Laboratory studies of water column separation

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Abstract. Results of experimental studies of water column separation following an upstream valve closure are presented. Different geometrical arrangements with transparent PVC pipes are installed immediately downstream of the closing valve, namely, horizontal pipes, vertical pipes flowing down, and humpback profile pipes, the last two being used in order to obtain full pipe section vapor cavities. Maximum over pressures at water column rejoining, and maximum cavity lengths and duration, are compared with theoretical values and with previous experiments with horizontal pipes. Good agreement is found between theory and experiments, and interesting visual material is obtained.

1. Introduction.
Water column separation is a phenomenon occurring in pressurized water conveyance systems, originated by abrupt changes in the system boundary conditions, namely, sudden valve closures or pump failures, combined normally with low heads and/or topography profiles close to hydraulic grade lines. Water column separation has been studied since Joukowsky’s first paper on water hammer [1, 2], and has been in the last decades the subject of special conferences and IAHR Working Groups [3, 4].

In this paper, previous laboratory studies by the authors [5] are continued, in order to obtain final and conclusive laboratory data to confirm the theoretical curves and equations expressed in dimensionless variables. The conclusions of the mentioned published paper can be summarized as follows:

a) Water column separation is a transient phenomenon that can be explained and classified using dimensionless parameters: $M$, the magnitude of the transient, equal to $\frac{\sqrt{\rho g h_0}}{H_0}$; and $\Delta H_r$, the relative maximum overpressure, equal to $\frac{\Delta H_{\text{max}}}{\Delta h_f}$.

b) For low magnitude transients, superposition of positive pressure waves can occur during column separation, which are able to cause overpressures close to two times the Joukowsky value. For high magnitude transients, instead, energy losses considered, the Joukowsky overpressure will not be reached.

c) The highest $\Delta H_r$ values are obtained for low magnitude transients and for low water velocities. Medium and high magnitude transients, associated with large vapor cavities, long cavity times and large water velocities, do not cause pressures larger than Joukowsky’s, as the positive pressure waves attenuate significantly before being able to collapse the cavity.

d) Maximum relative overpressure can be expressed in terms of the transient magnitude, $M$:
\[ \Delta H_r = 1 + \frac{2}{M} \]  

(1)

In which the maximum overpressure \( \Delta H_r \) is the ratio of absolute pressure increase to Joukowsky’s overpressure, and the water hammer magnitude \( M \) is the ratio of Joukowsky’s overpressure to initial absolute head.

In addition, in these new series of experiments, new pipe arrangements are tested at the location where the water column separation occurs, namely, vertical pipes flowing downwards and humpback profile pipes (Figure 3).

The intention of these new arrangements is the following:
1.1. Obtain full pipe section vapor cavities and measure the \( m \), precisely, in order to compare them with the theoretical lengths. In previous experiments, the cavities formed after the upstream valve closure were “partial pipe section” vapor cavities (Figure 1).
1.2. Confirm the dynamics of growth and collapse of the vapor cavities, and compare them with the case of the vapor cavities developed in horizontal pipes.
1.3. Confirm the theoretical maximum overpressures, as established by equation (1), expressed in dimensionless parameters.

![Figure 1. Vapor cavity developed in horizontal pipe. Upstream closing valve shown at right. Scale in centimeters. Maximum cavity length, 105 cm. Initial water velocity, 1.51 m/s. Initial absolute head, 21 m. Transient magnitude M, 4.57.](image)

2. Theoretical developments.
Maximum pressure resulting from water column separation and the subsequent rejoining of the columns have been treated previously by the authors. The main conclusion is that the maximum theoretical overpressure is defined by equation (1). Other theoretical problems concern the development of the vapor cavity until it reaches its maximum size, the process leading to its collapse, and the corresponding development and collapse times. Jaeger [6] establishes that the maximum cavity length and its corresponding time can be calculated with the dynamic equation of hydraulic transients,

\[ \frac{L}{g} \frac{du}{dt} + H + Fv^2 = 0 \]  

