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Influence of Pipe Inclination Angle in Pressure Induced by a Hydraulic Transient

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Abstract-Transient flow is one of the main phenomena to be analyzed in projects for large hydraulic systems in industrial pipelines. These types of projects require inclined pipes due to the geographical and topographic conditions of the place, which during the operation of the system can generate a variation in the transient wave caused by the valve closing process. For this study, a specific circuit was established where simulations were carried out with different pipe inclination angles. The simulation was made using the computer program TRANSPETRO-1D, developed by the GDFE (Group of Dynamics and Fluid Structure) of the University of Brasília, which allows to represent forced tubular circuits in different conditions using the Method of Characteristics together with the Finite Difference Method. Finally, the influence of four different values of pipe inclination angle, with their main transient waves of pressure and speed, was verified, in order to evaluate the scenarios where they are used in hydraulic systems with predetermined characteristics.

Keywords- *Hydraulic Transient, Pipe Inclination Angle, Transient wave, Pressure*

I. INTRODUCTION

The study of the transient pressure phenomenon is of great interest due to its relevant impact on the systems used to transport fluids. In the technical literature, researchers from all over the world have studied the most important concepts and the main equations for their analysis. Pioneering research was developed and confirmed experimentally by Joukowsky [1], Allievi [2] and Streeter and Wylie [3], the latter being the authors of the most important and complete work on this phenomenon, serving as the basis for several studies that address since the concepts from the phenomenon to applications in more complex problems, highlighting the methods of analysis, and several computational algorithms based especially on the Characteristics Method.

Among recent studies, Brunone [4] published their experimental results for variations in speed of the closing a valve. Izquierdo and Iglesias [5] presented a mathematical model for the analysis of hydraulic transients, which resulted in the development of the DYAGATS program. Izquierdo and Iglesias [6] compared the results obtained by commercial software SURGE5. Pires, Barreto and Ladeia [7] studied the transients in short ducts generated by the rapid closing of valves. Magzoub and Kwane [8] used the graphic method and the Characteristics Method in the construction of models to calculate and simulate transients in some conduits. Silvore [9] developed a transient analysis program in Java that allowed working with shut-off valves. Bratland [10] writes the book “Pipe Flow 1: Single-phase Flow Assurance” which addresses more complex problems such as the variation in heat calculated by the Characteristics Method. Seleghim [11] developed the study of wave propagation in fluid transport ducts through the analysis of acoustic attenuation and velocity propagation. Fontes, Lima and Bezerra [12] did a practical job to determine fatigue in pipes subjected to the transient phenomenon. Bratland [13] writes the second book “Pipe Flow 2: Multi-phase Flow Assurance” in which determine the flow regime, analysis of flows that have presence of liquid and gas, and solutions by numerical methods. 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 [14]; Vélez [15], Vélez and Pedroso [16] and Vélez, Silvera, Rego and Sousa [17].

II. THEORETICAL FORMULATION

The transient phenomenon will be approached using the equations of continuity, motion and state. The hypotheses and simplifications used for the study are: fluid homogeneous, viscous and slightly compressible, isotropic monophasic flow, and negligible thermodynamic effects. The deformations at the duct wall are considered.

A. Continuity Equation

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

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

Using classical expressions for ducts and some simplifications, we obtain the following expression called continuity equation for ducts that suffer infinitesimal strains.

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

$$a=\frac{\sqrt{k/\rho}}{\sqrt{1+\left(k/E\right)\left(D/e\right)C}} \qquad (3)$$

In which, a: Pressure wave speed (m/s);

k: Fluid Bulk modulus Fluid (N/m²);

ρ: Fluid density (kg/m³);

E: Young's modulus (N/m³);

D: Inner diameter of the pipe (m);

e: Pipe wall thickness (m);

C: Pipe constraint coefficient (dimensionless parameter that describes the effect of pipe constraint condition on the wave speed).

