IMPACT OF PLASTIC MATERIAL ON MITIGATING A WATERHAMMER IN A PRESSURIZED PIPE

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Abstract: *Water hammer, or hydraulic shock, is an overpressure caused by a sudden change in flow boundary conditions. To control this phenomena and improve the reliability and longevity of pipeline conveying transient flow , a replacing part of the main pipe with a plastic pipe segment can be an effective solution. This work is carried out in the case of a one-dimensional transient flow. The set of partial differential equations to be solved is of the hyperbolic type and is ideally suited to the method of characteristics. The effect of the plastic pipe element on the overpressure generated by the water hammer is examined*

1 INTRODUCTION

Hydraulic networks are subject to pressure variations in transient regimes and these variations can be very critical in some cases. The increase in their diameter and operating pressure increases the risk of fracture initiated from defects (notches, cracks, inclusions, cavities,).The fast closure or opening of valve, or sudden shutdown or start of pump or turbine lead, usually, to a sudden rise or drop of pressure in the flow, estimated usually in classical theory by the well-known Joukovsky formula, [1-4],$\Delta P = a\,\rho\,\Delta V$,where ΔV is the initial variation of the velocity of the fluid,ρ the density of the fluid and a the celerity of water hammer named, also acoustic wave speed pipe-fluid and given by :

$a = \sqrt{(\kappa/\rho)}\ \sqrt{1 + \xi\kappa\ D_m/eE}$, where κ denotes bulk modulus of the fluid,D_m: average diameter of pipe, e: thickness of pipe, ρ: density of the fluid and ξ:is a coefficient depending on the pipe constraints. In certain cases, this pressure limit can be surpassed, especially during cavitation events[5-6].The choice of pipes according to transient pressures can significantly increase the cost of the network. To do this, it is sometimes more interesting to equip the network with anti-ram protection means in order to limit the intensity of these transient pressures. The role of protective devices is to absorb or compensate for a large part of the variation in flow rate, which in turn is the cause of transient regimes. There is a wide range of devices to protect against water hammer, but they differ according to the nature of the pressure [7-9]. The device we present here has the advantage of being effective. It can respond to congested conditions that make it difficult, in some cases, to use other means. This shock absorber is simply made up of a section of high-density polyethylene pipe placed downstream in series with the pipe to be protected. This device is therefore crossed by the entire wave and flow of the pipe, unlike other anti-ram systems which are installed in bypass. Both linear elastic and Kelvin Voigt linear viscoelastic behavior of the pipe material are examined.

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2 BASIC FORMULATION

This work was carried out assuming that the fluid is barotropic, isentropic and Newtonian. The pipe material is isotropic, linearly elastic and linearly viscoelastic for the additional polymer element. Furthermore, the pipeline is assumed to be circular and cylindrical in the horizontal plane, with one end firmly anchored to an upstream tank, while the other end is provided with a shut-off valve on a fixed support. The flow is assumed to be one-dimensional and axisymmetric along the pipe axis and the velocity of the fluid is negligible compared to the speed of the water hammer. Under the previous assumptions, by denoting ρ : the density of the fluid, t: time, x:longitudinal coordinate, S: cross section of pipe, V: average velocity of the flow, P:average pressure of pressure across a section, D:innerdiameter of pipe, τ_p : the stress friction of the fluid on inner surface of pipe, the governing equations for main pipe and device element, averaged a cross section S of pipe lead, in condensed form, to:

Law conservation of mass:

$$\frac{(\rho\ S)}{\partial t} + \frac{\partial(\rho S V)}{\partial x} = 0 \qquad (1)$$

Law conservation of momentum:

$$\rho \frac{\partial V}{\partial t} + \frac{\partial P}{\partial x} + g\ \frac{\partial z}{\partial x} = 4\frac{\tau_p}{D} \qquad (2)$$

and

$$\tau_p = \lambda \frac{V(t)|V(t)|}{2(t)} + \frac{4\mu}{(t)} \int_0^t W(t-t') \frac{\partial V(t')}{\partial t'} dt' \qquad (3)$$

the stress friction of the fluid against the inner pipe wall, where W(t) is the weight function introduced by Zielke[10], Vitkovsky et al.[11] to take into account, the profile variations of velocity of flow across section of pipe, $\lambda =$ coefficient of friction that depends on the regime of the flow [1-2].

