REVIEWING AIR VALVES SELECTION

Cabrera E., Fuertes V.S., García-Serra J., Arregui F., Gascón L., Palau V.
Institute for Water Technology. Universidad Politécnica de Valencia. Spain.

SUMMARY

In this paper boundary conditions for the most critical function of air valves (the outlet air phase) are reviewed. The isothermal behavior, proposed by the standard books, of the trapped air into the pipe is compared with the adiabatic process, a more realistic approach for fast transients. It is realized that the unfavorable hypothesis (the adiabatic one) is not used in practice. This is because the pressure of the water hammer due to the chock of the water- column against the dead end of the pipe (higher in the adiabatic analysis) exceeds the maximum peak of pressure reached by the air trapped (bigger under the isothermal hypothesis).

With the size of the air valve, the water hammer increases whereas the maximum pressure of the air decreases. The final selection will look for the most favorable combination, a compromise between both effects. Then, in order to select the appropriate air valve,a correct analysis of the transient with the appropriate hypothesis should be performed.

INTRODUCCIÓN

Transient pressures resulting from pipeline filling operation can be significant, mainly due to the presence of entrapped air pockets, especially in systems with an undulating profile. To avoid them, air valves are usually installed at the highest points of the pipe. Air valves, allowing the admission of air into the pipe, avoid depressions and consequently the collapse of the pipe. But they are also required to release the air previously admitted. Otherwise, due to presence of entrapped air, high peak pressures could be reached. This is the most critical phase, because the outlet airflow must be enough to avoid fast and violent compressions of the air. But this process must be controlled. High outlet airflow allows fast speed water columns that can generate, after their shock with the blocking water column, important water hammers. Then, and in order to select the air valve size, it is very important to perform the correct analysis of the outlet flow phase. For this study, adequate boundary conditions are required.

Air valves boundary conditions are widely covered by standard books on transients (Wylie and Streeter, 1993; Chaudhry, 1987). All them consider the air behaviour into the pipe isothermal, while the airflow throughout the valve (in both ways, inlet and outlet flows) is assumed adiabatic. This is because the valve’s diameter is smallest than the pipe’s diameter.

Concerning the kind of process to be assumed (adiabatic or isotherm), the hypothesis should be adopted from the transient’s characteristics. Fast transients have no time to allow thermal transfers and, because of that, the air behaviour should be considered adiabatic. By the contrary, if air is slowly compressed the isothermal hypothesis looks adequate. Between both cases, a wide range of situations can be found. All in all, adiabatic air behaviour inside the pipe has not been, in our knowledge, explored and because results show important differences between adiabatic and isothermal approaches, this is not an irrelevant question.

It is important to quote that while the air behaviour inside the pipe has always been considered isothermal, the air process inside an air vessel has been widely discussed. Due to the generalised use of these protector devices, this subject has attracted the interest of many authors. They have considered all the possibilities, from an adiabatic process to an isothermal one, covering as well the intermediate (polytropic) case. The exponent k of the air's evolution defines the model. Values of k range from 1 (isothermal) to 1,4 (adiabatic) with midway figures for the polytropic process.

Entrapped air inside the pipes have been modelled for different k values (Martin, 1976; Izquierdo et al, 1999). It has been noticed that the greatest peaks of pressure correspond to the isothermal process (Abreu et al, 1991), although there are not criteria with regard to how fast must be a transient to reject thermal transfers. Experimental data available in the literature (Lee and Martin, 1999; Fuertes et al., 2000), are limited by reduced sizes of a lab set up. All are fast transients (just some few seconds) well represented by an adiabatic exponent (k = 1,4).

For the air vessel case, most of the authors (Chaudhry, 1987; Fox, 1989; Thorley 1991; Swaffield and Boldy, 1993) do not propose any value for k. All them state that should be close to 1 for slow transients, while in fast transients a value near 1,4 would be more adequate. Some others, (Evans and Crawford, 1954; Parmakian, 1955; Ruus and Karney, 1997), give straightforward the average value (k = 1,2). And, perhaps because these lack of criteria, Betamio de Almeida and Koelle (1992) state that in this field additional research is still required. In fact just Graze (1968), trying to establish the right value of k for the air process (compression-expansion) inside an air vessel, performed studies including thermal transfers. But given the difficulties to evaluate these thermal transfers, the method has been rarely applied.

