ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

MODEL DEVELOPMENT AND NUMERICAL SIMULATION FOR DETECTING PRE-EXISTING LEAKS IN LIQUID PIPELINE

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Abstract. *The transportation of products through pipelines is the most common option, both in industrial applications involving long distances as well as in distribution networks in which a product must be delivered to a number of processes or customers. The analysis of hydraulic transients has been particularly useful for leak detection purposes. The analytical solution for unsteady flow is obtained by using the equations for continuity and momentum. The application of these equations leads to a couple of nonlinear partial differential equation which must be solved numerically. This paper describes the numerical model suited to the simulation of a new leak detection technique, based on active acoustic inspection of the pipeline, which is capable of detecting pre-existing leaks. Numerical results were compared to the ones obtained from experimental tests conducted at the pilot pipeline of the Industrial Multiphase Flow Laboratory at University of São Paulo, campus of São Carlos – SP and experimental data from literature. Results confirm that the numerical model captures the correct physics of the propagation phenomena and validates our model as an on-line predictor to be used in a LDS system.*

Keywords: *detection, acoustic inspection, numerical simulation, hydraulic transient.*

1. INTRODUCTION

The transportation of products through pipelines is the most common option, both in industrial applications involving long distances as well as in distribution networks in which a product must be delivered to a number of processes or customers. Pipelines are considered the best means of fluid transportation; pipeline systems are the safest means to move petrochemical products. Due to safety and environmental reasons, the operation of such pipelines must include an on-line Leak Detection System (LDS), which promptly detects and assesses the occurrence of a leak, particularly if the transported product is toxic or inflammable. This need is absolutely clear in view of the significant number of accidents that have been occurring, usually with important economical and environmental consequences. The techniques currently applied cover a large variety of methods, going from visual inspection to sophisticated hardware/software-based specialist systems. Focusing on LDS's requiring on-line instrumentation installed at the ends of the pipeline, or, at least, at a few locations kilometers apart, these techniques can be grouped into two categories: 1) fast signal processing based methods and 2) slow process signal based methods.

Among the fast signal processing techniques, probably the most applied method relies on detecting the presence of pressure waves associated with the flow transient (acoustic) caused by the appearance of the leak (Silk and Carter, 1995). Generally speaking, acoustic LDS is applicable to liquid, gas and some multiphase pipelines, is a fast method and locates the leak accurately, but the precision of the estimated leak flow rate is poor. Another important characteristic is that an acoustic LDS is not suited for detecting gradually developing leaks.

The analysis of hydraulic transients has been particularly useful for calibration and leak detection purposes. The system observation for such analysis can reveal a substantial amount of information concerning physical properties and the integrity of the system, since water hammer waves are affected by different features and phenomena, including leaks. The basic mathematical model of a pipeline is a nonlinear distributed parameter model. It describes the one dimensional compressible fluid flow through the pipeline and is represented by a set of nonlinear partial differential equations (Streeter and Wylie, 1993). However, no general closed-form solution of these equations have been known yet. Numerical approaches, like the Method of Characteristics must be used instead. The objective of this work is the development and validation of a model for the simulation of a new leak detection technique, based on active acoustic inspection of the pipeline, capable of detecting pre-existing leaks.

2. NUMERICAL SOLUTION OF THE NONLINEAR PIPELINE MODEL

The assumptions in the development of transient flow equations are:

1) The flow in the pipeline is considered to be one-dimensional with average velocity and uniform pressure at a section.

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2) The fluid is single-phase, homogeneous and compressible (the compressibility of the fluid is incorporated into the speed of propagation of the elastic wave).

3) Variations in the density of the fluid flow and temperature during the transition are negligible compared to variations in pressure and flow.

4) Unsteady friction losses are approximated as quasi-steady state losses.

5) There is no axial motion, i.e. the fluid-structure interaction is neglected.

6) The pipe is rectilinear and horizontal, with an area of constant cross section and without lateral flow (although variations in the cross section and lateral flow can be included as control conditions).

