} = 0 \qquad (1)$$

$$\text{Continuity} : U\frac{\partial H}{\partial x} + \frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial U}{\partial x} = 0 \qquad (2)$$

(see section 6 for the meaning of the symbols used.)

These partial differential equations of the non-linear hyperbolic type have no analytical solution, so numerical solution methods need to be applied. In common practice the method of characteristics with a first order approximation for the friction term is used in a rectangular x,t- grid.
The boundary condition for a classical air vessel is expressed as:
momentum equation for the connection pipe:

$$\frac{gA_3}{L_3}\left(H_3 - H_t - k|Q_3|Q_3|\right) = \frac{dQ_3}{dt} \tag{3}$$

where

$$H_t = \frac{C_o}{V_{g,t}^{\ n}} + z_o + z_t + H_b \tag{4}$$

$$H_3 = T_1 - T_2 \cdot Q_3 \tag{5}$$

and

$$T_1 = 0{,}5\left[H_B + H_A - \frac{a}{gA}(Q_B - Q_A) + \frac{f\Delta x}{2g\ DA^2}(Q_B|Q_B| - Q_A|Q_A|)\right] \tag{6}$$

$$T_2 = \frac{a}{2gA} \tag{7}$$

Substituting eq. (4) and (5) in (3) gives a partial differential equation from which Q_3 is solved.

In case of a flow through system, using equation (3) for both the in- and outflow pipe gives the solution for in- and outflow of the reservoir. If the main pipe passes through the tank without geometrical changes, the in- and outflow can also be calculated from the normal characteristic equations using the gas bubble pressure as a boundary condition. In all cases the gas and water volume variation in the vessel is calculated from the continuity equation.

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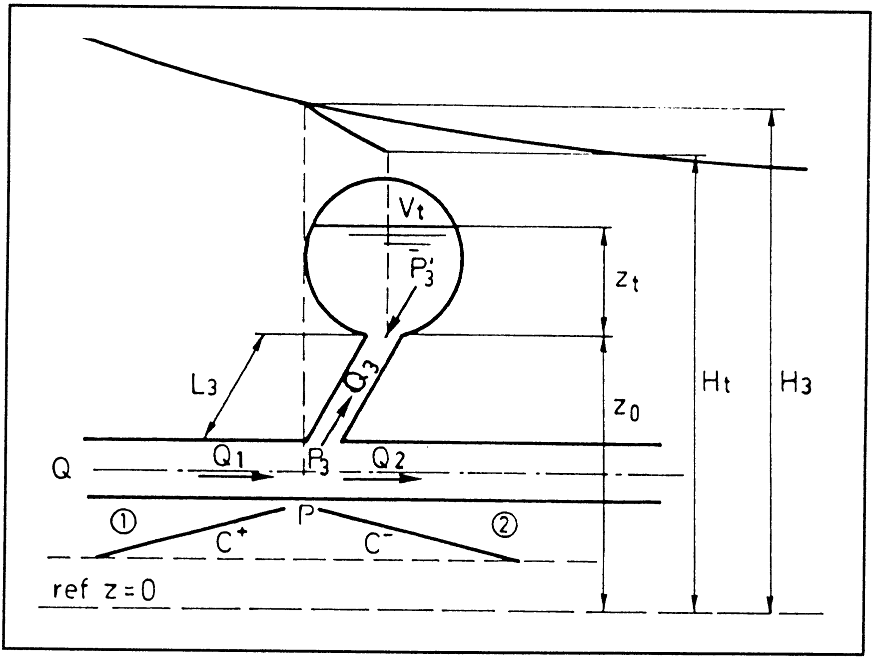

Figure 4. Numerical implementation

For an AARA vessel, once the liquid level drops below the sink pipe level, the pressure H_t in equation (3) is put equal to atmospheric pressure.

4 Some examples

4.1 A 1825 m long pipe, small velocity

The first example deals with an asbestos cement pipe of diameter 150 mm transporting .015 m^3/s over a length of 1825 m and a height of 4.5 m. The steady state velocity equals .85 m/s and the transient situation (as in all examples) is induced by a sudden pump failure. Different types of air vessels each with a total content of .350 m^3 are put on the system. Figure 5a and 5b clearly show how a transient wave is accurately damped in all cases. It can be seen that there is only little difference between a solution using a single pipe connection and a flow through vessel. One also remarks the slightly bigger pressure variation in case of a AARA vessel when compared to a classical air vessel.