In this paper, pressures generated during the air compression process are calculated for both extremes (adiabatic and isotherm behaviours). The water hammer due to the water column chock against the dead end of the pipe is evaluated as well. The flow throughout the air valve itself is considered always adiabatic. Additional work (experimental and theoretical) is required to determine previously which value of k applies in a given transient. An energetic analysis, still to be performed, would help to understand the results.

MATHEMATICAL MODEL OF THE SYSTEM

Being the purpose of this paper the analysis of results derived from extreme behaviours of trapped air inside the pipe, the system considered has been simplified as much as possible (see Fig. 1). The irregular profile allows the existence of trapped air inside the pipe to be released throughout the air valve located at highest point of the pipe. A dead end blocks the filling water column once the air has been totally released. This element reproduces the effect of a downstream high inertia water-blocking column.

A pump provides the source of energy to move the water-filling column. The head – flow curve of the pump (H_P - Q) is known (see Figure 1). For simulating different transients (fast and slow ones) the different parameters of the system are modified. Two different water filling column lengths and, consequently, two initial air pocket sizes are considered. A same number of air valve's sizes is explored while three manoeuvre's time of the valve are analysed. All in all, twelve different cases are studied. For this particular case (Cabrera et al., 1992) the water column movement can be analysed without take into account the elastic effects of the system (water and pipe).

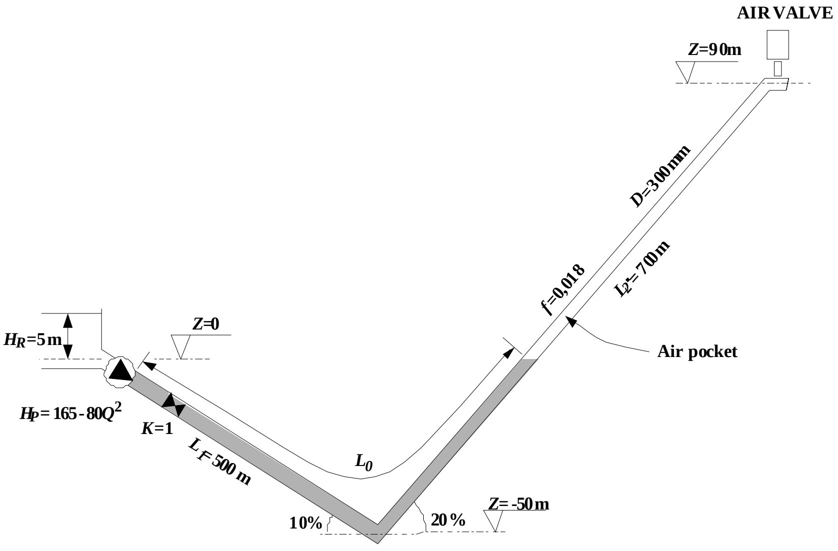

Figure 1.- Physical system considered.

To model the system, the following equations apply:

a) Filling water column dynamics:

Mass oscillation equation

$$\frac{dv}{dt} = \frac{p_0^* - p_1^*}{\rho L} - g\,\frac{\Delta z}{L} - \frac{f\,v\,|v|}{2\,D} \tag{1}$$

Interface position

$$L = L_0 + \int_0^t v\,dt \qquad \left(\frac{dL}{dt} = v\right) \tag{2}$$

being v = water column velocity, t = time, p_0^* = upstream pressure, p_1^* = entrapped air pressure, p_{atm}^* = atmospheric pressure, ρ = water density, L = water column length (initial, current and final or total, according the subscript), g = gravity factor, Δz = geometric head between the extrems of the water column, f = Darcy-Weisbach factor and D = pipe diameter, (* means absolute pressure).

b) Entrapped air pocket.

Mass balance applied to the air pocket

$$m_a(t) = m_a(t_0) + \int_0^t m_a dt \tag{3}$$

with m_a = mass of the air inside the pipe.

c) Air pocket behaviour:

case b1.- Isothermal

$$p_1^* \forall = p_1^* (L_T - L) A = m_a R T_i \tag{4}$$

case b2.- Adiabatic (Zhou et al., 2002)

$$\frac{dp_1^*}{dt} = k\,\frac{p_1^*}{\forall}\frac{d\forall}{dt} - \frac{p_1^*}{\forall}\frac{k}{\rho}\frac{dm_a}{dt} \tag{5}$$

in which $\forall$ = air volume, R = universal gas constant and T = temperature (internal or external, according the subscript -i or a-).

d) Upstream boundary condition. A pump (see Figure 1), is the source of energy. For such conditions, $p_0{}^*$ is given by:

$$H_R + \frac{p^*_{atm}}{\gamma} + H_B = \frac{p^*_0}{\gamma} + \frac{v^2}{2g} + \varsigma \frac{v^2}{2g} \qquad (6)$$

being ς = valve losses coefficient.

e) Downstream boundary condition (Chaudhry, 1988).