The creep function of the device material can be discretized to a linear generalized Kelvin-Voigt model as:

$$J(t) = \frac{1}{E} + \sum_{l=1}^{Nk} \frac{1}{E_l}(1 - e^{-t/\tau_l})(4)$$

Which the shape shown in figure 1 below [12-14]

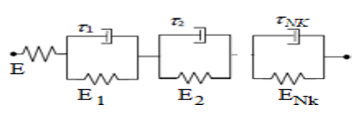

Fig. 1 Generalized Kelvin-Voigt model

Where:$_l$, is the spring modulus of the ith Kelvin Voigt element in parallel with the viscous dampers η_l, leading to a time of material relaxation $\tau_l = E_l\eta_l$.
Taking into account the previous transformations, the averages equations became :

For main pipe :

$$\frac{\partial P}{\partial t} + \rho\ a_1^2 \frac{\partial V}{\partial x} = 0, \qquad (5)$$

$$\rho \frac{\partial V}{\partial t} + \frac{\partial P}{\partial x} + g \frac{\partial z}{\partial x} = -4\ \frac{\tau_{p,1}}{D_1}. \qquad (6)$$

For device element :

$$\frac{\partial P}{\partial t} + \rho\, a_2^2 \frac{\partial V}{\partial x} + 2\rho\, a_2^2 \frac{\partial \varepsilon_r}{\partial t} = 0, \tag{7}$$

$$\rho\frac{\partial V}{\partial t} + \frac{\partial P}{\partial x} + g\frac{\partial z}{\partial x} = -4\,\frac{\tau_{p,2}}{D_2} \tag{8}$$

$$\frac{\partial \varepsilon_r}{\partial t} = \int_0^t \frac{\zeta D_{m2}}{2}\,\frac{\partial P(x,t-\tau)}{\partial t}\,\frac{dJ(\tau)}{d\tau}\, d \tag{9}$$

Where τ_p, is the term friction of the fluid at inner pipe wall, g; intensity of gravity, z:height of the pipe cross-section in relation to the horizontal position and a is the water hammer celerity in each pipe, given by the following expression:

$$a_j = \left(\rho\left[\frac{1}{\kappa} + \frac{\zeta D_{mj}}{e_j E_j}\right]\right)^{-1/2} \tag{10}$$

Where, the index j =1, is relative to the main pipe , and j=2 for to the plastic section element.

κ : bulk modulus of the fluid and ζ is the parameter depending on pipe type constraint. For a pipe no anchored:

$$\zeta = 1 + \frac{e_j^2}{D_{m,j}^2} + 2\frac{\nu e_j}{D_m E_j} \tag{11}$$

And

$$\zeta = 1 + \frac{e_j^2}{D_{m,j}^2} + 2\frac{\nu e_j}{D_{m,j} E_j} - \nu^2\left(1 - \frac{e}{D_{m,j}}\right)^2 \tag{10}$$

For a pipe anchored at its extremities.

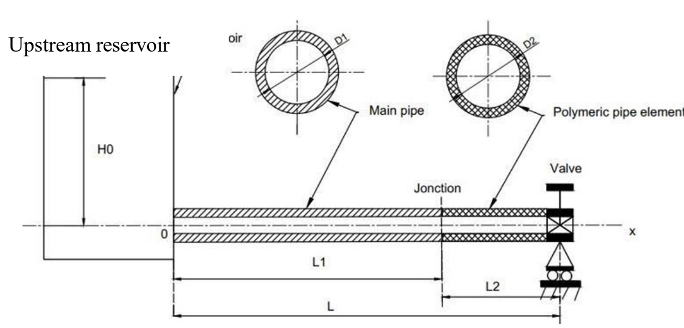

Fig.2. Scheme of installation studied

3 BOUNDARY AND INITIAL CONDITIONS

The pipe is assumed to be anchored at one end to a tank that imposes constant pressure at the inlet, and, at the other side, to a fast closing valve. In addition, at the junction point, we have the equality of pressures and flow rates.

