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A Study of the Influence of Pipes Materials in Pressure Induced by a Hydraulic Transient

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ABSTRACT
The materials are a major component of any civil engineering project, the advancement of technology has enabled the development of different techniques and methodologies that allow you to modify and / or mix the physical, chemical and mechanical properties of those materials already existing order to obtain new specifications and different characteristics depending of the requirements. This work investigated the influence on the transient response in forced pipeline five different material types (steel, concrete, galvanized iron, ductile iron and polyvinyl chloride - PVC). The approach is to study the transient phenomena in ducts through the analysis of transient pressure waves in the fluid using the method of characteristics and finite difference method developed in computational program Transpetro-1D, beyond the analytical formulations and experimental data found in literature. For this study, different simulations were performed varying the modulus of elasticity, relative roughness, thickness and internal diameter of the duct which are the main properties that intervene in this phenomenon. The results show a great similarity between the experimental, analytical and numerical results.
Keywords–Transient, Pressure ducts, Characteristics method, Transpetro-1D.

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I. INTRODUCTION

Nuclear power plants, dam adducts, oil and gas pipelines, and other major projects require the use of forced pipelines in their hydraulic systems, which may have different sizes and materials according to the system specifications and requirements. By the technological advances new materials that allow better applications in any field of civil engineering have been developed, including hydraulics. The construction of pipelines as a means of transportation is a typical example of how previous analysis makes possible to obtain optimal solutions of balance between technical, economic and environmental conditions.

Besides materials, it is vitally important to make a detailed analysis of the effects from different phenomena inside the forced ducts, including the transient phenomenon, which can be caused by the sudden closing or opening of a valve, among many others. There are some commercial programs that do single phase (liquid or gas) or multiphase (oil plus water plus gas) transient analysis. However, this work proposes to use the TRANSPETRO-1D software, developed with C++ programming language by the dynamics and fluid-structure interaction group of the University of Brasília (UnB). It is noteworthy that the software have previous versions, namely RETRANS (Neri and Pedroso, 1999), TRANS-III (Pedroso and Barbosa, 1994) and TRANS-II and TRANS (Pedroso, Macedo and Barbosa, 1993).

Nascimento (2002) developed the TRANSPETRO-1D software based on the characteristic method, which allows to identify and characterize the transient effects caused by pressure waves under many boundary conditions. Magzoub and Kwame (2007) used the graphical method and the characteristic method to calculate and simulate transients in pipelines. Sirvole (2007) developed a transient analysis software to work with sudden and close shutoff valves, pump power failures, and sudden changes in junctions. Costa (2011) developed the study of wave propagation in ducts through the analysis of acoustic attenuation and velocity propagation. Bratland (2009) developed analyzes of transient problems such as heat exchange calculated by the characteristic method. Bratland (2013) expanded his research with different boundary conditions, flow regime determination, liquid and gas flow analysis and numerical solutions.

Other similar softwares and studies can be found in Allievi (1903), Joukowsky (1898), Lima and Pedroso (2004), Nascimento and Pedroso (2002), Pedroso, et all (2001), Tullis (1989).

Given this, this work evaluate forced ducts and compares some materials that can be used in the manufacture of these ducts. This was accomplished through the analysis of the transient pressure waves, which variates when a disturbance of time or space is generated in the state of flux. Finite differences and characteristics method implemented in the TRANSPETRO-1D software together with experimental data and analytical formulations were used to analyze the influence of some of the most commonly used construction materials and dimensions on pressure ducts when used in a hydraulic system.

The Dynamics and Fluid-Structure group has developed, over the last years, several studies related to fluid-structure interaction, covering themes, in special, pipeline[Nascimento (2002); Vélez (2015)]and dams [Silveira and Pedroso (2018); Mendes (2018); Silveira *et al*. (2019)].

II. THEORETICAL APPROACH

The hypotheses and simplifications used for the study of the phenomenon are: homogeneous, viscous and slightly compressible fluid, isotropic monophasic flow, and negligible thermodynamic effects.

This transient phenomenon will be approached using the equations of continuity, motion and state which consider the deformation at the duct wall.