Case d1.- Subsonic air velocity through the valve ($p^*_{atm} \rangle p^*_1 \rangle 0{,}53 p^*_{atm}$)

$$\dot{m}_a = \frac{dm_a}{dt} = C_d A_v \sqrt{7 p^*_{atm} \rho_{atm} (\frac{p^*_1}{p^*_{atm}})^{1{,}43} \left[1 - (\frac{p^*_1}{p^*_{atm}})^{0{,}286} \right]} \qquad (7)$$

Case d2.- Sonic air velocity through the valve ($p^*_1 \leq 0{,}53 p^*_{atm}$)

$$\dot{m}_a = \frac{dm_a}{dt} = 0{,}686 C_d A_v \frac{p^*_{atm}}{\sqrt{RT_a}} \qquad (8)$$

with C_d = discharge coefficient and A_v = air valve section.

From this set of eight equations the six unknowns, no matter the hypothesis used, can be calculated. Four of these unknowns are the boundary pressures and the characteristics of the water column (p^*_0, p^*_1, L o $\forall$ and v). The two last unknowns are the variables that characterize the air pocket at any time (ρ y m_a). Four of the eight available equations are common to all considered cases ((1), (2), (3) y (6)), while, depending on to the hypothesis realised, the other four equations ((4) - (5) and (7) - (8)) are alternatively used. All in all, six independent equations balance the six unknowns of the problem.

ANALISYS OF THE RESULTS

The system depicted by Figure 1 is considered. Once the pump is running at its nominal speed the transient starts with the opening of the valve. Different manoeuvre's times are considered. For the purpose of this paper, the more relevant variables are the maximum pressure reached by the air and the residual velocity. This velocity corresponds to the water column, once the air has been released, and just in the moment that the column reaches the dead end of the pipe.

Attending three different circumstances, twelve cases are analysed:

a) Air valve size. Two diameters (1" y 2") are considered.
b) Initial length of the water column. The system is studied for two values (1 m and 750 m)
c) Opening time. Three different values have been selected. The instantaneous one and two lineal manoeuvres (5 minutes and 20 minutes of duration).

For each case, both adiabatic and isotherm behaviours of trapped air inside the pipe are explored. In particular Figure 2 show the evolution of the most significant variables for an 1" size air valve, an initial water length of 750 m, (L_0 = 750 m) and an instantaneous opening (T_c = 0). The results depicted show a high sensitivity with the assumed hypothesis. The isotherm peak of pressure is higher than the adiabatic one, and then, finding the water a bigger resistance, the residual (final) velocity is small. Because of that, although from a first glance the current isotherm hypothesis should appear as the most conservative one (it provide a higher pressure, -116 m against 96 m-), if water hammer effects are considered the opposite applies. For instance for a wave celerity a = 1000 m/s and for the residual calculated velocities (0,83 m/s and 1,68 m/s), the water hammer give important peaks of pressure (83 m y 168 m). In summary, the adiabatic process put the pipe to a highest stress (168 m) than the isotherm one.