4 NUMERICAL SOLUTION

The previous set of equations for both main pipe and additional polymeric element are of hyperbolic nature and suitable to be solved by method of characteristics [15-16]. For the sake of simplification, we limit ourselves to the viscoelastic case, the elastic case is deduced for appropriate parameters, by setting the delayed deformation zero, so the transformation of these equations along the characteristic curves leads to the following algebraic relationships:
- Along positive characteristic $dx/dt = a_2$

$$P_i^{n+1} - P_{i-1} + \rho\, a_2 (V_i^{n+1} - V_{i-1}^n) = 4a_2 \frac{\tau_{p\,i,2}^{i}}{D_2} \Delta t$$
$$-2\rho a_2^2 \left[\sum_{l=1}^{NKv} \frac{\zeta\, D_{m,}}{2e_2 \tau_l} (P(x,\ t) - P(x,\ 0)) - \frac{\varepsilon_{r,l}}{\tau}\right]_{-1}^{i} \Delta t \quad (12)$$

- Along negative characteristic $\frac{dx}{dt} = -a_2$

$$P_i^{n+1} - P_{i+1} - \rho\, a_2 (V_i^{n+1} - V_{i+1}) = -4a_2 \frac{\tau_{p\,i,2}^{i+1}}{2} \Delta t$$
$$+2\rho a_2^2 \left[\sum_{l=1}^{NKv} \frac{\zeta D_{m,2}}{2e_2 \tau_l} (P(x,\ t) - P(x,\ 0)) - \frac{\varepsilon_{r,l}}{l}\right]_{i}^{i+1} \Delta t \quad (13)$$

-Along the characteristic of slope $\frac{dx}{dt} = 0$,

$$\varepsilon_{r\,i}^{n+1} = \varepsilon_{r\,i}^{n} + \Delta t \left(\sum_{l=1}^{NKv} \frac{\zeta D_m}{2e_2\tau_l} (P_i^n - P_i^0 - \frac{\varepsilon_{r,l}^n}{\tau_l}\right) \quad (14)$$

5 APPLICATION AND RESULTS

In this application, we consider the simple case of a horizontal steel pipe, anchored upstream to a reservoir filled with water and of piezometric height pressure $H_0$and ending downstream with a valve that is closed abruptly. The parameters of the fluid and the pipes are grouped in Tables I and II below.

Table I: Physical characteristics of the fluid

Piezometric pressure of the tank H_0 (m)	10
Flow initial velocity (m/s)	1
Kinematic viscosity of the fluid μ (Pa.s)	1×10^{-3}
Bulk modulus of the fluid κ (GPa)	2.2
Density of the fluid ρ (Kg/m^3)	1000

Table II: Physical characteristics of the pipe

Parameter	Main pipe (steel)	Short pipe (polymer)	
Lenth of pipe (m)	104	6	
Inner diameter of pipe (mm)	50	50	
Thickness of pipe (mm)	1	4	
Poisson's ratio	0.34	0.45	
Young Modulus (GPa)	120	3.6	
Spring modulus (Gpa)		3.6	3.6

The numerical results for the temporal evolution of the piezometric pressure at the valve, expressed in meters of water column $H = P/\rho g$ (mCE) are displayed in the figures below. The curve (a) correspond to the case of hydraulic transient in steel pipe without water hammer control ($\mathrm{E} = 210\mathrm{Gpa}$, $\mathrm{L} = 100\mathrm{m}$).

In Figure 3, the curve (b) corresponds to the hydraulic transient with replacing short length of main pipe by polymer pipe control element (polyethylene) without taking account its viscoelastic behaviour by neglecting the relaxation time effect, for two length 5m (curve b) and 10m(curve c), ($L_2 = 5\mathrm{m}$, $\mathrm{E} = 3.4$ Gpa).