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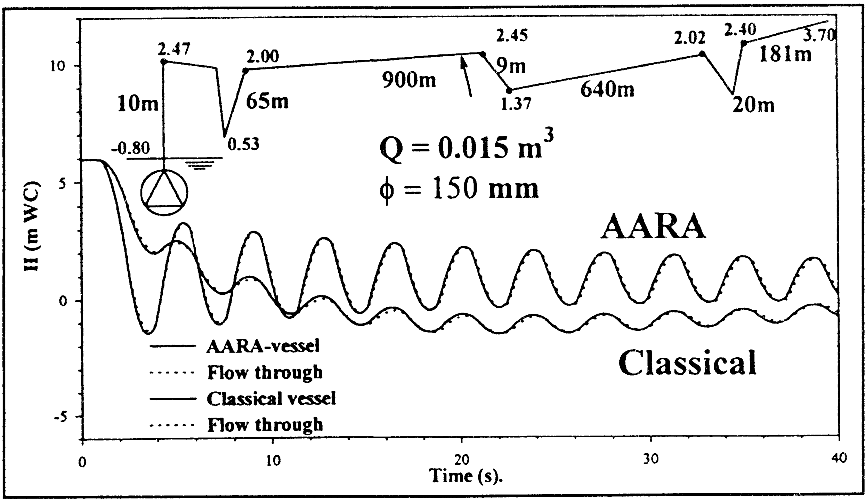

Figure 5. Long pressure pipe - small steady-state velocity

4.2 A 760 m pipe, high velocity (figure 6)

In this example a 760 m long Polyethylene pipe with a diameter of 257.6 mm transports .097m^3/s with a static pump head of 3.25 m. The steady state velocity now equals 1.86 m/s. A safe protection can be realized using a classical single pipe connection air vessel of 1.5 m^3. In case of an AARA vessel the volume needed rises to 2.0 m^3. Although the total water content of the second system (40 m^3) is only a little bit higher then the water volume of the first pipe (32.3m^3), the air vessel volumes become 4 till 5 times higher. This is mainly due to the much bigger steady state velocity in the latter case than in the previous one. Again the resulting pressure variation is bigger in case of a AARA vessel when compared to the classical one.

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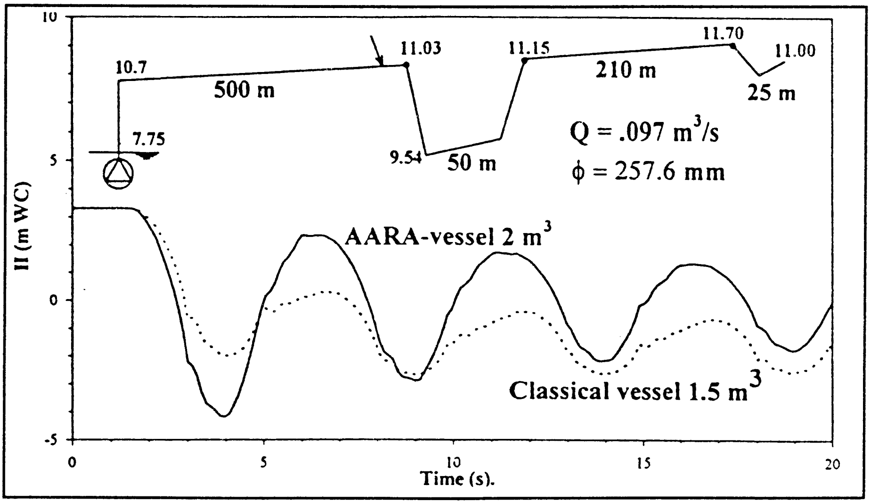

Figure 6. Medium pipe length - high steady-state velocity

4.3 A 280 m pipe, average velocity

Now a polyethylene pipe of small length (280 m) transporting .100m^3/s is considered. The diameter is 300 mm, the steady state velocity equals 1.41 m/s and the static pump head 9.60 m.The respective volumes for a protection with the different vessel types are .350 m^3 for both classical tanks and for the AARA vessel with single pipe connection and .400 m^3 for a flow through AARA system. From both figures 7a and 7b one can again conclude that damping with a flow through system is smaller than in case of a single connection pipe. In case of an AARA flow through system a larger volume is needed. The classical vessels have a slightly better damping effect than the AARA vessels, but in all cases an effective waterhammer protection is realized.