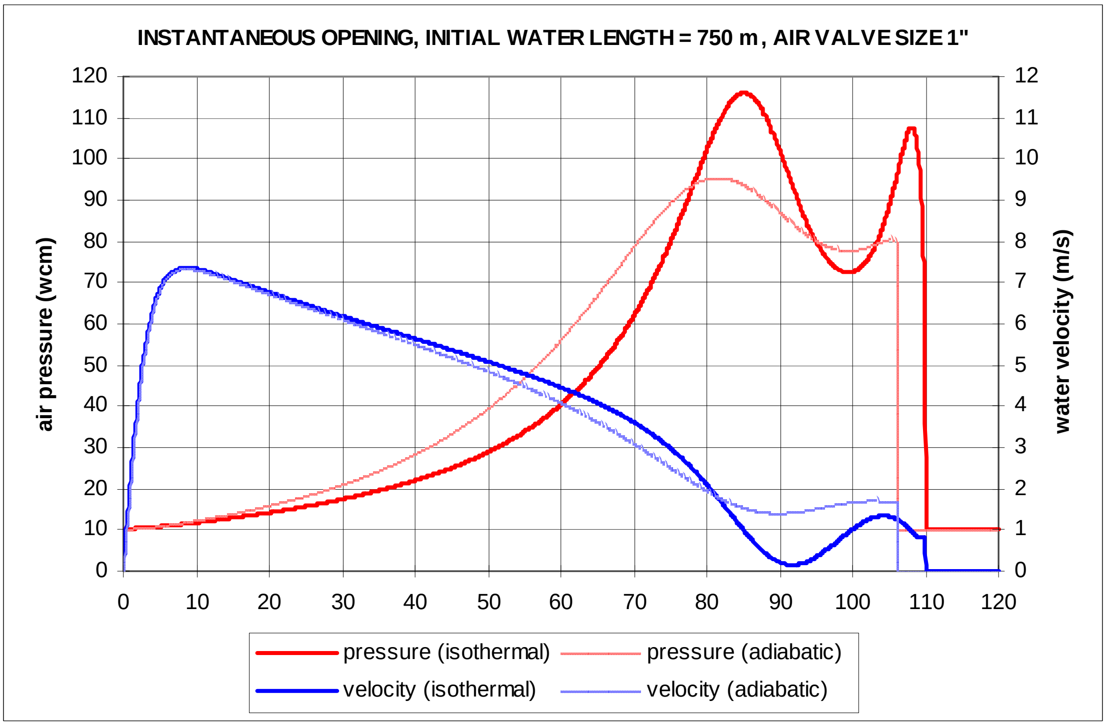

Figure 2.- Case corresponding to air valve size 1", L_0 = 750 m, T_c = 0 s. Main results .

Tables 1 to 4 show the results of the considered cases. From their analysis can be concluded:

- The results show an important sensitivity to the air behavior (isotherm or adiabatic).
- In any case, the highest air peak pressure corresponds to the isotherm process. For the residual velocity the opposite applies. Because of that, the less favorable assumption is the not used in practice, the adiabatic one.
- As can be seen, the maximum air pressure depend first on the air valve size, second on the considered process and last on the maneuver's time of the valve.
- The most critical factor, the residual speed of the water column, follow a similar tendency.
- Just as far as the transient duration concerns, a different trend can be appreciated. The most influent parameter is L_0 , although the results show sensitivity to the air valve size and to the maneuver's time of the valve as well. Nevertheless, the supposed process has not any influence on the transient duration.

		Opening time T_c = 0	Opening time T_c = 5 m	Opening time T_c = 20 m
Maximum pressure	Isothermal	110 m	109 m	105 m
	Adiabatic	106 m	105 m	99 m
Residual water velocity	Isothermal	0,94 m/s	0,94 m/s	0,94 m/s
	Adiabatic	1,68 m/s	1,68 m/s	1,67 m/s
Transient duration	Isothermal	230 s	275 s	357 s
	Adiabatic	215 s	260 s	342 s
Maximum air temperature	Isothermal	15 ºC	15 ºC	15 ºC
	Adiabatic	287 ºC	286 ºC	276 ºC

Table 1.- Air valve size 1". Initial water length 1 m.

		Opening time T_c = 0	Opening time T_c = 5 m	Opening time T_c = 20 m
Maximum pressure	Isothermal	116 m	113 m	101 m
	Adiabatic	96 m	93 m	81 m
Residual water velocity	Isothermal	0,83 m/s	0,84 m/s	0,95 m/s
	Adiabatic	1,68 m/s	1,69 m/s	1,64 m/s
Transient duration	Isothermal	110 s	138 s	196 s
	Adiabatic	106 s	134 s	192 s
Maximum air temperature	Isothermal	15 ºC	15 ºC	15 ºC
	Adiabatic	271 ºC	266 ºC.	246 ºC

Table 2.- Air valve size 1”. Initial water length 750 m.