A. Continuity Equation

The principle of conservation of mass is valid in any field of the flow, regardless of anysimplification. In this expression, the time rate of total mass variation per unit volume is zero.

$$\frac{\partial \rho}{\partial t} + \nabla\left(\rho \cdot \vec{V}\right) = 0 \qquad (1)$$

Where ρ is the fluid density (kg/m³) and V is the flow velocity (m/s).Using classical expressions for ducts and some simplifications, we obtain the following expression called continuity equation for ducts that suffer infinitesimal strains.

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

B. Equations of Motion

The sum of all forces acting on the fluid in longitudinal direction is equal to the product between his mass and acceleration. This expression considers the balance of forces.

$$\rho\frac{\partial \vec{V}}{\partial t} + \rho\vec{V}\nabla\left(\vec{V}\right) + \nabla\left(P\right) - \mu\left[\Delta\vec{V} + \frac{1}{3}\nabla\left(DIV\left(\vec{V}\right)\right)\right] = 0 \qquad (3)$$

Where ρ is the fluid density (kg / m³) and V the flow velocity (m/s).

The Poiseuille equation gives the equation of motion applied to a mass of fluid that presents a slight variation with respect to pressure variation.

$$\frac{1}{\rho}\frac{\partial P}{\partial x} + g \cdot sen\left(\alpha\right) + \frac{f \cdot V \cdot \left|V\right|}{2D} + V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} = 0 \qquad (4)$$

Many researcheshas been carried out to determine the friction factor between the duct wall and the fluid. In this work the Swamee-Jain equation will be used to directly calculate the Darcy-Weisbach friction coefficient for a duct, which presents similar results from the obtained by the implicit Colebrook-White equation (Swamee-Jain, 2012).

$$f\left(V, D, \nu, \varepsilon\right) = \frac{0.25}{\left(\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{RE\left(V, D, \nu\right)^{0.9}}\right)\right)^2} \qquad (5)$$

WhereV is the fluid velocity (m/s), ε is the roughness size projections (m), RE is the Reynolds number and D theinner diameter of the duct (m).

C. State Equation

The relation associates the variables of pressure and volumetric mass with the velocity of sound in the fluid (a ∞ for an incompressible fluid). This relation from the theoretical point of view allows to eliminate the specific mass (ρ) of the problem, making the formulation expressed only with the variables P and V. Incompressible and dense fluids, such as water, are considered slightly compressible when they are made. phenomena such as degassing (dissolved air in water) and elasticity in the duct wall are present. Neri and Pedroso (1999) present the following equation:

$$P = \rho \cdot a \cdot V_0\left(1 + \frac{V_0}{a}\right) \qquad (6)$$

Where, $a^2 = \dfrac{k/\rho}{\left(1 + V_0/a\right)\left(1 + \left(k/E\right)\left(D/e\right)c\right)}$ (7)

and, *K* is Volumetric modulus of elasticity of fluid (Pa), *ρ* isthe fluid density (kg / m³), *E* the Modulus of elasticity of material (Pa), *e* theduct wall thickness(m), and *c* aconstant which depends on axial movement of the duct (currently *c* = 1).

$$a^2 = \frac{k/\rho}{1 + \left(k/E\right)\left(D/e\right)c} \rightarrow a = \sqrt{\frac{k/\rho}{1 + \left(k/E\right)\left(D/e\right)c}} \qquad (8)$$

Since Vo << a the term Vo/a is negligible and we have a new expression to define the acceleration of the transient pressure wave and the velocity in the duct, which depends on the mechanical and physical properties of the duct (geometry and materials), the physical properties of the fluid (density and compressibility modulus) and the boundary conditions of the system. The focus of this work is to make a set of simulations modifying the duct properties.

III. SOLUTION METHODS

The Characteristic Method is a numerical method with important advantages, like the flexibility for introducing boundary conditions (Streeter and Wylie, 1967). It transforms partial differential equations into total differential equations, which are solved by the first order finite difference technique.

