ISSN 1453 – 7303 **"HIDRAULICA" (No. 2/2019)**
Magazine *of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics*

Study of Mass Water Oscillations and Water Hammer Occurrence in Hydraulic Installations

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Abstract: *In present paper the author presents both a theoretical approach of water mass oscillations and of water hammer phenomenon, also experimental analyses on a laboratory stand. There are calculated and measured the hydraulic losses and pictured versus fluid velocity and Reynolds number. Instant images from the oscilloscope are presented and the period of movement oscillations of the masses of water is calculated. The analyses show that the mathematical modeling of oscillations is close to experimental simulation.*

Keywords: *Water hammer, fluid oscillations, hydraulic losses*

1. Introduction

The water hammer is a non-permanent, undulating phenomenon of water, which is manifested by the increase followed by the pressure drop in pressure hydraulic installations, forced ducts of hydropower plants or pumping stations. The phenomenon occurs at the sudden closure or opening of the valves at the downstream end of the pipes**.** The water hammer creates an overpressure, alternately positive and negative, which adds to the permanent pressure in fluid movement and is independent of this pressure.
The overpressure created by water hammer must be considered especially in the forced pipelines of the hydropower plants. Phenomenon occurs at the rapid closing of the hydrants, at the passing over a hose of a heavy vehicle, the hose lines forming bends in pipes, with valve closing and in other situations. This phenomenon will be analysed in pipelines, in this paper. The theoretical study of the phenomenon is presented in detail in the works [1], [3], [4], [6] and experimental in [5],[6],[7].

2. Theoretical approach of water mass oscillations

A tank installation and piezometric tube for analysing the oscillations of the water body is illustrated in Fig. 1.The following assumptions are made: the volume of water in the reservoir is much higher than in the pipe and the piezometric tube, so the energy of the water in the tank is neglected; the considered losses are linear ones in the pipe and the local one at the entrance to the pipe diameter D = 2R. Y_0 called piezometric height and reflects the kinetic energy loss.

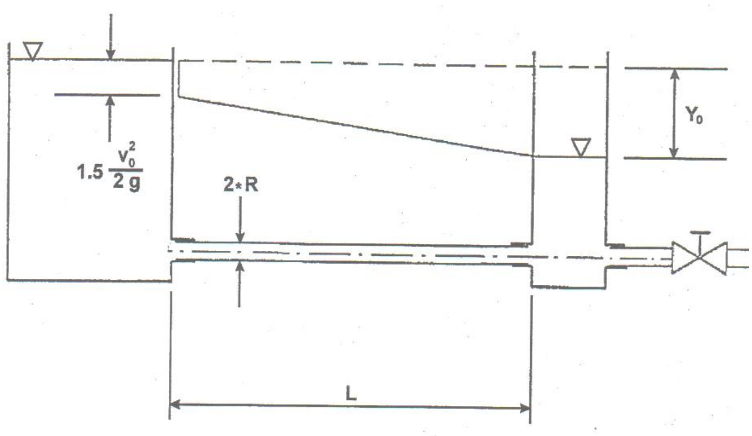


Fig. 1. Scheme of tank and the piezometric tube

Under normal conditions, Y_0 can be determined directly on the piezometric tube for different flow rate values in the pipe. Any operation of the valve leads to a change in the operating conditions, disrupts the flow in the pipe first and then into the tank. A level difference is created between the water level in the reservoir and that in the piezometric tube, some oscillations are produced which are amortized by the water level in the tank and the fluid velocity in the pipe. Two situations at the limit are considered: 1) Closing of the valve leading to zero flow 2) Opening of the valve which causes the flow to rise from zero to the maximum value. An oscillation between the maximum and minimum level in the tank compared to the normal / static water level with the maximum Y_{max} value and the oscillation period τ during t time, are shown in Fig. 2. When closing the valve, the value ΔY_{max} can be determined with the relationship:

$$\Delta Y_{\max} = v_0 \sqrt{\frac{S}{s}\frac{L}{g}} \tag{1}$$

and the period of oscillation is

$$\tau = 2\pi \sqrt{\frac{S}{s_p}\frac{L}{g}} \tag{2}$$

S – tank section, s_p – pipe section, L – pipe length, g – gravitational acceleration, v_0–water velocity in the duct under normal conditions (before or after valve handling)

