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Water Hammer Velocities for Different Pipe Materials

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Abstract— In the last 50 years, different pipe materials have been produced and installed in the construction industry, changing the hydraulic behavior of pipes against the water hammer phenomenon. One of water hammer parameters influenced directly by the pipe material is water hammer wave velocity. The wide use of High-Density Poly Ethylene (HDPE), Glass Reinforced Plastic (GRP) and Ductile Cast Iron (DCI) pipes in water transmission systems has raised the need to study in detail the transient velocities on these pipe materials. The complex elastic properties of pipe materials and the influence of other factors on these properties makes wave velocity calculations a challenge in a water hammer analysis. In this paper, efforts were made to calculate the wave velocities for different pipe materials as regards to their elastic and viscoelastic properties.

Index Terms— Water hammer, Wave velocity, Young's modulus, Poisson's coefficient, High Density Poly Ethylene (HDPE), Ductile Cast Iron (DCI), Glass Reinforced Plastic (GRP), Stiffness

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1 Introduction

Any change of velocity in a pipe will increase the pressure, starting from the device which changed the flow conditions and transferred through the pipe in the form of wave with velocity *a*. When the velocity changes slowly and the pipeline is short. the pressure increase is small and the transferring velocity of the pressure wave will not be influenced by the elastic deformations of the pipe walls and the fluid itself. However, for a rapid change of flow conditions (abrupt change in velocity) and a relatively long pipeline, the elastic properties of the pipe walls and the fluid become significant factors in the phenomenon. When the velocities in a pipeline change so rapidly that the elastic properties of the pipe material and the fluid should be considered in analysis of the hydraulic behavior of the system, the hydraulic transient condition is known as water hammer.

In Fluid Mechanics literature, including the Elementary Fluid Mechanics by Street, Watters, and Vennard [1], it is explained in detail what happens in a simple pipeline and valve connected to a reservoir (Figure 1), assuming that the steady flow occurs in the pipeline with velocity V. In absence of friction, the head along the pipe is H. If suddenly the valve is closed, an increase in pressure will be caused on the pipe starting from the valve section, and a negative pressure will occur at the opposite side of the valve. Considering the pipe section upstream of the valve, the velocity upstream of the valve will reach zero and the head at the valve increases with an amount of $\Delta H = a\,V/g$.

The focus of this study is on what will happen in the pipe and the fluid by this change in pressure. The increased pressure tends to enlarge the diameter of the pipe and also to increase the flow density to occupy less space within the pipe. After the first confrontation layer of the moving water to the valve gate, which resulted on flow stoppage, a second layer will be confronted with the first and start to move the increased pressure upstream with a velocity *a*. The magnitude of the pressure wave velocity depends on the elastic properties of the pipe walls and the fluid itself. Within the scope of this study, we will not explain the propagation of the pressure wave upstream and downstream of the pipeline but the velocity with which the wave is moving and its dependence on the wall pipe and fluid properties.

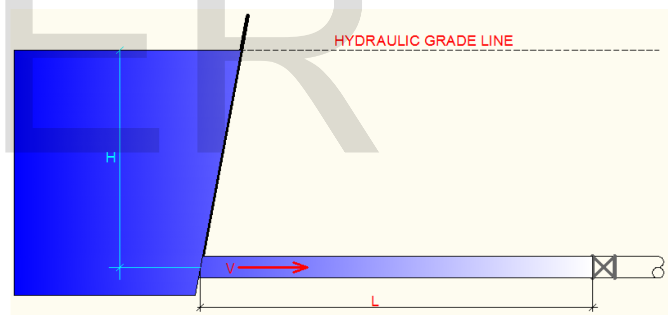

Figure 1 Simple pipeline system in absence of friction

2 Water Hammer wave velocity equation

As explained above, the pressure wave caused by the valve closure tends to enlarge the pipe walls and compress the fluid. Based on the scale of these attempts, it will affect the propagation of the wave pressure along the pipeline. As a result, to develop an equation for the pressure wave velocity two effects should be quantified, the change on the volume of the pipe as result of enlargement and the change in liquid volume due to compressibility.