A. General Characteristics Method

The final equations for solving the transient problem are the equation of motion and equation of continuity, which are respectively

$$L_1 : V\frac{\partial P}{\partial x} + \frac{\partial P}{\partial t} + \rho a^2 \frac{\partial V}{\partial x} = 0 \quad (9)$$

$$L_2 : \frac{1}{\rho}\frac{\partial P}{\partial x} + g \cdot sen(\alpha) + \frac{f \cdot V \cdot |V|}{2D} + V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} = 0 \quad (10)$$

By algebraic treatment to these equations it comes to the characteristic equations for calculating the pressure and velocity at any point along the pipe at a given time:

$$V_{PP} = \frac{1}{2}\left[V_{PR} + V_{PS} + \frac{1}{\rho a}(P_{PR} - P_{PS}) - 2g\Delta t \cdot sen(\alpha) - \frac{f \cdot \Delta t}{2D}\left(V_{PR}|V_{PR}| + V_{PS}|V_{PS}|\right)\right] \quad (11)$$

$$V_{PP} - V_{Ps} - \frac{1}{\rho a}(P_{PP} - P_{PS}) + g(t_{PP} - t_{PS})sen(\alpha) + \frac{f}{2D}V_{Ps}|V_{Ps}|(t_{PP} - t_{PS}) = 0 \quad (12)$$

The different devices and mechanisms along the duct generate the so-called boundary conditions, which are essential due to their direct influence on the transient phenomenon. At the hydraulic system to be studied, there are initial and final boundary conditions, and the left condition of the system (upstream) is a steady level or constant pressure reservoir, and the right condition of the system (downstream) is a valve; if the valve is suddenly closed, the imposed boundary condition, Vs (fluid output speed), is zero; When the valve is closed as a function of time, the downstream boundary condition varies as a function of time.

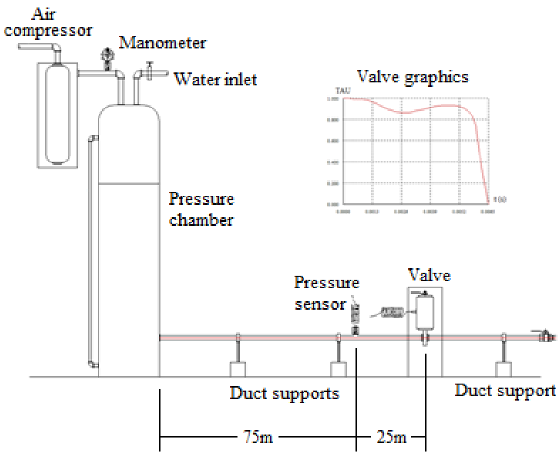

Figure 1. Experimental hydraulic system schema(Adapted Contractor 1965)

IV. TRANSPETRO 1D

The TRANSPETRO 1-D software was developed by the Dynamics and Fluid Structure Group (GDFE) of the University and Brasilia (UnB), in the master's dissertation of Nascimento (2002), as a tool for the analysis of the transient phenomena at the oil industry. It is noteworthy that the code was written in C ++ language, using Visual C ++ 6.0, which allows the creation of graphic resources that facilitates the user-program interaction. Based on the computational routines presented by Streeter and Wylie (1967).

A. Validation

To evaluate the Transpetro - 1D software, a comparison was made between the experimental results obtained in the experiment performed by Contractor (1965) and the numerical results obtained through the program. Table 1 presents the general data of the experiment.

Table 1: Experimental data

Duct length (L)	40 ft – 12.2 m
Diameter (D)	0.328 ft – 0.1 m
Pipe-fluid interface coefficient of friction (f)	0.24
Fluid density – water (ρ)	1.94 slug/ft³ – 998.2 kg/m³
Gravity acceleration (g)	32.18 ft/s² – 9.81 m/s²
Sound propagation velocity at the fluid (a)	4429.13 ft/s – 1149.5 m/s
Initial velocity at the valve (Vo)	1.20 ft/s – 0.366 m/s
Initial pressure at the valve (Po)	12468.604 lb/ft² – 597213.972 Pa

Fig.1 presents the experiment configuration, which has three important components, namely a pressure chamber fixed at the beginning edge, a valve with its closing curve at the ending edge and a duct joining them.

Fig. 2presents the experimental results of the transient pressure wave obtained in the Contractor experiment (1965) and the numerical results obtained by the Transpetro-1D software for the pressure sensor duct point, located at ¾ parts of theduct length between pressure chamber and valve (9.15 m).A great similarity can be observed between the experimental and analytical results in the first cycle. At the subsequent cycles, increasingly noticeable differences appear due to the lag effect and the existence of pressure drops generated by the friction factor that cannot yet be adequately represented by the software.