Figure 4 presents results under the same general conditions, but now accounting for the viscoelastic properties of the polymer control device element,($L_2 = 5\mathrm{m}$, $\mathrm{E} = 3.4$ Gpa,$E_1 = 3.4$ Gpa, $E_2 = 3.4$ Gpa τ_1= 0.1s and τ_2= 0.4s) allowing to show the effect of viscoelasticity (curve b) on the reduction and attenuation of jumps of pressure waves compared to the purely elastic control element (curve b).

Figure 5 further examines the influence of different relaxation times of the control device element for the same polymer pipe element, ($L_2 = 5\mathrm{m}$, $\mathrm{E} = 3.4$ Gpa,$E_1 = 3.4$ Gpa, $E_2 = 3.4$ Gpa) by considering two sets values of the relaxation time (τ_1=0. 1s and τ_2=0. 4s) (curve b) and (τ_1=0.01s and τ_2=0.04s) (curve c), of the control device element.

These results clearly highlight the shock-absorbing properties of this type of material in reducing pressure shock in pressurized pipes. This damping is more significant with taking into account the effect of viscoelasticity of the material pipe of the control device element and its lenght.

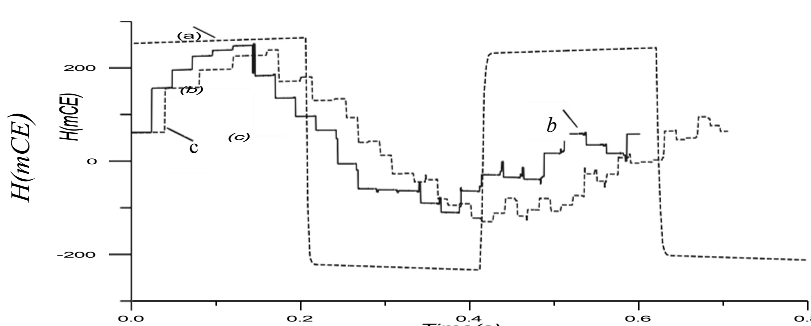

Fig.3 Temporal evolution of piezometric pressure ($H = P/\rho g$) at the valve for elastic control device behaviour for length (b) 5m and (c) 10m.

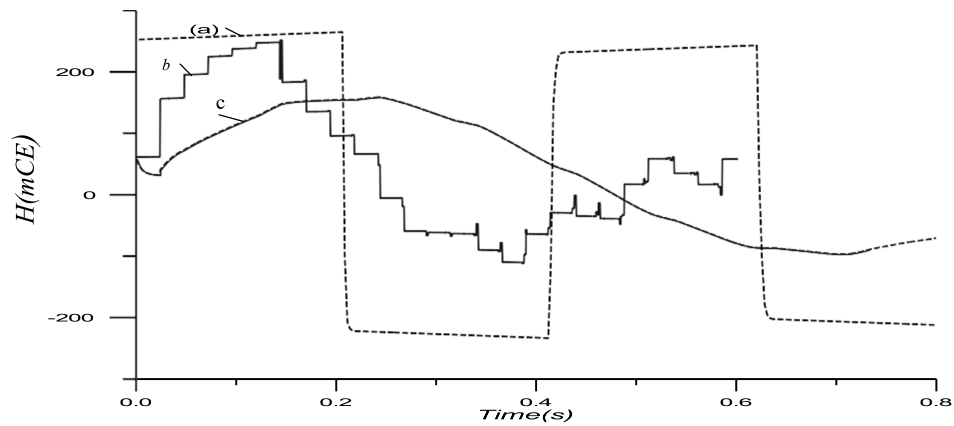

Fig.4 Temporal evolution of piezometric pressure ($H = P/\rho g$) at the valve with taking or not into account the relaxation times of control device for length 5m.