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.

$$\begin{aligned}&\rho\frac{\partial\vec{V}}{\partial t}+\rho\vec{V}\,\nabla\left(\vec{V}\right)+\nabla\left(P\right)\\&-\mu\left[\Delta\vec{V}+\frac{1}{3}\nabla\left(DIV\left(\vec{V}\right)\right)\right]=0\end{aligned} \qquad (4)$$

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

$$\frac{1}{\rho}\frac{\partial P}{\partial x}+g\cdot sen\left(\alpha\right)+\frac{f\cdot V\cdot\left|V\right|}{2D}+V\frac{\partial V}{\partial x}+\frac{\partial V}{\partial t}=0 \qquad (5)$$

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).

$$f\left(V,D,\nu,\varepsilon\right)=\frac{0.25}{\left(\log_{10}\left(\frac{\varepsilon}{3.7D}+\frac{5.74}{\mathrm{Re}\left(V,D,\rho,\mu_{f}\right)^{0.9}}\right)^{2}\right)} \qquad (6)$$

In which, ε: Roughness size projections (m);

RE: Reynolds number;

α: Inclination pipe angle (°).

C. *State Equation*

The relation associates the variables of pressure and volumetric mass with the velocity of sound in the 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 [18] present the following equation continuity:

$$P=\rho\cdot a\cdot V_{0}\left(1+\frac{V_{0}}{a}\right) \qquad (7)$$

Since Vo << a the term Vo/a is negligible and we have a new expression to define the transient pressure and velocity wave in the pipe, 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. In this work is to make a set of simulations modifying the inclination pipe angle.

III. SOLUTION METHOD

The Characteristic Method transforms partial differential equations into total differential equations, which are solved by the first order Finite Difference Method. It is a numerical method with important advantages, like the flexibility for introducing boundary conditions [3].

A. *Characteristics Method*

Pressure and velocity are two time-dependent variables, this can be seen in Equations [2] and [5] which are the partial differential equations; with the equations of continuity and motion, Equations [8] and [9], respectively, the development of the Characteristics Method is carried out.

$$L_{1}=V\frac{\partial P}{\partial x}+\frac{\partial P}{\partial t}+\rho a^{2}\frac{\partial V}{\partial x}=0 \qquad (8)$$

$$L_{2}=\frac{1}{\rho}\frac{\partial P}{\partial x}+g\cdot sen\left(\alpha\right)+\frac{f\cdot V\cdot\left|V\right|}{2D}+V\frac{\partial V}{\partial x}+\frac{\partial V}{\partial t}=0 \qquad (9)$$

Between Equations [8] and [9], a linear combination is made through the multiplier λ, where the following equation results:

$$L_{1}+\lambda L_{2}=0 \qquad (10)$$

Expanding the total differential equations over time in partial differences, for the variables Pressure (P) and Velocity (V) and comparing with the terms of Equation [10]. It is concluded that for the ordinary differential terms as:

$$\lambda=\pm\frac{1}{\rho\cdot a} \qquad (11)$$

$$\frac{dx}{dt} = V \pm a \qquad (12)$$

Substituting Equations [11] and [12] in Equation [10] and after a rearrangement there are characteristic equations, which are valid once Equations [13] and [15] are satisfied.

$$a^{+} \begin{cases} \dfrac{1}{\rho \cdot a} \cdot \dfrac{dP}{dt} + \dfrac{dV}{dt} + g \cdot sen(\alpha) + \dfrac{f \cdot V \cdot |V|}{2D} = 0 & (13) \\ \dfrac{dx}{dt} = V + a & (14) \end{cases}$$

$$a^{-} \begin{cases} -\dfrac{1}{\rho \cdot a} \cdot \dfrac{dP}{dt} + \dfrac{dV}{dt} + g \cdot sen(\alpha) + \dfrac{f \cdot V \cdot |V|}{2D} = 0 & (15) \\ \dfrac{dx}{dt} = V - a & (16) \end{cases}$$

B. Finite Difference Method

To solve Equations [14] and [16] Finite Difference Method are used. In this work we will use the finite difference method. First, it shows how the method is developed in the plane (x-t), in Figure 1 where the characteristic curves a^{+} and a^{-} are known as characteristic lines.

