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Effects of Pipe's Roughness and Reservoir Head Levels on Pressure Waves in Water Hammer

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ABSTRACT: Water hammer is a transient flow in pipes that was created by suddenly change in velocity in pipes. This phenomenon can cause serious positive and negative pressures in pipes and often with several hazards in pipelines. Overall water hammer creates by closing valves rapidly, suddenly shut off or restarting pumps, and has one of most destructive hydrodynamic phenomena in pressurized pipelines. In this study, governing equations about water hammer is numerically solved by using MATLAB programing language, and then sensitivity analysis in pressure fluctuations has been investigated by changing some effective variables such as pipe roughness type and reservoir head. Numerical solution is based on characteristic lines method. Results show that with increasing in pipe roughness, negative and positive pressures ranges, decreased. Also increasing reservoir water level causes intensive negative and positive pressures in pipe.

Keywords: Water hammers, Transient Flow, Pump, Positive and Negative Pressure, MATLAB

INTRODUCTION

In some of pressurized hydraulic systems such as water conveying pipelines, water distribution networks, pipelines ending to turbine, water tunnels, and pumping systems, water hammer phenomenon creating rapid and transient waves causes damages. Sometimes the power of pressure waves are too much that has destruction results such as rupturing and breaking of pipelines in conveying and distributing systems, breaking valves, control valves, and pumps (Streeter, 1960).

The velocity of this wave may exceed 1000 m/s and the values of pressure may oscillate from very high to very low values. Design and operation of any pipeline system requires that the distribution of head and flow in the system is predicted at different operating conditions. Many researchers have attempted the simulation of transient flow in pipeline systems with different methods. These events in water conveying projects are usual and annually imposes high amount of damages to pressurized systems (Afshar et al., 2008).

Water hammer is produced by a rapid change of flow velocity in the pipelines that may be caused by sudden valve opening or closure, starting or stopping the pumps, mechanical failure of a device, rapid changes in demand condition, etc. (White, 1979). It could result in violent change of the pressure head, which is then propagated in the pipeline in the form of a fast pressure wave leading to severe damages (Parmakian, 1963).

In a research, numerical study on an air tank in order to balance the water hammer pressure has been performed. The study has shown that increasing reservoir volume will result in decreasing negative pressure and positive pressure and decreasing water levels in reservoir. Studies shown that the amount of control valve opening and materials of system has effects on hydraulic characteristics of flow in water hammer phenomenon that the way check valves got closed in system, has remarkable effects on transient flow characteristics of the water hammer (Bergant et al., 2006). Also the severe pressure fluctuation in pipelines and severe fluctuations in water volume in pipelines as a result for water hammer, plays an important role in analysis and design of water conveying systems. It is visible that changes in materials used in the pipelines has remarkable changes in downstream check valve closure process (Ghidaoui et al., 2005).

For theoretical simulation, many researchers have used hybrid models to solve water hammer problems. Among them, the method of characteristics line (MOC) is the most popular one in modeling the valve-induced water hammer equations because of its feasibility and advantage for complex systems (Wenxi et al., 2008) Studding water hammer in pipelines using implicit method of characteristic lines (IMOC) has shown that it will be helpful to use implicit method of characteristic lines instead of the explicit characteristic lines method in order to lower and balance the limitation (Tan et al., 1987).

In another research the effect of size in pressurized air reservoir in reducing maximum and minimum pressure due to water hammer has been studied. The research on optimization of conveying systems with pumps for water hammer using mathematical optimization method had shown that within increasing pipe diameter, effect of sudden pump stoppage especially negative pressure will be lowered. Within this method, the diameter and thickness of pipe

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will be optimized in order to prevent water hammer occurrence and unnecessarily expenses (Vetter et al., 1989). The hydraulic simulation study on water hammer phenomenon using multiple diameters and materials in pipes showed that the changes in material must be in order of the pipe with higher elasticity module to the pipe with lower elasticity module, and the closer elasticity module is, the lower pressure change will be occurred. In case change in material and change in diameter simultaneously occurs, it is better to use the bigger size of pipe for second one to lower pressure change range (Ghidaoui et al., 2005; Meniconi et al., 2012).