Fig.3 shows the numerical results for the time variation of transient pressure wave at each duct point that is subjected to the transient phenomenon. It shows that the phenomenon varies in time and space.

V. SYSTEM DESCRIPTION

In order to find the influence of the main properties governing this phenomenon, such as mechanical and physical properties of the duct (geometry and materials), a set of simulations were made to a hydraulic system similar to the one presented in the Contractor experiment. The system used has three main components and a pressure sensor. His configuration is shown in Fig.1.Simulations were made with five different types of materials, which are used in the construction of the ducts, and five distinct usual dimensions for the duct. Thephysical properties of materials that influence the transient phenomenon are presented in Table 2, while the geometrical (internal diameter)and mechanical (thickness)properties of materials who influence the transient phenomenon are presented in Fig.4 and Table 3.

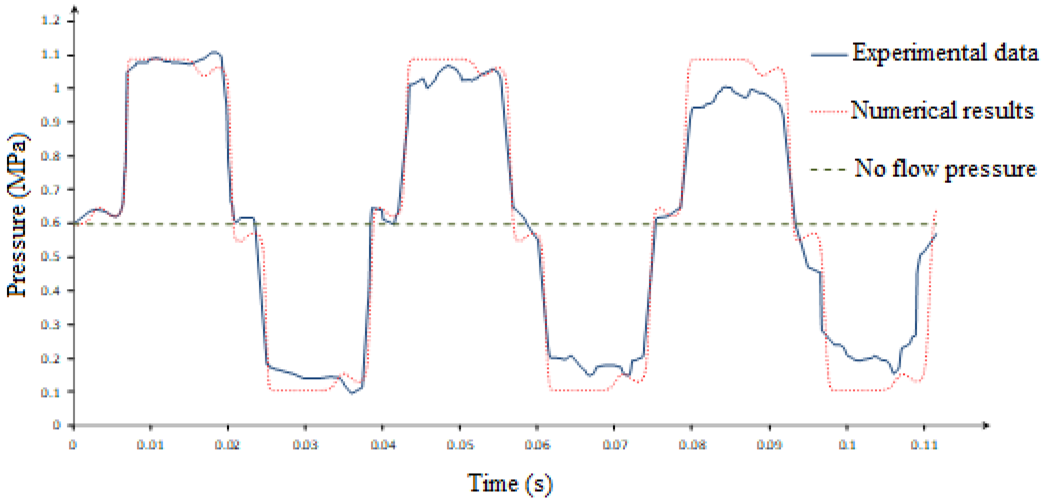

Figure 2. Pressure evolution at pressure sensor point – Experimental and numerical results (modified – Contractor, 1965).