The foundation for the calculations of the change in the volume due to compressibility is the application of the mass conservation law on a control volume and the equation which relates the increase in pressure and decrease in volume which defines the bulk modulus of elasticity of the liquid. Whereas to calculate the change in the volume due to elastic properties of the pipe, the basis is the mechanics of the solid materials which shows the relationship between the pipe wall strains in two perpendicular directions. If a solid material is strained in one direction, a strain will occur in the perpendicular direction, with the condition that the material is free to strain on that direction (no stresses developed in that direction). Following the principles given above, the well-known equation for calculation of the water hammer wave velocity is developed. Wylie and Streeter (1993) [2], gave this equation in the following form:

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1+\frac{K}{E}\frac{D}{e}(C)}}$$

Where:

K – Bulk modulus of elasticity of the fluid (N/m^2)
ρ – The density of the liquid (kg/m^3)
E – Bulk modulus of elasticity of the pipe material (N/m^2)
D – Internal diameter of the pipe (mm)
E – Thickness of the pipe wall (mm)
C – Pipeline installation conditions coefficient

1. C = 5/4 – μ (pipeline anchored upstream only)
2. C = 1 – μ^2 (pipeline anchored both upstream and downstream)
3. C = 1 (pipeline free to move on both directions (expansions joint along the pipeline)

3 WAVE VELOCITY EQUATION PARAMETERS

The pipe materials considered in this paper are those more used in practice, like steel, DCI, HDPE and GRP. The elastic properties of these materials and their behavior against water hammer conditions are different. In addition, some of the parameters involved in the wave velocity calculation and their influence on the velocity value will be analysed.

3.1 Bulk modulus of elasticity of pipe material

The most important parameter involved in the wave velocity equation, which influences considerably the wave velocity, is the modulus of elasticity or Young's modulus of the pipe material. In metallic pipes, the modulus of elasticity does not change considerably with temperature. Within the range of practical use of the pipe temperatures the modulus of elasticity of steel is changed by about 0.03% for each degree.

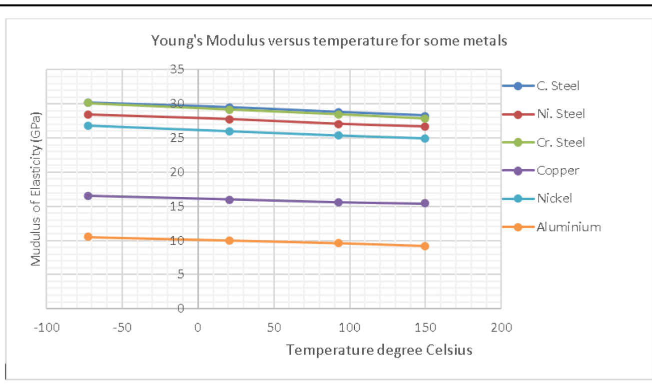

Figure 3 Young's Modulus vs. temperature for metals

Figure 2 shows the dependence of Modulus of elasticity versus temperature in degrees. For a viscoelastic material like HDPE, the E-modulus is not constant and appropriate values should be selected from a set of curves or from tables. The E-modulus for HDPE pipes is influenced by the temperature, the stress level in the material and the duration of loading. A higher temperature will give a slightly decreased modulus and a lower temperature will give a slightly increased E-modulus. The changes of E-modulus for each degree within the range of the practical temperatures is about 1.5 – 1.6%. On the other hand, the E-modulus will decrease on load duration time. The change of the E-modulus during the time interval between 1 hour and 50 years load is about 75% for the temperature 23°C. The figure below shows the graphs presenting the changes of the E-modulus vs. temperatures and load duration.

3.2 Thickness of the pipe wall

Thickness of the pipe wall influences considerably the wave velocity calculations as it contributes directly on the wave velocity equation, evident in metallic pipes. The effect of the increased thickness on the equation is moderated by the increased diameter of the pipes, so the ratio D/e remains almost constant. The influence of the pipe wall thickness in the wave velocity is shown in the following sections.

3.3 Poisson's coefficient

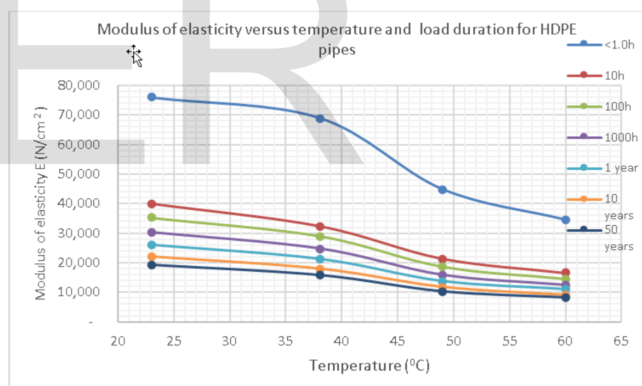

Figure 2 Modulus vs. temperature for HDPE pipes

Poison's coefficient influences the wave velocity based on the installation conditions of the pipeline, depending if anchored or not on the two sides. Three possible types of the pipeline anchoring and the respective value of the coefficient C is given in section 2 above.