Comparison for control of transient hydraulic waves of water hammer showed that protective actions and design of expansion joints is based on low flow velocity, using check valves, control valves, balancing reservoirs, and air reservoirs. In another research about water hammer in hydroelectric power plants, results imply that numerical analysis about water hammer has a high correspondence to reports from the projects designer. But tolerances are visible due to simplifications and inaccessibility of some required data. Assessment of water hammer simulation using laboratory and numerical CFD models showed that numerical CFD simulation model of water hammer has high reliability and can be used as a proper numerical model to calculate maximum and minimum pressure. In a research about modeling turbulence in 2D simulation of water hammer in low Reynolds number range has been evaluated (Wahba 2009; Nathan et al., 1988).

Mutual assessment between water hammer and centrifugal pumps showed that the centrifugal pumps especially in high energy level and velocity generate remarkable pressure fluctuations. Interaction effect can increase the effects, so that the pressure fluctuation should not be neglected (Ismaier 2009). Assessment of water hammer simulation using implicit method of characteristics represents high reliability of this method, which can simulate discharge and water levels in all considered cases (Afshar 2008).

In this study the purpose is to solve the governing equations about water hammer phenomenon and analysis of the sensitivity. For this purpose a program has been written in MATLAB environment and fluctuations of pressure by changing diameter, length, and velocity parameters of pipe, will be studied. Sensitivity analysis of the numerical model by changing parameters, contributes to a better understanding about water hammer (Wylie et al., 1993; Balino et al., 2001).

MATERIALS AND METHODS

Governing Equation

The general equation of water hammer is obtained from Newton's second law and the equation of continuity of flows. For obtaining Newton's second law, a small element of pipe would be considered and the acting forces would be as follows (Fig. 1).

Equation 1 is known as the Euler equation or the momentum equation. The Eq. 1 is used for non-compressible fluids.

$$\frac{1}{\rho}.\frac{\partial P}{\partial x}+\frac{fV|V|}{2D}+g.\sin\alpha+V\frac{\partial V}{\partial x}+\frac{\partial V}{\partial t}=0 \qquad [1]$$

In Eq. 1 parameter D is internal diameter of pipe, P is pressure, x is location dimension, t is time dimension, f is friction coefficient, V is average flow velocity, and L is pipe length.

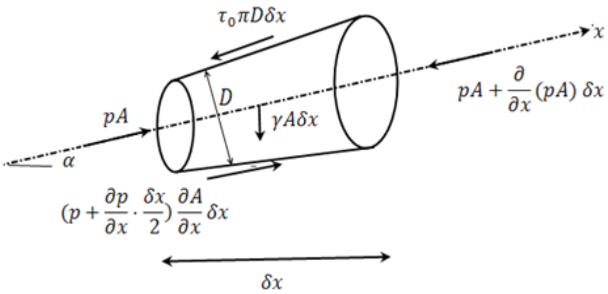


Figure 1. Forces on a pipe element of length δx.

According to Fig. 2, if continuity equation considered for an element of pipe length, the Eq. 2 would be obtained.

$$a^2.\frac{\partial V}{\partial x}+\frac{1}{\rho}\frac{\partial P}{\partial t}+\frac{1}{\rho}V\frac{\partial P}{\partial x}=0 \qquad [2]$$

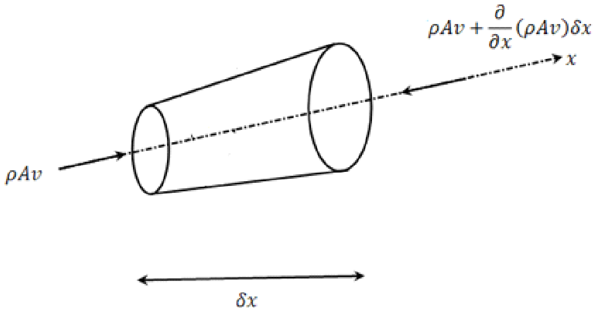


Figure 2. Control volume to obtain the continuity equation.

The characteristic lines method for numerical solution

History of water hammer analysis is an implication for various methods development to solve Euler and continuity equation (Eqs. 1, 2). The variety of these methods is depended on numerical analysis ability and innovation of these methods. The characteristic lines method is one of the most accurate methods to assess water hammer phenomenon because it considers minor losses and also it is customizable for various boundary conditions.