2.1. The study of oscillations in the event of the occurrence of the water hammer

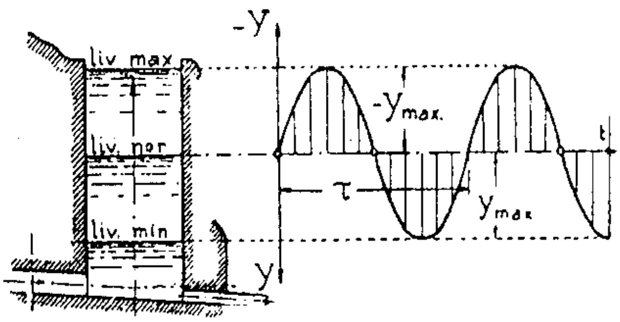


Fig. 2. Variation of the height Y to the fluid oscillations in the tank

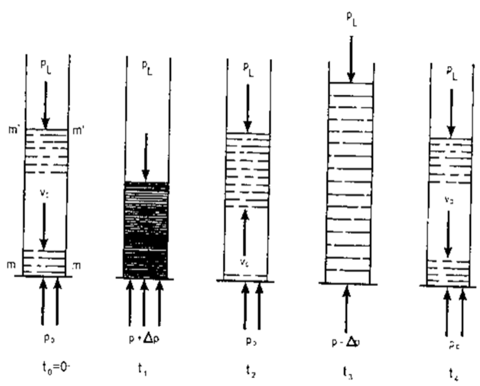
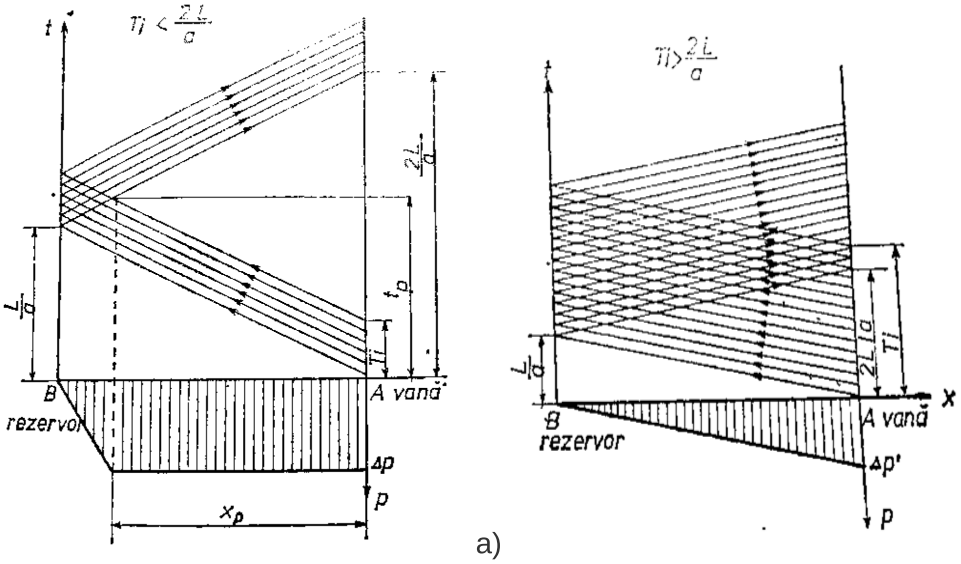


Fig. 3. Pressure oscillations [1]

The phenomenon of water hammer strike that occurs when the valves are suddenly closed is accompanied by a variation in pressure, first a compression of the water column, then a return to the normal condition, a drop-in pressure and finally a return to the initial pressure. These

oscillations and variations of pressure can be seen in Fig. 3, with a sequence of states - normal, compressed, normal, dilated, and again normal.
Comparative analysis of valve shut-off times - in a sudden manoeuvre, see Fig. 4a) and in slow manoeuvring in Fig. 4b). After the liquid hits the tap, it first suffers a contraction, then a distraction that is transmitted upstream to the pipe until it reaches the tank.
The shot of the water hammer is even more violent as the pipe is longer and closure faster. Instead, the phenomenon is reduced in short ducts and slow maneuvering of valves and taps, at the inlet on the duct of a capacity to accumulate liquid and the outlet of the liquid through a pipe passage.



a) b)

Fig. 4. The phenomenon of the water hammer at the sudden and slow closure of the valve, *Li*-closure time, *a* water velocity [1]

To the sudden closure, the closure time is $T_i < t_f = \frac{2L}{a}$

With t_f – phase time. A part of the length x_p pipe to the tap is under the action of a larger Δp overpressure to the valve, so this part of the pipe is more stressed compared to the tank side, where the direct waves interfere with the reflected ones and the overpressure is smaller (fig. 4a).