		Opening time T_c = 0	Opening time T_c = 5 m	Opening time T_c = 20 m
Maximum pressure	Isothermal	49 m	47 m	39 m
	Adiabatic	38 m	36 m	30 m
Residual water velocity	Isothermal	3,3 m/s	3,4 m/s	3,3 m/s
	Adiabatic	3,9 m/s	3,9 m/s	3,7 m/s
Transient duration	Isothermal	153 s	200 s	285 s
	Adiabatic	152 s	199 s	284 s
Maximum air temperature	Isothermal	15 ºC	15 ºC	15 ºC
	Adiabatic	144 ºC	139 ºC	118 ºC

Table 3.- Air valve size 2”. Initial water length 1 m.

		Opening time T_c = 0	Opening time T_c = 5 s	Opening time T_c = 20 s
Maximum pressure	Isothermal	50 m	45 m	29 m
	Adiabatic	30 m	28 m	21 m
Residual water velocity	Isothermal	3,6 m/s	3,5 m/s	3,1 m/s
	Adiabatic	4,0 m/s	3,9 m/s	3,3 m/s
Transient duration	Isothermal	82 s	111 s	172 s
	Adiabatic	82 s	111 s	172 s
Maximum air temperature	Isothermal	15 ºC	15 ºC	15 ºC
	Adiabatic	117 ºC	108 ºC	80 ºC

Table 4.- Air valve size 2”. Initial water length 750 m.

Other additional remarks can be stated:

a) The importance of the air valve size. From the results it is clear that the most convenient air valve size is 1”. If a 2” air valve should be selected, the highest maximum pressure would rise three times more. In other words, the size of the valve is a compromise solution. If the air size is big, the water column is not braked and an important residual velocity will provoke a significant water hammer. By the contrary, if the size is too small, the air is compressed excessively, and very high peaks of pressure can arise.

b) In a pipe with an 1” air valve and with a wave celerity a = 1000 m/s, the order of magnitude of the maximum air pressure is the same than the originated by the residual velocity. For a 2” air valve size, the water hammer pressure is ten times more than the air peak pressure.

c) As Figure 2 depicts, small air valve’s sizes, can generate two peaks of pressure because the air valve has not enough section for a fast air release, giving rise to a second peak of pressure a later compression of the remaining air.

d) The type of process of the trapped air (adiabatic or isotherm) it is not a minor question. The peak of pressure strongly depends on the assumed behavior. In fact it can be concluded that:
   - For the small size air valve (1” diameter) and with L_0 = 750 m and T_c = 0, supposed an adiabatic evolution, the maximum pressure is due to the residual velocity. For a current celerity wave (a = 1000 m/s), it reaches 168 m. With an isotherm behavior, the maximum pressure of the system corresponds to the trapped air (116 m).
   - For the second air valve considered (2” diameter) the maximum pressure, no matter the process assumed, is given by the water hammer induced for the residual water velocity. In this case, with the same parameters (a = 1000 m/s, L_0 = 750 m and T_c = 0), the final values are respectively 400 m and 360 m.
   - Taking into account the transient durations neither fast nor slow, -110 seconds and 106 seconds for the small air valve, and 82 seconds for the bigger one-, both hypothesis look a priori reasonable.

CONCLUSIÓN

Taking into account the influence on the final results of the process followed by trapped air inside the pipe, a research with regard to the field of validity of each hypothesis looks necessary. This research, supported by experimental measurements, should include a deep energetic balance of the transient. The authors have performed some measurements under the framework of the research project “Dynamic behavior of air valves”, supported by the EC (Access to Major Research Infrastructure Program, project HPRI-CT-1999-00103) that will be used to clarify this question. The main objective of the additional research will be put on the identification of the range of validity of each process, considering the intermediate process (polytropic) as well.

The importance of an adequate selection of the size of the air valve has been highlighted. It is important to remark that the highest peak of pressure is currently due to the shock of the water column against the dead end of the pipe. That can be find in practice with very inertial long water blocking columns.

And last, but not least, it is important to underline that the hypothesis currently adopted (isotherm process) gives rise to the highest peak of pressure of the air, although it is not the worst scenario. Due to that, the proposed additional research looks necessary. The energetic balance should be important to clarify the obtained results. A first analysis show that in the adiabatic process the air temperature at the end of the transient can be significant, and this additional thermal energy diminishes the elastic energy invested in the air compression. The additional compression, in form of a higher pressure of the trapped air, contributes to brake the water column and then to minimize the water hammer derived from the shock of the water column. In any case, all these questions will wait for a deeper, theoretical and experimental, work.

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