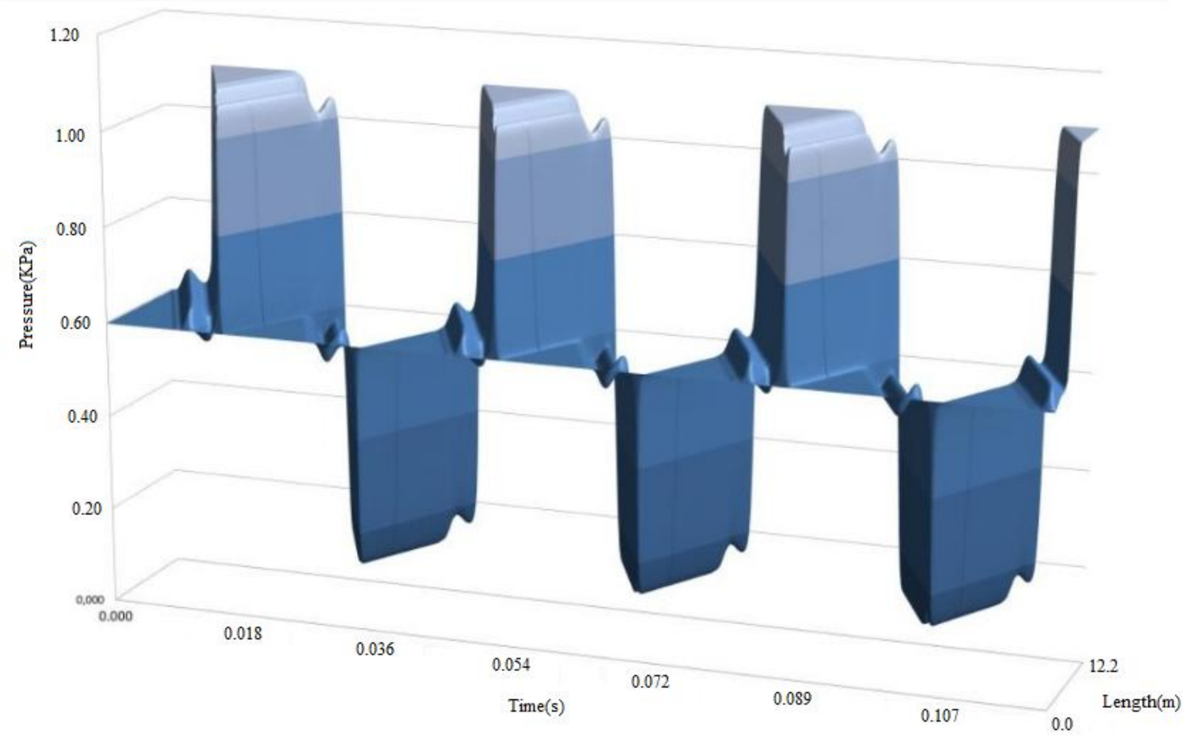

Figure 3: Transient pressure wave surface

Table 2: Materials properties for simulations

Material	E (GPa)	ϵ (mm)
Steel	210.00	0.045
Concrete	3.70	3.0 - 0.30
Galvanized iron	19.00	0.15
Cast iron	10.00	0.26
Polyvinyl chloride	2.26	0.0015
E = Young modulus		
ϵ = strain		

Table 3: Ducts geometry

e / D int	D int (m)	e (m)
0.005	5.005	0.025
0.09	0.452	0.041
0.018	0.201	0.036
0.250	0.182	0.045
0.350	0.161	0.056

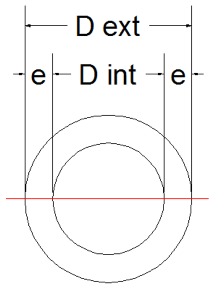

Figure 4: Cross section of duct

VI. SIMULATIONS AND RESULTS

For this study were performed a comparison between the analytical and numerical methods, making a simulation with five material types and five e/D ratios, presented in the previous section.Fig.5 shows a graph of the friction factor as a function of the Reynolds number according to (5).According to Fig.5, it can be stated that the highest material roughness is given when there is a higher friction factor, generating larger pressure drops. Concrete is the material with the highest coefficient of friction, generating the highest-pressure drops and being a very useful material, but not very efficient in piping systems. There is a vertical displacement in the friction factor curves for different materials. When there is sudden closing of the valve, a ΔP overpressure arises, generated by the speed reduction, Δv, which is usually estimated by the Joukowsky equation (Streeter and Wylie, 1967), determined for a frictionless flow.

$$\Delta P = \rho a \Delta V \qquad (13)$$

From (13) and (8) we obtain (14) and from it, dividing by the initial pressure (P_0), we obtain (15), which allows the analytical calculation of the relation between the initial pressure and the final pressure generated by a sudden closing of the valve for different types of materials and for different dimensions. Besides that, it is also compared to the numerical results obtained with the Transpetro-1D simulation.

$$\Delta P = \rho a \Delta V = \rho \cdot \Delta V \cdot \sqrt{\frac{k/\rho}{1+\left(k/E\right)\left(D/e\right)c}} \qquad (14)$$

$$\frac{P_f}{P_0} = 1 + \frac{\rho \cdot \Delta V}{P_0} \cdot \sqrt{\frac{k/\rho}{1+\left(k/E\right)\left(D/e\right)c}} \qquad (15)$$