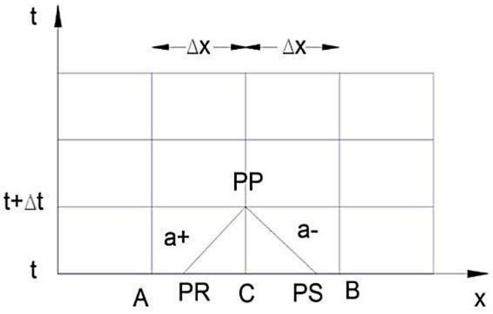


Figure 1. Characteristic lines (Adapted Nascimento 2002).

For characteristic curve a^{+} and a^{-}, respectively

$$V_{PP} - V_{PR} - \frac{1}{\rho a}\left(P_{PP} - P_{PR}\right) + g\left(t_{PP} - t_{PR}\right) sen(\alpha) + \ldots$$
$$\frac{f}{2D} V_{PR} \left|V_{PR}\right| \left(t_{PP} - t_{PR}\right) = 0 \qquad (17)$$

$$V_{PP} - V_{Ps} - \frac{1}{\rho a}\left(P_{PP} - P_{PS}\right) + g\left(t_{PP} - t_{PS}\right) sen(\alpha) + \ldots$$
$$\frac{f}{2D} V_{Ps} \left|V_{Ps}\right| \left(t_{PP} - t_{PS}\right) = 0 \qquad (18)$$

Adding Equations [17] and [18], the following expressions are obtained to determine the pressure value and velocity at the point PP:

$$V_{PP} = \frac{1}{2} \begin{bmatrix} V_{PR} + V_{PS} + \dfrac{1}{\rho a}\left(P_{PR} - P_{PS}\right) - 2g\,\Delta t \cdot sen(\alpha) \ldots \\ -\dfrac{f \cdot \Delta t}{2D}\left(V_{PR}\left|V_{PR}\right| + V_{PS}\left|V_{PS}\right|\right) \end{bmatrix} \qquad (19)$$

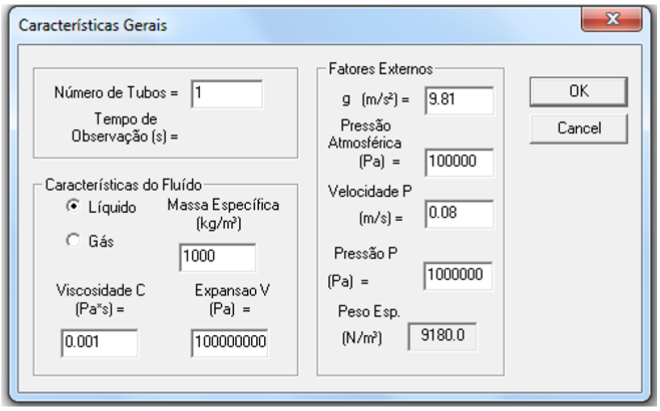
$$P_{PP} = \frac{1}{2} \begin{bmatrix} P_{PR} + P_{PS} + \left(\rho \cdot a\left(V_{PR} - V_{PS}\right)\right) \ldots \\ -\dfrac{f \cdot \Delta t}{2D}\left(V_{PR} \cdot \left|V_{PR}\right| - V_{PS} \cdot \left|V_{PS}\right|\right) \end{bmatrix} \qquad (20)$$

Since both conditions P and V are unknown at points PR and PS, the specified Time Intervals Method is used as a solution [3].

IV. TRANSPETRO 1D

The TRANSPETRO 1D software was developed by the Dynamics and Fluid Structure Group (GDFE) of the University of Brasilia (UnB), in the master's dissertation of Nascimento [14], 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 [3]. The GDFE, based on these routines, developed new programs in the FORTRAN90 computer language: first TRANS, Pedroso, Macedo and Barbosa [19], TRANS-II e TRANS-III, Pedroso, Brito and Barbosa [20], and later RETRANS [18], both oriented to transient problems in circuits of Nuclear reactors. With the experience obtained in the validation of the formulation and the theory employed, a new program was reoriented for transient problems in the oil sector called TRANSPETRO 1-D.