(2)

Following an upstream valve closure, or a pump failure or shutdown, the flowing water column will be decelerated by the static head \( H \) and by the friction head \( Fv^2 \). The vapor cavity will grow until the water velocity is zero, reaching its maximum size. Integration of equation (2) leads to an exact solution allowing the calculation of the maximum length of the vapor cavity, \( L_{c \max} \), and the time to reach this maximum length, \( t_{dev} \).
From the equations presented by Jaeger, we can state the mathematical formulas to calculate the time required for the development of the cavity to its maximum size, $t_{\text{dev}}$, and the maximum cavity length, $L_{c\text{max}}$, assuming a full pipe section cavity, for the friction and frictionless cases.

\[
\begin{align*}
    t_{\text{dev}} & = \frac{L}{g} \frac{v_0}{\sqrt{\frac{F}{H}}} \arctan\sqrt{\frac{F}{H}} & F \neq 0 \\
    L_{c\text{max}} & = \frac{L}{2gF} \ln\left(\frac{Fv_0^2}{H} + 1\right) & F = 0
\end{align*}
\]

3. Experimental installations

The experiments were developed in two laboratory installations, in San Luis Potosí (1900 m above sea level) and at the UNAM, in Mexico City (2200 m above sea level), meaning that the vaporization pressure is in both cases very close to -8 m, manometric.

Both installations are equivalent in general arrangement, consisting in 114 mm diameter pipes, 104 or 277 m long, with hydropneumatic constant head tanks at its upstream and downstream ends, with automatic butterfly valves at both ends, which allow for downstream or upstream valve closures (Figure 2). Transparent PVC sections are also installed at the pipe extremes, for cavity visualization purposes. These sections can have the different geometrical arrangements mentioned: horizontal pipe, vertical downstream pipe, and humpback profile pipe.

Pressure transducers record the pressure history. Video recordings register timing, growth, maximum size and collapse of the cavities. Velocity is measured with differential mercury manometers. Two 11 kw pumps can be used in series or in parallel, allowing pressures up to 8 kg/cm$^2$ (80 m) and flows up to 20 lt/s, with water velocities ranging from 0.56 to 3.60 m/s.

Pipe material is steel, for the San Luis Potosí installation (length, 277 m, pressure wave celerity, 989 m/s, system period $2L/c$, 0.56 s), and PVC for the Mexico City installation (length, 104 m, pressure wave celerity, 344 m/s, system period $2L/c$, 0.61 s). Wide ranges are available for Joukowsky overpressures (25 to 245 m) and for transient severity $M$ (1 to 10).

The physical arrangements for the vertical pipe and for the humpback profile pipe are shown in Figure 3.
4. Experimental results
Figure 4 shows the maximum relative overpressures resulting from the experiments, for the horizontal pipe, the vertical pipe and the humpback arrangements. They follow the tendencies resulting from previous experiments, shown in Figure 5.

**Figure 3.** Geometrical arrangements downstream of closing valve.

**Figure 4.** Maximum relative overpressures versus, $M$. Experiments reported in this paper.

**Figure 5.** Maximum relative overpressures versus, $M$, in previously reported experiments [5].
Regarding the development and collapse of the vapor cavity, results are presented in Figure 6, for a vertical pipe arrangement. Figure 7 shows the theoretical and the experimental maximum vapor cavity lengths versus transient magnitude $M$.

Figure 6. Growth and collapse of vapor cavity, and recorded pressure, versus time.

Figure 7. Theoretical and experimental maximum cavity lengths versus transient magnitude $M$.

Figure 8. Maximum length of vapor cavity versus water velocity.

Figure 9. Theoretical versus experimental maximum cavity lengths.

Figure 8 shows the relation between the maximum cavity length and the water velocity, and Figure 9 shows the theoretical maximum cavity length versus the experimental maximum cavity length, for the vertical and humpback pipes, in which full pipe section vapor cavities were obtained.