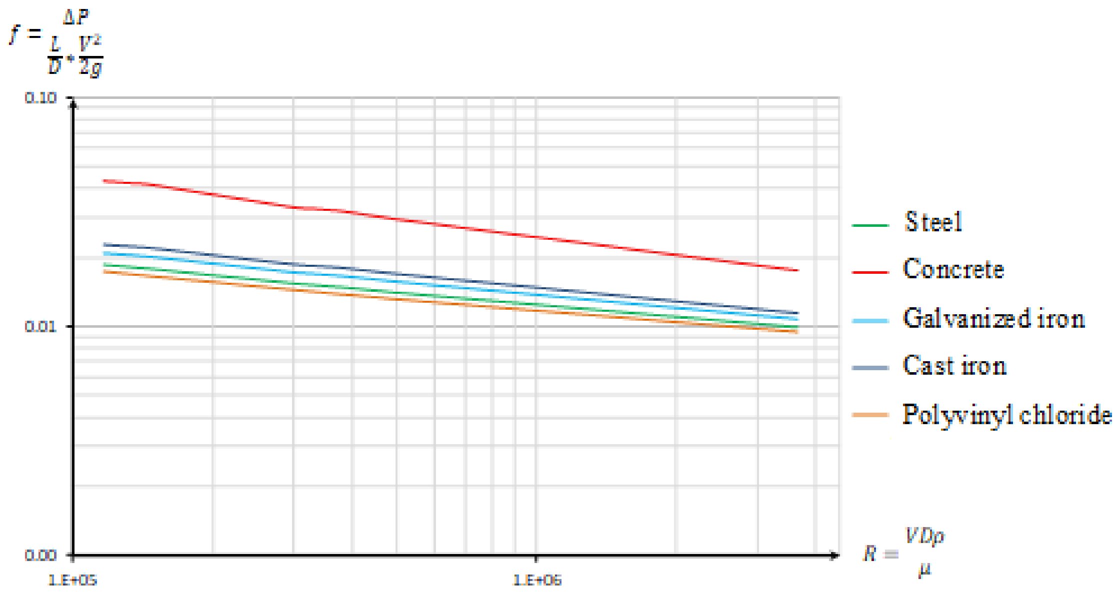

Figure 5: Coefficient of friction as a function of Reynolds number "R"

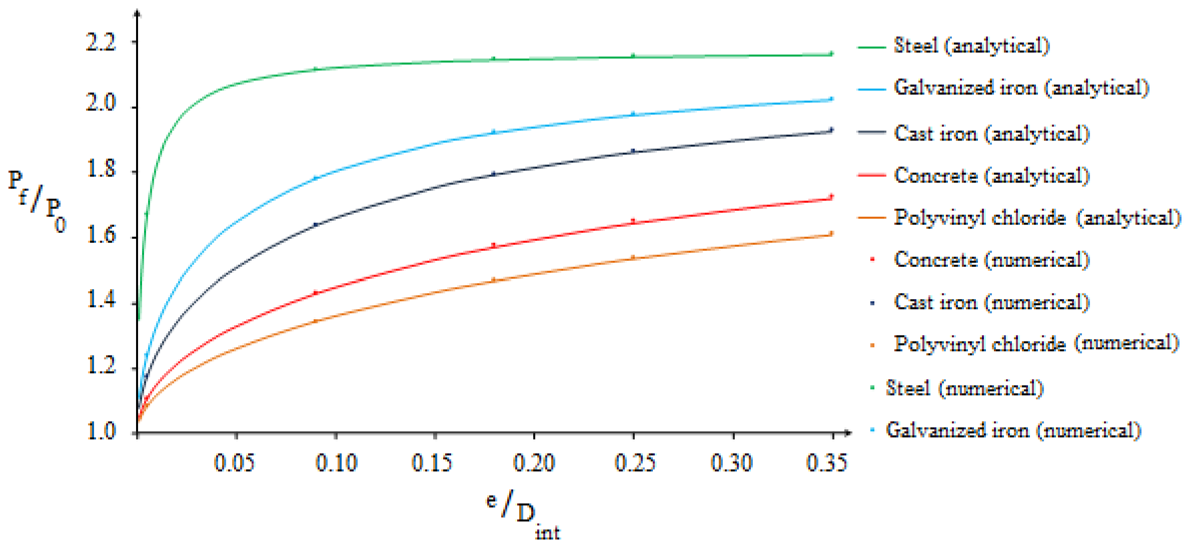

Figure 6: Analytical and numerical results dor relation between pressures depending on geometry and material