Figures 2 and 3 presents the input the options to enter the physical properties of the fluid and the physical and mechanical properties of the pipe including the pipe inclination angle.



Características Gerais

Número de Tubos = 1

Tempo de Observação (s) =

Características do Fluído

● Líquido

○ Gás

Massa Específica (kg/m³) 1000

Viscosidade C (Pa*s) = 0.001

Expansao V (Pa) = 100000000

Fatores Externos

g (m/s²) = 9.81

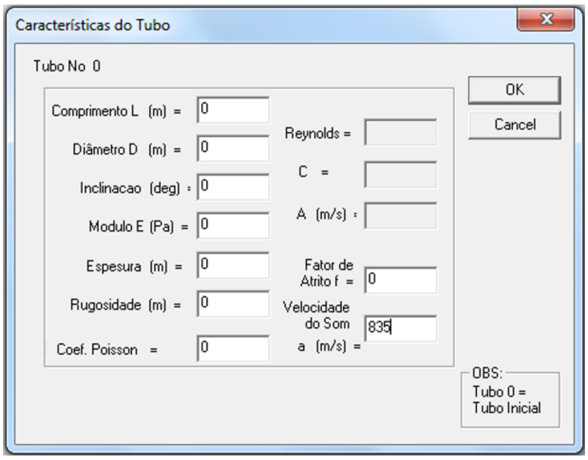
Pressão Atmosférica (Pa) = 100000

Velocidade P (m/s) = 0.08

Pressão P (Pa) = 1000000

Peso Esp. (N/m³) 9180.0

Figure 2. Input physical properties of the fluid – TRANSPETRO 1D.



Tubo No 0

Comprimento L (m) = 0
Diâmetro D (m) = 0
Inclinacao (deg) = 0
Modulo E (Pa) = 0
Espesura (m) = 0
Rugosidade (m) = 0
Coef. Poisson = 0
Reynolds =
C =
A (m/s) =
Fator de Atrito f = 0
Velocidade do Som a (m/s) = 835

OBS: Tubo 0 = Tubo Inicial

Figure 3. Input the physical and mechanical properties of the pipe including the pipe inclination angle – TRANSPETRO 1D.

V. SIMULATIONS AND RESULTS

In order to find the influence of the inclination pipe angle for this phenomenon, 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 Figure 4. Simulations were made with four different pipe angles (0°, 5°, 10° and 20°). The general data of the experiment are presented in Table 1.

TABLE I. CONTRACTOR EXPERIMENTAL DATA

Properties	Experimental values		
	Property	*Unity*	*Value*
System	Initial velocity at the valve	m/s	0.366
	Initial pressure at the valve	Pa	597213.972
	Pressure wave speed (a)	m/s	1149.5
	Gravity acelaration (g)	m/s²	9.81
Fluid	Fluid density (ρ)	Kg/ m³	998.2
Pipe	Length (L)	m	12.2
	Diameter (D)	m	0.1
	Coefficient of friction		0.24

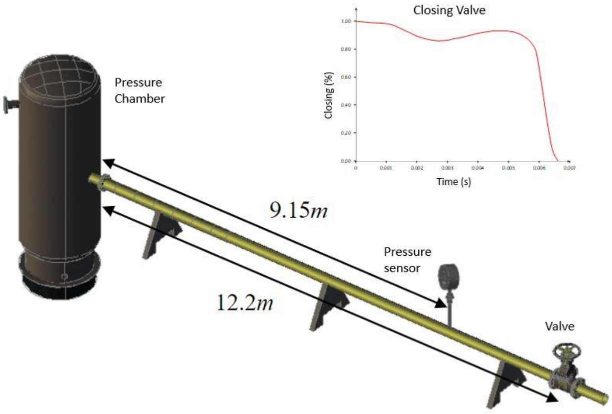


Figure 4. Scheme of experimental hydraulic system (Adapted Contractor 1965).