4 WATER HAMMER WAVE VELOCITIES

Water hammer wave velocities have been calculated for 4 different materials: Steel, DCI, HDPE and GRP. The parameters for these materials and the pipe dimensions have been generated from different catalogues of commercial pipes and the wave velocities calculated for each diameter and pressure.

4.1 HDPE pipes

For HDPE pipes, the following parameters have been considered for calculations of water hammer wave velocities:

1. Bulk modulus of elasticity of the fluid K (2.19×10^9 N/m^2)
2. The density of the liquid ρ (998 kg/m^3)
3. Bulk modulus of elasticity of the pipe material E (7.59×10^8 N/m^2)
4. Internal diameter of pipes with OD = 200, 250, 315, 355, 400, 450, 500, 560, 630, 710, 800 & 1,000 (mm)
5. Thickness of the pipe wall e (mm) for the above diameters and pressures: 6, 10, 16 & 20 bar
6. Coefficient considering the installation conditions of the pipeline $C = 1 - \mu^2$ and $\mu = 0.46$. The HDPE pipelines are buried and welded, so the pipeline is considered anchored on both sides due to the fact that the friction does not allow deformations along pipeline length.

The results for calculation of the water hammer velocity on the HDPE pipes are presented in Figure 4.

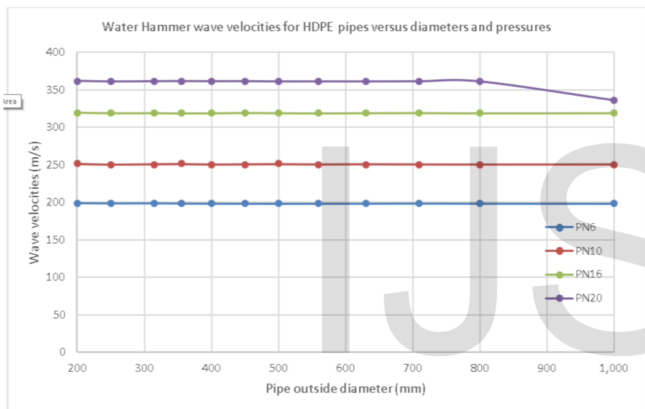

Figure 4 Water hammer velocity vs. pipe diameter and pressure

4.2 Steel pipes

For steel pipes, the following parameters have been considered for calculations of the water hammer wave velocities:

1. Bulk modulus of elasticity of the fluid K (2.19×10^9 N/m^2)
2. The density of the liquid ρ (998 kg/m^3)
3. Bulk modulus of elasticity of the pipe material E (2.0×10^{11} N/m^2)
4. Internal diameter of pipes with DN = 219, 323.8, 406.4, 508, 609.6, 711.2, 812.8, 914.4, 1016 (mm)
5. Thickness of the pipe wall e (mm) for the above diameters
6. Coefficient considering the installation conditions of the pipeline $C = 1 - \mu^2$ and $\mu = 0.46$. Steel pipelines usually are buried, welded and anchored on horizontal and vertical curves, so the pipeline is considered anchored on both sides including the fact that the friction of the pipe with backfilling does not allow deformations along pipeline length.

The results for the calculation of water hammer velocity on steel pipes are presented in the following Figure 5.

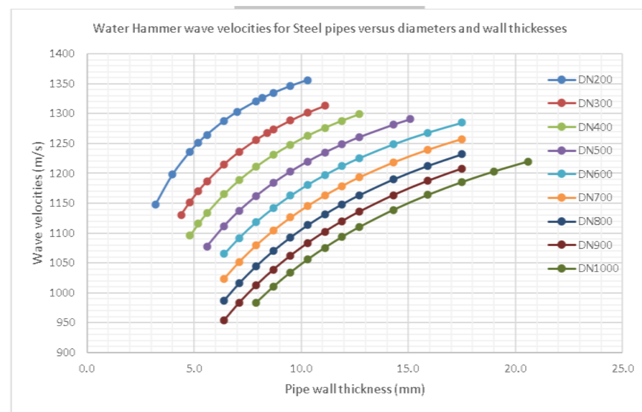

Figure 5 Water hammer velocity vs. pipe diameter and thickness

4.3 GRP pipes

For GRP pipes the problem is more complex. The GRP pipes are produced with different stiffnesses. Three stiffness values have been used for production of GRP pipes, SN2,500, SN5,000 and SN10,000. Water hammer wave velocities have been calculated by the producer and presented in the datasheets. These values have been used to compare with other pipe materials analyzed in this paper. The wave velocities calculated by the producer on GRP pipes are presented in Figure 6.