By enforcing mass and momentum balance one obtains:

$$\frac{\partial H}{\partial t} + V\frac{\partial H}{\partial x} - Vsin\theta + \frac{a^2}{g}\frac{\partial V}{\partial x} = 0 \tag{1}$$

$$g\frac{\partial H}{\partial x} + \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{fV|V|}{2D} = 0 \tag{2}$$

with piezometric head *H(x)*, velocity *V(x)* , gravitational acceleration *g*, coordinate along the pipe axis *x*, time *t*, celerity or pressure wave speed *a* and Darcy-Weibach friction factor *f*.

For most engineering applications, the convective terms $V(\partial H / \partial x)$, $V(\partial V / \partial x)$ are very small compared to the other terms and may be neglected (Chaudhry, 1987). A simplified form of Eqs. (1) and (2) using the discharge $Q=VA$ instead of the flow velocity V is:

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \tag{3}$$

$$\frac{\partial H}{\partial x} + \frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{fQ|Q|}{2gDA^2} = 0 \tag{4}$$

Equations (3) and (4) represent the nonlinear distributed parameters model of a pipeline.

2.1 Numerical Solution by the Method of Characteristics

The method of characteristics was applied to solve the system of Eqs. (3) and (4). According to this method, the solution is given by the linear combination of these two equations, therefore $L = L_1 + \lambda L_2$. Being

$$L_1 = \frac{\partial H}{\partial x} + \frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{f}{2gDA^2}Q|Q| = 0 \tag{5}$$

$$L_2 = \frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0, \tag{6}$$

thus

$$\lambda\left(\frac{\partial H}{\partial t} + \frac{1}{\lambda}\frac{\partial H}{\partial x}\right) + \frac{1}{gA}\left(\frac{\partial Q}{\partial t} + \lambda a^2\frac{\partial Q}{\partial x}\right) + \frac{f}{2gDA^2}Q|Q| = 0 \tag{7}$$

The two variables *H (x, t)* and *Q (x, t)* are functions of *x* and *t*, requiring a dependency between *x* and *t*, we obtain the value of parameter λ:

$$\lambda = \pm\frac{1}{a} \tag{8}$$

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Equation (7) can be expressed by

$$\frac{dQ}{dt} + \lambda\, gA \frac{dH}{dt} + \frac{f}{2DA} Q|Q| = 0 \tag{9}$$

A transformation into four ordinary differential equations grouped into two pairs of equations by the method of characteristics is possible

- along the C^{+} characteristic line ($dx/dt = +a$)

$$\frac{dQ}{dt} + \frac{gA}{a}\frac{dH}{dt} + \frac{fQ|Q|}{2DA} = 0 \tag{10}$$

- along the C^{-} characteristic line ($dx/dt = -a$)

$$\frac{dQ}{dt} - \frac{gA}{a}\frac{dH}{dt} + \frac{fQ|Q|}{2DA} = 0 \tag{11}$$

To satisfy these characteristics relation, the x-t grid is usually chosen to ensure $dx/dt = +a$ (stability condition).

These equations may then be integrated to yield finite difference equations, which are conveniently handled numerically.

The friction factor, explicitly used in Eqs (10) and (11), is expressed as the sum of the quasi-steady part f_q and the unsteady part f_u. The computation of the quasi-steady part f_q is straightforward, whereas the unsteady part f_u is related to the instantaneous local (temporal) acceleration $1/A(\partial Q/\partial t)$ and instantaneous convective (spatial) acceleration $1/A(a\,\partial Q/\partial t)$, i.e.,

$$f = f_q + f_u = \frac{fQ|Q|}{2DA} + k_3\left(\frac{\partial Q}{\partial t} - a\frac{\partial Q}{\partial x}\right) \tag{12}$$

The Brunone friction coefficient k_3 can be predicted either empirically or analytically. The analytical definition of k_3 using Vardy and Brown's shear decay coefficient C* (Vardy and Brown, 1996) is used in this paper.