To the slow closure$T_i > t_f = \frac{2L}{a}$, the entire length of the pipe is interfering with the direct waves with the reflected ones, and the maximum overpressure Δp is no longer reached in any section, not even the valve. The overpressure decreases linearly over the length of the pipe, as in Fig. 4b).

Mathematical solving of water mass oscillations involves the writing of propagation equations

$$\frac{\partial^2 v}{\partial x^2} = \frac{1}{a^2}\frac{\partial^2 v}{\partial t^2} \qquad (3)$$

And the continuity equation where the velocity is v (x, t) and the pressure are y = y (x, t) = (p (x, t)) / γ and checks the same type of partial derivative as the vibrating chord equation.
By introducing boundary conditions and interfering equations, solutions can be found.
The water hammer propagation velocity can be calculated with Allievi's relationship [1],[3].

$$a = \frac{9900}{\sqrt{48.3 + k\frac{D}{\delta}}} \qquad (4)$$

K-is a constant value depending of the material (0.5 for steel, 5 for concrete, 10 for wood),

δ - is the thickness of the pipe wall.

The maximum overpressures that occur in the water hammer phenomenon can be calculated theoretically in this way:

$$\Delta p = \gamma(y - y_0) = \rho a V_0 \qquad (5)$$

The more popular practical methods to calculate the water hammer are the numerical methods of Allievi or Morozov, or the Lowy and Schnyder-Bergeron graphical methods [1],[3].

3. Experimental setup

If a valve R is fitted at the end of a pipe D (m) and length L (m) with which the flow rate is regulated, the water flow rate in the pipeline is considered v (m / s), it is noted that at a sudden closure of the valve, the liquid rises in a piezometric tube 8, placed as in Fig. 5, above the level of the liquid in the reservoir 1, i.e. above the horizontal line. In this case, the line pressure is much higher than H, which is the pressure at the end of the pipe, when the tap is closed and the liquid is in the static state. Details of the stand can be seen in Figure 6 a), b) and c).

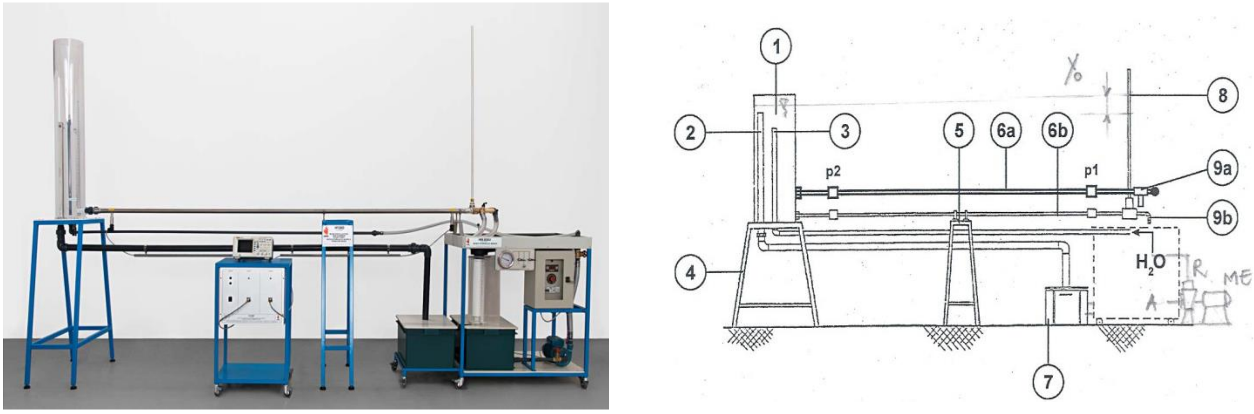


Fig. 5. Experimental stand a) image of the laboratory stand b) scheme [2]

 a)  b)  c)

Fig. 6. Experimental stand details a) reservoir, b) piezometric tube, valves, pressure transducers, c) drive pump [2]