Fig.6 shows the comparison between the results of the analytical solution (continuous line) expressed in (15) and the numerical solution (dots) obtained with the Transpetro-1D software. It is observed that as smaller the relation e/Dint is, it has greater influence on the propagation of waves, and when these relations are large the behavior is governed by the numerator (k/ρ).

$$a = \sqrt{\frac{k/\rho}{1+\left(k/E\right)\left(D/e\right)c}} \rightarrow \lim_{e/D \rightarrow \infty} : a = \sqrt{k/\rho} \qquad (16)$$

Higher overpressure is generated for stiffer materials, with steel being the material that generates the most overpressure. With the sudden closing of the valve, there is an over 100% increase in pressure for steel, making it an important case to be analyzed. It is observed that the steel present's greater increase in pressure due to the sudden closing of the valve, while the lowest value is observed for PVC.Table 4 presents the analytical and numerical results obtained by the different simulations, showing the absolute errors obtained for each of them.

Table 4: Simulation error

e/Dint	Steel	Concrete	Galvanized iron	Cast iron	Polyvinyl chloride
0.005	0.004 %	0.010 %	0.006 %	0.006 %	0.005 %
0.090	0.049 %	0.160 %	0.066 %	0.077 %	0.072 %
0.180	0.131 %	0.419 %	0.139 %	0.157 %	0.181 %
0.250	0.145 %	0.442 %	0.175 %	0.204 %	0.192 %
0.350	0.172 %	0.489 %	0.203 %	0.234 %	0.224 %

From the results obtained in the different simulations, the relations of the pressures were investigated as a function of a parameter "α" defined in (16), which is determined by the velocity of the transient wave propagation.

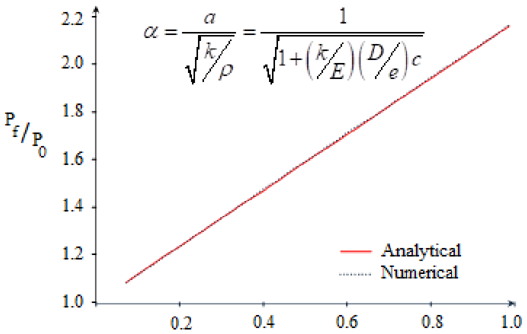

Figure 7: Analytical and numerical results for pressure relation as a function of α.

Table 5 presents the analytical and numerical pressure ratios obtained for the different simulations, with their respective errors.

Fig.7 shows in detail the relation between final pressure and initial pressure as a function of theα parameter defined by (16) for the simulations indicated in Table 5. The relation between final and initial pressure is directly related to the "α" parameter. In addition, it is important to clarify that this graphic also shows a variation of the inner diameter, thickness and material of the duct.

Fig.8 shows a signal of the history of the transient pressure wave for a point located at the duct (Fig. 1), in this case a modeling was made with a concrete pipe with 0.452 m internal diameter, a thickness of 0.045 m, and relative roughness of 0.003 m (f = 0.0329) and 0.0003 m (f = 0.0186). Not much difference in the first cycle is observed, but after the third cycle a difference is generated due to the difference in the friction factor, where the largest friction factor causes the largest fall to transient pressure wave

Table 5: Analytical and numerical pressure results

α	Pf/Po Analytical	Pf/Po Numerical	Error %
0.032	1.038	1.038	0.005
0.041	1.049	1.049	0.011
0.068	1.080	1.080	0.006
0.093	1.110	1.110	0.006
0.096	1.114	1.114	0.052
0.123	1.145	1.146	0.113
0.128	1.151	1.152	0.073
0.163	1.192	1.194	0.161
0.200	1.235	1.236	0.061
0.262	1.309	1.310	0.082
0.270	1.318	1.319	0.054
0.297	1.350	1.350	0.005
0.351	1.413	1.414	0.072
0.432	1.508	1.511	0.149
0.517	1.609	1.611	0.165
0.522	1.615	1.621	0.365
0.611	1.720	1.727	0.398
0.683	1.804	1.804	0.034
0.710	1.835	1.839	0.168
0.779	1.918	1.919	0.047
0.786	1.925	1.929	0.186
0.811	1.955	1.958	0.144
0.868	2.022	2.026	0.162
0.977	2.151	2.153	0.118
0.986	2.160	2.163	0.130