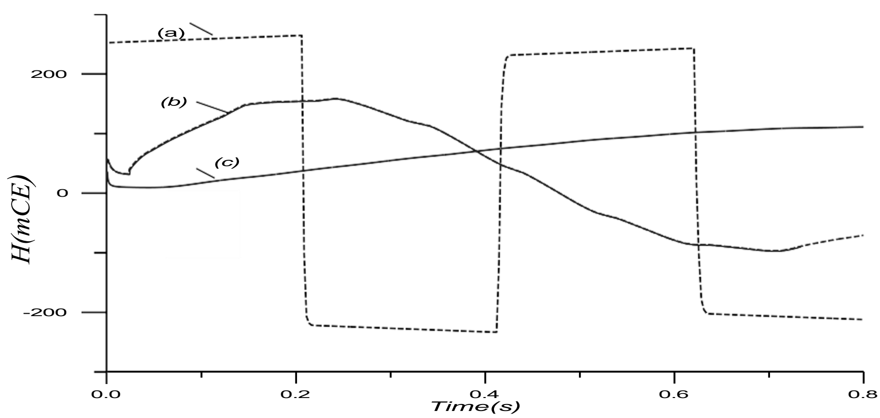

Fig.5 Temporal evolution of piezometric pressure ($H = P/\rho g$) at the valve with control device for relaxation times (b) τ_1= 0.1s , τ_2= 0.4s and (c) τ_1= 0.01s and τ_2= 0.04s, for length 5m.

CONCLUSION

This study highlights the feasibility of controlling water hammer in steel pipelines by replacing a short section of main pipe with innovative materials such as polyethylene. We emphasize that this material contributes significantly to buffering pressure along a pipeline. The results also show that low-modulus polyethylene can be used as an optimal strategy to control water hammer and ensure the safety of hydraulic installations.

References

1. M.H.Chaudhry, Applied Hydraulic Transient. Van Nostrand Reinhold Company, New York, (2014)
2. E.B. Wylie, V.L Streeter, Fluid Transients in Systems. Prentice Hall, Englewood Cliffs, NJ,(1993):
3. M.S, Ghidaoui, M. Zhao, A.M. Duncan, H.A. David, A review of water-hammer theory and practice. Appl. Mech.Rev. 58, 49–76, (2005).

4. M. MEUNIER ,Coups de bélier dans les réseaux sous pression, Edition ENGREF, (1978).
5. A. Bergant, A.R. Simpson, A. Tijsseling, (2006).: Waterhammer with column separation: a historical review. J. FluidsStruct. **22**, 135–171,(2006).
6. A. Soares, D. Covas, N. Carriço, Transient vaporous cavitation in viscoelastic pipes. J. Hydraul. Res. 50, 228–235, (2012).
7. F. Massouh, R. Comolet , Étude d'un système anti-bélierenligne-study of a water-hammer protection system in line. LaHouille Blanche 5, 355–362, (1984).
8. W. Wan, B. Zhang, X. Chen & J. Lian, Water hammer control analysis of an intelligent surge tank with spring self adaptive auxiliary control system. Energies 12, 2527, (2019).
9. A. Triki, Multiple-grid finite element solution of the shallow water equations: water-hammer phenomenon. Comput. Fluids 90, 65–71, (2014).
10. W. Zielke, Frequency-Dependent Friction in Transient Pipe Flow, Transaction of the ASME, Journal of Basic Engineering, vol. 90, no. 1, pp. 109-115, ,(1968) .
11. J.P. Vitkovsky, M.F. Lambert,A.R. Simpson, A. Bergant , Advances in unsteady friction modelling in transient pipe flow.In; In the 8th International Conference on Pressure Surges, BHR, The Hague, The Netherlands, (2000).
12. E. Rieutord , A. Blanchard ,Écoulementnon permanentenconduiteviscoélastique - coup de bélier, Journal of Hydraulic research, V17(3), (1979).
13. R.M. Christensen, Theory of viscoelasticity. An introduction, Academic Press, New York, (1971).
14. H.F. Brinson, L.C. Brinston, Polymer Engineering Science and Viscoelasticity: An Introduction. Springer, New York, USA.(2010).
15. D.E. Goldberg, Characteristics method using time-line interpolations. J. Hydraul. Eng. 3, 109670–683,(1991).
16. H.A.A.Abdel-Gawad,.B. Djebdjian, Modelling water hammer in viscoelastic pipes using the wave characteristic method, Appl. Math. Model. 83, (2020).