The laboratory installation from the Hydraulic Laboratory of the UPB, according to Fig. 5b), consists in:

1. Tank from plexiglas
2. Overflow funnel
3. Flushing pipe
4. Support for tank
5. Support for stainless steel pipes, length L= 3 m diameter D = 25.4mm
6. a Pipe to test the water hammer phenomenon.
   b Pipe to test the oscillations of the slow valve closure
7. Supply tank, where a centrifugal pump sucks water (A-suction R-pump discharge, driven by an electric motor ME
8. Piezometric tube to visualise the oscillations
9. Valves / taps a- with sudden closing for ram, b- with slow closing, stepped

p1, p2 are 2 pressure transducers that output the information to a control unit with 2 channels of signal voltage conversion in electrical voltage. This unit / source is powered and converts the pressure into volts ± 15V, transmitting the signal to an oscilloscope. The sensitivity / precision of the oscilloscope image can be adjusted, depending on the maximum value, for each channel we have an image on the device in the form of a sine wave that is amortized over time. The calibration of the transducers is: for p1 10Bar / 100 mV, for p2 = 5 bar/100 mV.
By means of the valves 9 the flow can be varied abruptly (9a) or slow (9b), so it is possible to test and compare the phenomenon of the water hammer with the slow oscillations of the water masses.

3.1 Calculation formulas for experimental data processing

For tests the flow rate is measured, and then the fluid flow velocity is calculated.
It read the water levels in tank 1 and the piezometric tube and calculates the deviation y_0.

$$v = \frac{4Q}{\pi d^2} \text{ (m/s)} \tag{6}$$

Reynolds's number highlights that it is a turbulent flow, with high values being at the sudden closure of the valve:

$Re = \frac{vD}{\upsilon}$, υ - water kinetic viscosity = 1.006e^{-6}m^2/s.

It calculates the linear hydraulic load losses with the coefficient from Blasius relation:

$$\lambda = \frac{0.3164}{Re^{0.25}}, \tag{7}$$

Then the total hydraulic load losses are equal to the sum of the linear load for the 3 meters of the pipe and the local linear load at the inlet of the pipe as follows:

$$y_c = \lambda \frac{L}{D}\frac{v^2}{2g} + \xi\frac{v^2}{2g} \tag{8}$$

I consider local loss ξ=0.5.

Pressure values can be viewed on the oscilloscope; the corresponding scale also takes into account the water level in tank 1: if the water level is below 40%, the maximum pressure at p1 is 2 bar; if the water level in the tank is above 60%, the maximum pressure at the p1 transducer is 8-10 bar.
It is also possible to calculate the period of movement oscillations of the masses of water in the pipelines with the relationship (2) or

$$\tau = \frac{2L}{v} \tag{9}$$

3.2 Processing of experimental results

Table 1 centralizes measured and calculated physical quantities as follows:

Table 1: Data processing

	Tank level mm	tube piezom level mm	y_0 m	Q ml/s	v m/s	Reynolds	λ	τ	obs	$y_c$computed (m)
1	1050	1025	0.025	80	0.158	3988	0.0398	37,97	vana lentă	0.00662
2	1050	1015	0.035	100	0.197	4985	0.0377	30,45	vana lentă	0.00983
3	1060	1010	0.05	215	0.425	10719	0.0311	14,12	vana lentă	0.03833
4	1040	960	0.08	334	0.659	16651	0.0279	9,1	vana rapidă	0.08401
5	1040	955	0.085	340	0.671	16950	0.0277	8,94	vana rapidă	0.08672
6	1050	960	0.09	350	0.691	17449	0.0275	8,68	vana rapidă	0.09132
7	1060	975	0.085	370	0.731	18446	0.0271	8,2	vana rapidă	0.10083

The graphical representations of the measured hydraulic deviations / losses, calculated according to Reynolds numbers, respectively, according to the velocity of the propagation of the water in the pipe, as in Fig 7 and 8.
Some snapshots of the oscilloscope can be taken, as in Fig. 9, to see the results of the conversion of the pressure (bar) from the transducers to the electric voltage signals (V). The closure time of the valve is shown in Fig.9. We notice that the oscilloscope also has a damping of the pressure wave after about 540 ns. The oscilloscope images illustrate the damping of water mass oscillations, longer lasting at the p2 transducer furthest from the valve.