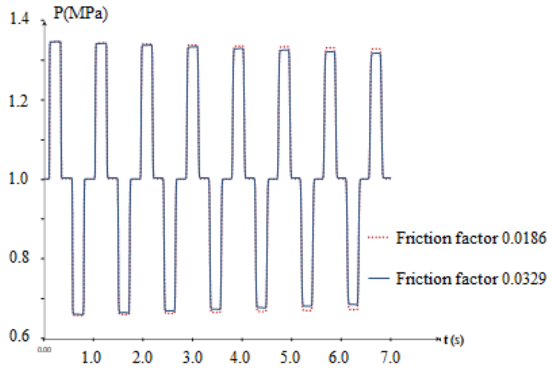

Figure 8: Transient pressure wave as a function of time and different relative roughness

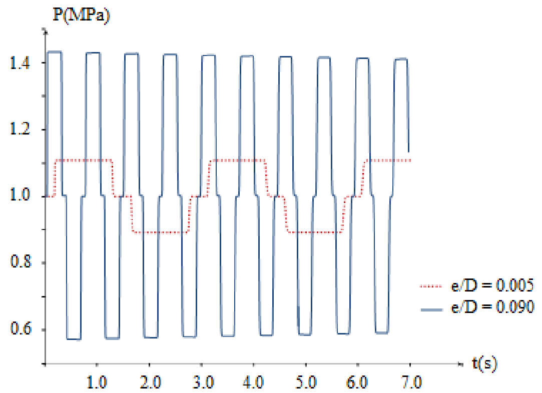

Figure 9: Transient pressure wave as a function of time and different inner diameter

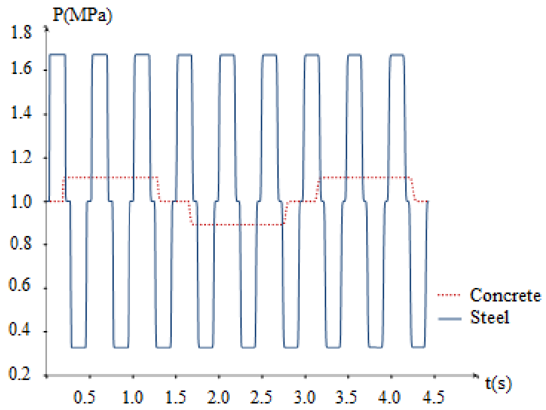

Figure 10: Transient pressure wave as a function of time and different materials

Fig.9 shows the history of the transient pressure wave for a point located in the duct (Fig.1), in this case a concrete duct with different relations between thickness (e) and internal diameter (D) was modeled, namely e/D = 0.005, and, e/D = 0.09.A considerable difference in the transient pressure wave of the system is observed, where for a greater relation between diameter and thickness it has greater pressures values and more cycles for a given time, as a consequence of the variation in acceleration of transient wave.

Fig. 10 shows the transient pressure wave history for a point located in the duct (Fig.1), in this case were made a modeling with a concrete duct and a steel duct with the same dimensions and system configuration (e/D = 0.005). There is a considerable difference in the transient pressure wave of the system, where steel shows higher pressures and more cycles for a given time, as a consequence of the variation of acceleration of the transient wave due to material stiffness.

VII. CONCLUSIONS

The physical and mechanical properties of the forced duct have a direct influence on the transient pressure waves generated in the hydraulic systems due to the sudden closure of a valve, as they modify the velocity of the waves by generating increases or decreases in waves magnitudes and cycles.

The experimental, analytical and numerical results are very similar, which allows to evaluate the methodology and the computational software used in the analysis of the transient phenomenon generated in hydraulic ducts forced by the sudden closure of a valve.

According to the simulation, it can be stated that for high stiff materials and low relations between thickness and internal diameter (e / D), transient pressure waves has greater magnitudes and velocities, which requires systems of most advanced and powerful control in the hydraulic systems.

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