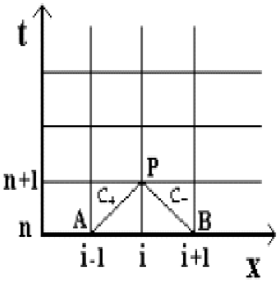
In this method, the partial differential equations of flow continuity and momentum convert to the two ordinary differential equations and then could be solved by finite difference method (Szymkiewicz et al., 2005). In the characteristic lines method, first the water hammer's main equations will simplified and then used. By performing some mathematical operations two ordinary differential equations are obtained as Eqs. 3 and 4.

$$\frac{\partial H}{\partial t}+\frac{c}{gA}\frac{\partial Q}{\partial t}+\frac{cf}{2gD}V|V|-\frac{Q}{A}\sin\alpha=0\ ,\ \frac{\partial x}{\partial t}=1+c \qquad [3]$$

$$\frac{\partial H}{\partial t}-\frac{c}{gA}\frac{\partial Q}{\partial t}+\frac{cf}{2gD}V|V|-\frac{Q}{A}\sin\alpha=0\ ,\ \frac{\partial x}{\partial t}=1-c \qquad [4]$$

Eqs. 3 and 4 are established on lines $\frac{\partial x}{\partial t}=1+c$ and $\frac{\partial x}{\partial t}=1-c$.

The Eqs. 3 and 4 on coordination screen of (x-t) are explainer of two straight lines of $1/c, -1/c$. So then the differential equation on these lines using finite difference method can be written as follows:



$$C^{+}:\ H_i^{n+1}=C_p-BQ_i^{n+1}$$

$$C^{-}:\ H_i^{n+1}=C_m+BQ_i^{n+1}$$

Figure 3. Characteristic lines

B, C_m, C_p are known coefficients based on value of H and Q in time step (n is present time). By solving these two linear Eqs., the two unknown values for Q_i^{n+1}, H_i^{n+1} in the next time step will be found.

In this study a computer program in MATLAB environment presented to solve the governing equations of water hammer (momentum and continuity of flow). The prepared program solves transient fluctuations in a simple pipeline, with an upstream reservoir, and a downstream valve (Fig. 4). The valve specification places as $C_D A$ in orifice formula (Eq.5).

$$Q_P=C_D A\sqrt{2gH_P} \qquad [5]$$

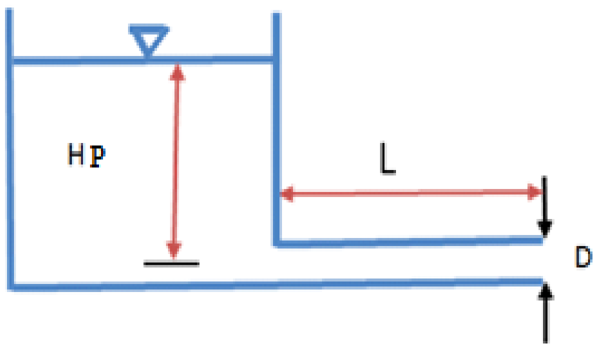


Figure 4. The system consists of a simple pipe with a reservoir at upstream and with a valve in downstream of the pipe.

Specifications of the system that MATLAB program has been designed for is:
[H_P=100 m, L=4800 m, D=2 m, f=0.022, a=1200 m/s]

Where H_P is reservoir water levels, L is pipe length, *f* is pipe's friction coefficient and *a* is the velocity of wave.

The datum for hydraulic levels is considered to be the geometrical axis of the pipe. The program in each time steps calculates the value of $C_D A$ which is CV in program using linear interpolation. Simultaneously the value of H_p and Q_p in valve would be calculated by solving the Eq. 5 and characteristic Eq. of C^+ (Eq. 3).

To specify permanent conditions for energy equation form reservoir to valve, neglecting minor losses will expressed as follows:

$$H_R-f\frac{L}{D}\frac{Q_0^{\,2}}{2gA^2}=\frac{Q_0^{\,2}}{2gCV^2} \qquad [6]$$

RESULTS AND DISCUSSION

In this part reaction of water hammer for system consisting of a pipe with various materials and also various water levels in reservoir will be examined. For this purpose a code in MATLAB language has been written that the parameters are allowed to be replaced and plotted. Method to solve the governing equations is the characteristics method. The fluctuation of pressure is calculated in 4 statuses (pipe's full length, pipe's $\frac{3}{4}$ length, pipe's $\frac{2}{4}$ length, and pipe's $\frac{1}{4}$ length). The results are presented as variable by applying different materials for pipe and for brevity the results are mentioned for darcy-weisbach roughness coefficient of 0.016 and 0.028 in the Figs. 5 and 6.