Figure 5 shows the scheme of the simulations made with the respective inclination pipe angle (degrees).

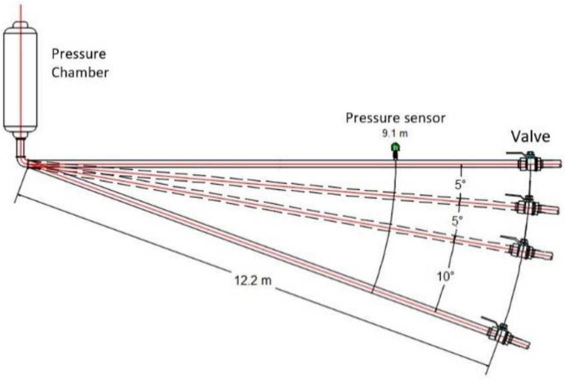


Figure 5. Scheme of the simulations with the inclined pipe angle.

Figure 6 shows the transient pressure wave to a point located on the pressure sensor. The magnitude of the pressure of the transient wave and the angle of inclination of the duct are inversely proportional.

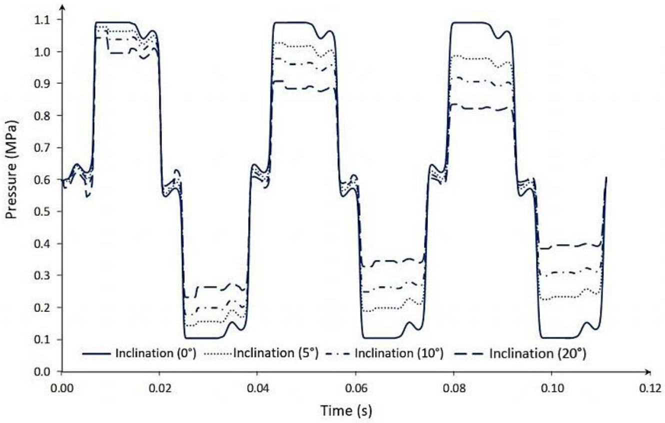


Figure 6. Transient pressure waves for different inclined pipe angles.

Figure 7 shows the transient velocity wave to a point located on the pressure sensor, and it is decrease with the inclination pipe angle increases.

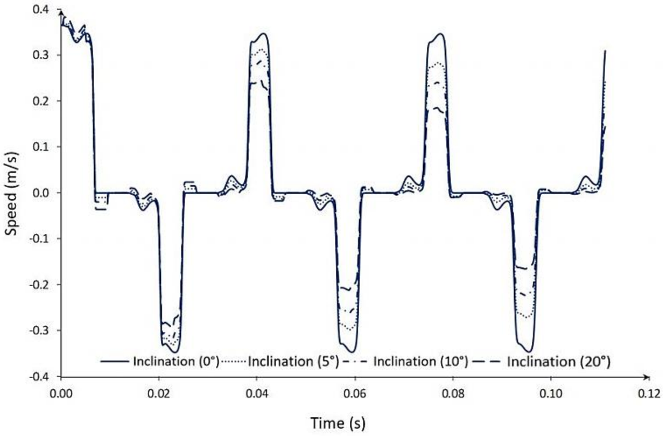


Figure 7. Transient velocity waves for different inclined pipe angles.

The graphs presented in Figures 6 and 7 show the same behavior in relation to the duct slope effect, making a detailed analysis it is identified that when one of them presents the highest magnitudes or the other has the lowest values. This is due to the relationship between pressure and velocity waves, where velocity is a proportional derivative of pressure.

VI. CONCLUSIONS

It can be said that as the duct slope increases, the overpressures generated in the transient phenomenon are lower, and it is conservative to make an analysis of the duct in a horizontal position. Additionally, it is observed that the losses are greater for each cycle that has passed. These conclusions are partial, being necessary to be evaluated with experimental results and/or other numerical methods.

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