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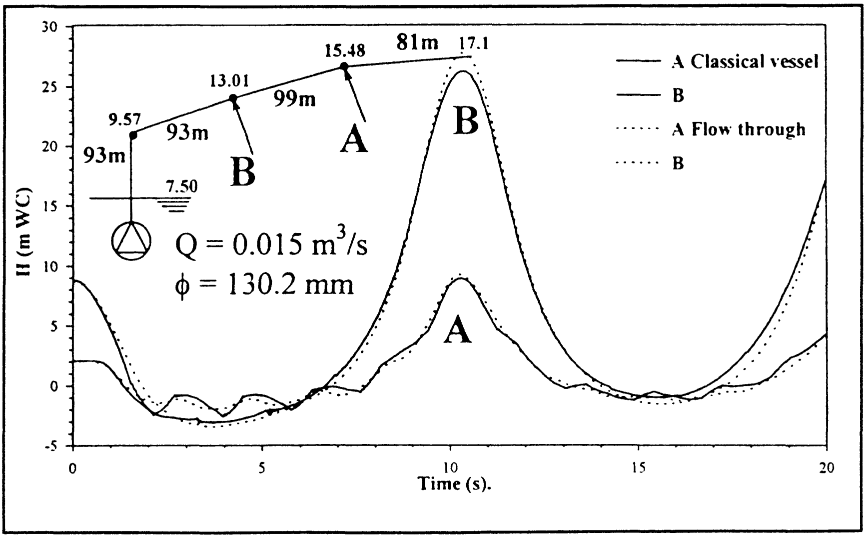

Figure 7a. Average velocity - short pipe - Classical vessel

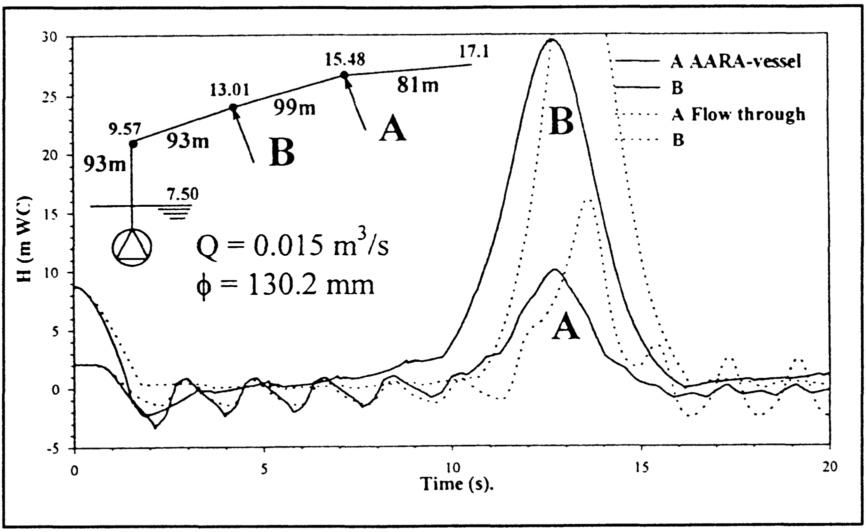

Figure 7b. Average velocity - short pipe AARA vessel.

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5 Conclusions

It can be stated that all types of air vessels discussed in this paper offer efficient waterhammer protection opportunities. Generally speaking, the classical single pipe connection vessel gives the best damping characteristics. The design volumes to ensure a proper water hammer protection will be a little higher for an AARA vessel when compared to a classical one, but thanks to its simplicity, the latter will still offer the most economical solution. Also the volume of a flow through vessel is mostly somewhat greater than in case of a single pipe connection.
If the outflow level of the pipeline is about the same as or lower than the suction level in the pumping station, an AARA vessel should not be used as a protection device.
From the point of view of maintenance, a single pipe connection vessel has some advantages when compared with a flow through system. The latter should preferentially not be used for protection of waste water transport systems, because of the danger of accumulation of floating objects in the tank. The AARA vessel is certainly the easiest to maintain.
Finally one must take care that when installed on a waste water transport system, the tank should be situated above the main pipe with a vertical connection, in order to avoid sedimentation in the connection pipe.

6 List of symbols

a	=	shock wave velocity	[m/s]
A	=	cross section	[m^2]
C_o	=	gas constant	
D	=	pipe diameter	[m]
f	=	friction coefficient	[-]
g	=	gravity acceleration	[m^2/s]
H	=	pressure head	[mwC]
H_t	=	gas pressure head in tank	[mwC]
H_3	=	pressure at connection pipe entrance	[mwC]
H_b	=	atmospheric pressure head	[mwC]
Q	=	discharge	[m^3/s]
t	=	time	[s]
U	=	velocity	[m/s]
x	=	distance	[m]
z	=	elevation above reference level	[m]

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