It is clear that the experimental results agree very closely with the theoretical calculations, particularly in the case of the vertical pipe. Figure 10 and 11 show the full pipe section cavities obtained. For the case of horizontal pipes, Figure 1 shows a typical case, in which the full pipe section cavity is not reached, although its length can be approximated by twice the theoretical length, being the cavity roughly a half pipe section cavity. For the specific case of the figure, the total experimental cavity length is 1.8 times the theoretical length.
5. Conclusions and design recommendations

a) The theoretical maximum overpressure, as expressed in equation (1), resulting from the vapor cavity collapse following water column separation, was confirmed with new experiments and new pipe configurations at the location of the vapor cavity (Figures 4 and 5).

b) The maximum theoretical length of a vapor cavity was confirmed by the experiments, obtaining full pipe section cavities for vertical pipe and for humpback profile pipe arrangements, immediately downstream of the closing valve. For the case of horizontal pipes and medium to large magnitude transients, the cavity length can be assumed roughly as twice the theoretical length, as the cavity can be considered a “half pipe section” vapor cavity.

c) Very long cavities, both in length and time, were obtained for large magnitude \( M \) transients, with low initial heads and large water velocities. Although the maximum relative overpressures do not exceed or even attain the Joukowsky overpressure, these experiments and the associated video and pressure recordings are important from the conceptual and academic point of view, as they illustrate clearly the water column separation phenomenon and the correspondence between theoretical developments and experiments.

d) Adequate predictions of the variables involved in water column separation (maximum and minimum pressures, cavity length and duration) can be made during the preliminary design stage using the theoretical formulas and experimental figures presented. As they are expressed and presented in terms of dimensionless parameters, they cover all possible practical cases.

e) Final design must of course be verified by specific tests and numerical calculations.

Notation

- \( H \) Pressure head, m
- \( H_0 \) Absolute initial pressure at upstream valve, m
- \( H_{max} \) Absolute maximum transient pressure, m
- \( \Delta H_{max} \) Maximum transient overpressure, equal to \( H_{max} - H_0 \), m
- \( \Delta h_j \) Joukowsky overpressure, m
- \( \Delta H_r \) Relative maximum overpressure, equal to \( \Delta H_{max} / \Delta h_j \), dimensionless
- \( M \) Magnitude of transient, equal to \( \Delta h_j / H_0 \), dimensionless
- \( v_0 \) Initial water velocity, m/s
- \( t_{cav} \) Total duration of cavity, s
- \( t_{dev} \) Time for development of cavity, to its maximum size, from valve closure, s
- \( L \) Length of pipe in physical model, m
- \( c \) Celerity of pressure waves, m/s
- \( D \) External diameter of pipe
- \( F \) Friction factor, equal to \( fL/(2gD) \), \( s^2/m \)
- \( f \) Friction coefficient in Darcy-Weisbach formula
- \( L_{c,\text{max}} \) Maximum length of vapor cavity

References

[1] Joukowsky N 1904 Water Hammer (St. Louis AWWA)
[2] Bergant A, Simpson A R and Tijsseling A S 2006 Journal of Fluids and Structures 22 135 – 171
[3] Cabrera E and Fanelli A editors 1991 Hydraulic transients with water column separation 9th and Last Round Table of the IAHR Working Group (Valencia, Spain, 4-6 September 1991)
[4] Fanelli M 2000 Hydraulic transients with water column separation \textit{IAHR Working Group 1971-1991 Synthesis Report}

[5] Autrique R and Rodal E 2012 Physical model studies of water column separation \textit{XXVI IAHR Congress on Hydraulic Machinery and Systems (Beijing, China, 19-23 August 2012)}

[6] Jaeger C 1977 \textit{Fluid Transients in Hydroelectric Engineering Practice} (London: Blackie)

[7] Wylie E B and Streeter V L 1993 \textit{Fluid Transients in Systems} (New Jersey: Prentice Hall)