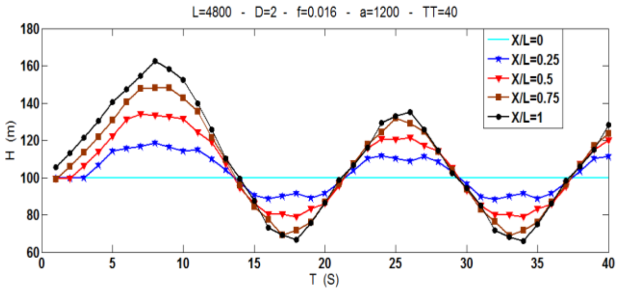


Figure 5. Pressure fluctuations at different positions along the pipe with friction factor of 0.016

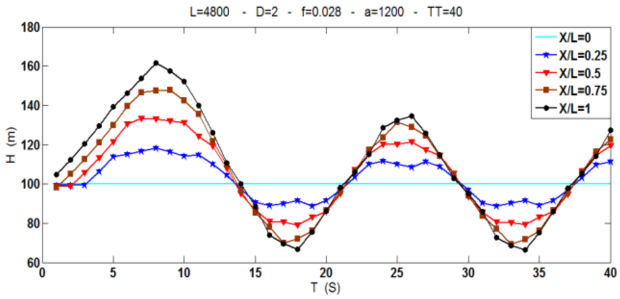


Figure 6. Pressure fluctuations at different positions along the pipe with friction factor of 0.028

According to Figs. 5 and 6 it is visible that by increasing darcy-weisbach coefficient (f), the areas with negative pressure would have much pressure reduction and in the areas with positive pressure would have less pressure increment; the reason is that the much darcy-weisbach coefficient is, the more rough the pipe would be, so that it causes much energy loss of the pressure waves and dissipation of them much rapidly. The range of pressure fluctuation would reduce remarkably by increasing darcy-weisbach coefficient.

According to Fig. 5, result is that the maximum pressure increment in pipe with *f*= 0.016 would be 62.5% of static pressure of reservoir and pressure decrement would be 33.48% of static pressure of reservoir. So that controlling of pipe material in order not to break pipes and also controlling the danger of cavitation due to pressure decrement should be considered by designer (Sadafi et al., 2012). Also according to Figs. 5 and 6, it is clear that the maximum and minimum pressure occur at the end of pipe, so that the end of pipe is considered as critical zone in design criteria.

Fluctuations of pressure at the end of pipe and middle of pipe for pipes with respective *f*= 0.002 to 0.1 are plotted in Figs. 7 and 8.

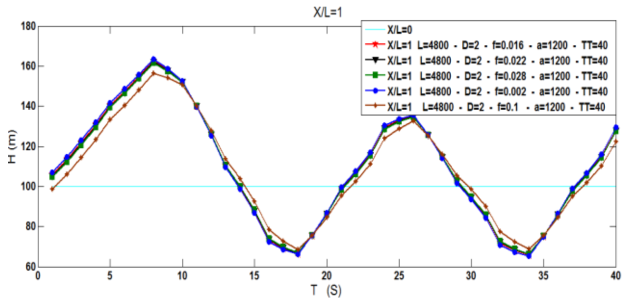


Figure 7. Pressure fluctuations at the end of the pipe, the pipes in roughness of *f*=0.002 to 0.1

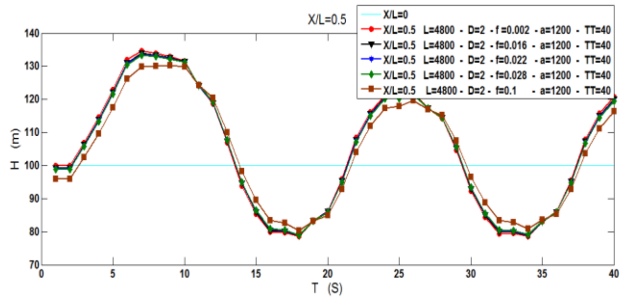


Figure 8. Pressure fluctuations in the middle of the pipe, the pipes in roughness of *f*=0.002 to 0.1

According to Figs. 7 and 8 it is visible that within rougher pipes the range of pressure fluctuation would decrease and energy dissipation would occur much rapidly. In the other words within increasing of *f*, instability of the water hammer waves would be further. But in general *f* does not have much impact on pressure waves. It is clear that the designer must consider the expenses of the pipeline's roughness and must perpend the optimized design about decreasing pressure and decreasing expenses of purchasing and setting up the pipeline.