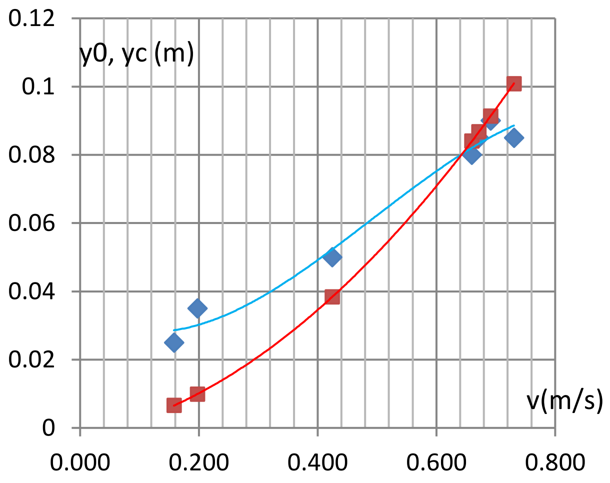


Fig. 7. Hydraulic losses versus water velocity

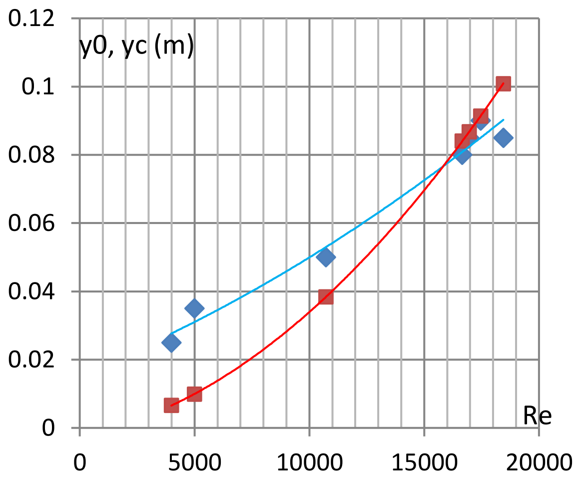


Fig. 8. Hydraulic losses versus Reynolds number

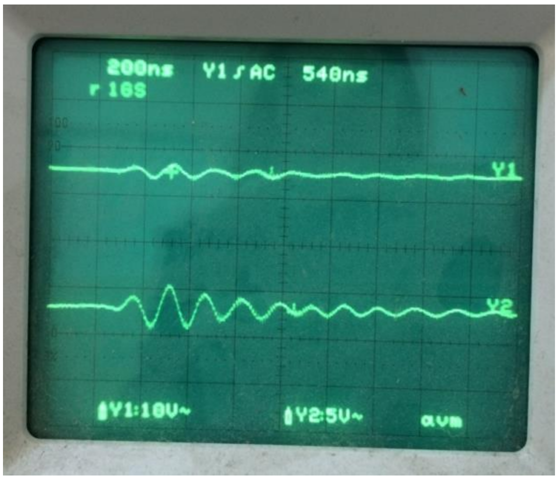


Fig. 9. Instant image taken from the oscilloscope

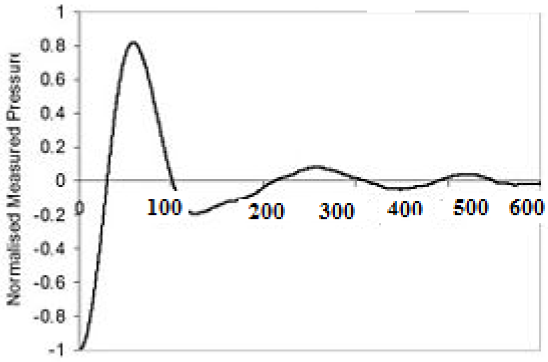


Fig. 10. Damping time (ns)

4. Conclusions

From this study it can be seen that the measured hydraulic losses are quite close to the calculated losses, especially in the case of the last four sets of values recorded at the sudden closure of the valve, that is, at the water hammer.

This demonstrates that mathematical modeling of oscillations is close to experimental simulation. The oscilloscope images illustrate the damping of water mass oscillations, longer lasting at the p2 transducer furthest from the valve.

Further development of the study can be done on the analysis of the instability of the water mass movement at the water hammer and on the transposition of the results on similarity criteria at large scale installations.

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