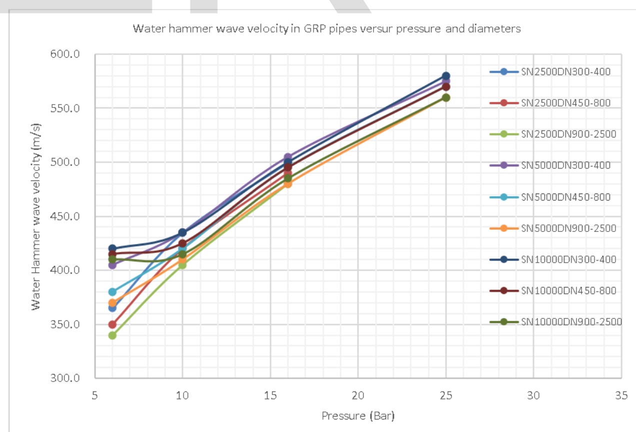

Figure 6 Wave velocity vs. diameter, stiffness and pressures

4.4 DCI pipes

For DCI pipes the calculation has been performed for three pipes classes, Class C, Class K7 and K9. The following parameters have been considered for calculations of the water hammer wave velocities:

1. Bulk modulus of elasticity of the fluid K (2.19×10^9 N/m^2)
2. The density of the liquid ρ (998 kg/m^3)

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3. Bulk modulus of elasticity of the pipe material E (1.7×10^{11} N/m^2)
4. Internal diameter of pipes with OD = 222, 326, 429, 532, 635, 738, 842, 945, 1048 (mm)
5. Thickness of the pipe wall e (mm) for the above diameters
6. Coefficient considering installation conditions of the pipeline $C = 1 - \mu^2$ and $\mu = 0.29$. The DCI pipelines usually are buried and anchored on horizontal and vertical curves, so the pipeline is considered anchored on both sides including the fact that the friction of the pipe with backfilling does not allow deformations along pipeline length.

The results for calculation of the water hammer velocity on steel pipes are presented in Figure 7.

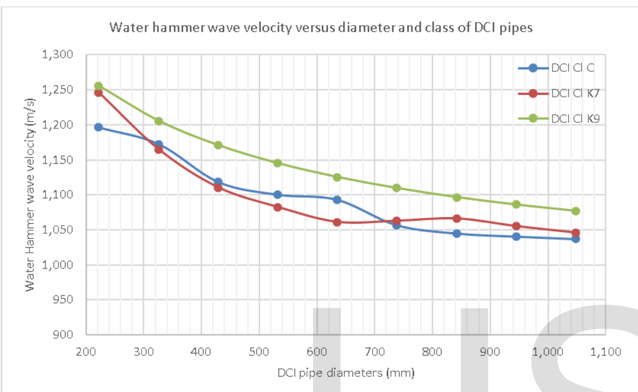

Figure 7 Water Hammer velocity vs. diameter & classes of DCI pipes

5 Conclusions

From the above analysis and calculations of water hammer wave velocities, we can conclude the following:

1. Water hammer wave velocities in HDPE pipes range from 200–360 m/s. By increasing the pipe pressure, the wave velocity increases. However, the wave pressure does not change considerably by increasing the diameter of the pipes. This occurs because with diameter thickness of the pipe wall also increases. The temperature and the load duration have a considerable influence on the E-modulus and consequently on wave velocity.
2. In steel pipes, water hammer wave velocities range from 950–1360 m/s. By increasing the pipe thickness and pipe diameter, wave velocity increases. The E-modulus for steel pipes within the practical operating temperatures do not change such as to influence the wave velocity.
3. Water hammer wave velocities in GRP pipes range from 350–600 m/s. By increasing pipe pressure, wave velocity increases. However, the wave pressure does not change considerably by increasing the diameter and the stiffness of the pipe material.
4. In DCI pipes, water hammer wave velocities range from 1000–1250 m/s. By increasing the pipe diameter, wave velocity increases. However, the wave pressure velocity does not change considerably by changing the DCI class.

6 References

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