In the next phase, the water level in the reservoir is variable and other parameters are constant; for brevity the results for water levels of 90 m and 110 m are mentioned in Figs 9 and 10.

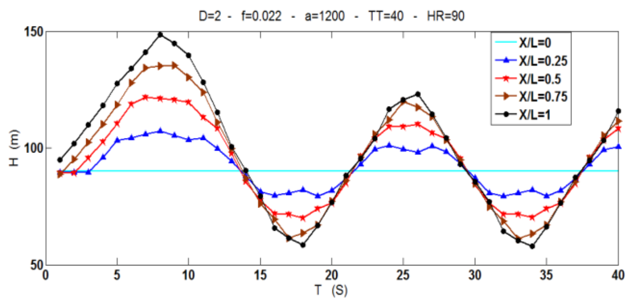


Figure 9. Pressure fluctuations in pipe with reservoir water level of 90 meters

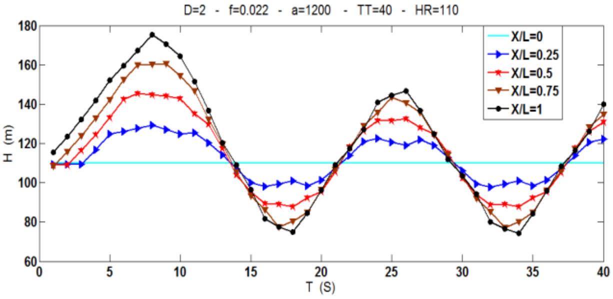


Figure 10. Pressure fluctuations in pipe with reservoir water level of 110 meters

According to Figs. 9 and 10, it is visible that increasing in water levels would increase intensity of pressure waves. The low water level in reservoir is, the low pressure wave's intensity would be. As a result for low water levels the energy of pressure waves would dissipate rapidly.

For thorough study of pressure fluctuation at the end of the pipe and middle of the pipe for water levels of 50 m to 150 m are presented in Figs. 11 and 12.

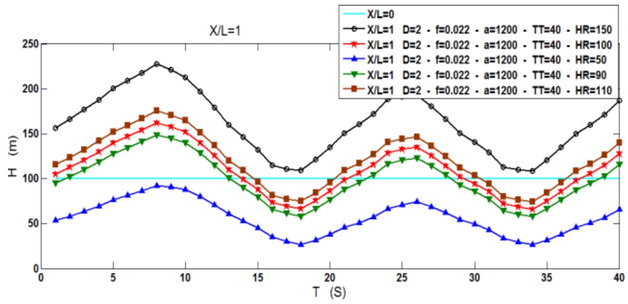


Figure 11. Pressure fluctuations at the end of the pipe with levels of water reservoir 50 to 150 meters.

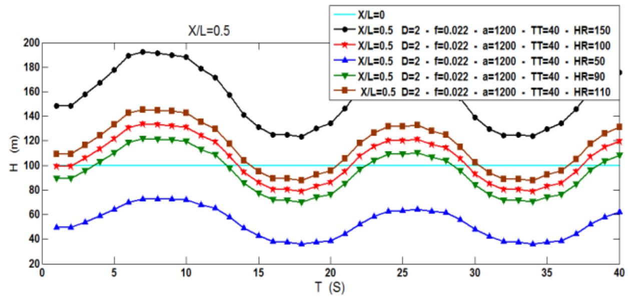


Figure 12. Pressure fluctuations in the middle of the pipe with levels of water reservoir 50 to 150 meters.

Evaluation between Figs. 11 and 12 explains that at the end of pipe the pressure is more intensive than middle section or the beginning section of pipe. So that practically and executively, the materials for sections close to the end of pipe must be tolerable materials. According to Figs. 11 and 12, it can be expressed for the result, the lower water level of reservoir is, the lower pressure of fluctuation would be. Accordingly the energy of waves would dissipate much rapidly.

CONCLUSION

- Within increasing darcy-weisbach coefficient (*f*) in pipe, in the areas with negative pressure wave, would have more pressure reduction and in the areas with positive pressure wave, would have less pressure increment. The pressure fluctuation range within increasing of darcy-weisbach coefficient would decrease slightly.

- Increasing water level in reservoir will increase intensity of pressure waves. The lower water level of reservoir is, the less energy would have the pressure waves.
- Maximum and minimum of pressure would occur at the end of pipe, and so that ending section of pipe is critical zone for design.

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