3. NUMERICAL SOLUTION OF THE NONLINEAR PIPELINE MODEL

The numerical software was developed together with the numerical model suitable for the simulation of a leak detection technique, based on an active acoustic inspection of the pipeline. More precisely, acoustic pulses were artificially produced and injected in to the flow at one of the ends of the monitoring pipeline section. These pulses traveled to the other end, where an acoustic pressure sensor was placed to measure the corresponding signal. During the travel from one side of the pipeline to the other, attenuation and distortion result from the flow characteristics and pipe's geometry. If a leak existed somewhere in the acoustic path, the measured pulse would be different from the one measured prior to the existence of the leak. In other words, a leak can be detected by assessing attenuation and distortion and comparing the corresponding parameters with reference to the one previously determined without leaks.

The simulator developed for hydraulic analysis in the transitional was encoded in FORTRAN language and implemented by Force 2.0. The routines that allow the evaluation of different contour conditions are reservoir-level variable or constant, leakage and demand variables using the formulation of leaks in-line-valve and atmosphere-valve.

3.1. Experimental Procedure

The numerical results were compared to the ones obtained from experimental tests conducted at the pilot pipeline of the Industrial Multiphase Flow Laboratory at University of São Paulo, campus of São Carlos - SP. The test section is constituted of 50mm internal diameter metal tubes extending through approximately 1000m between the exit of the water pump and the entrance of the separation reservoir. This experimental setup is shown in the following figure:

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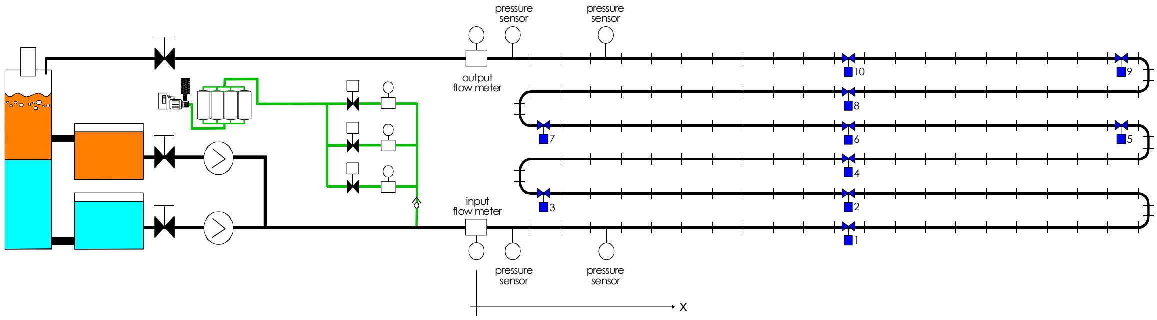

Figure 1. Schematic representation of the pilot pipeline at the Industrial Multiphase Flow laboratory.

Four pressure sensors and two magnetic flow meters were positioned at the inlet and outlet sections of the pipeline. Ten solenoid valves were distributed along the pipeline and used to simulate leaks at known positions.
In this work, 13 pump frequencies and ten leak positions were simulated in triplicate to constitute a total of 390 experimental tests. The duration of each test corresponded to 80 seconds and the whole experiment cycle took 4 and a half hours, approximately. The acoustic inspection pulses corresponded to water hammers generated by closing a fast action valve placed at the exit end of the pipeline.

A National Instruments electronic hardware is responsible for acquiring all test or process signals (temperatures, pressures, flow rates, etc.), as well as for generating all command signals to pumps, solenoid valves, and so on. Specifically, a PXI1000B chassis equipped with an NI8176 controller module (5000MHz Pentium processor) runs the experiment driver written in LabView. The PXI chassis is equipped with NI6025E modules through which all input and output signals are A/D converted. The experiment driver executes several operations cyclically in order to assure that each experimental test will be executed precisely the same way. A typical experimental cycle is as follows:

1- Set water pump frequency and open leakage simulation valve
2- Wait for 30 seconds
3- Start acquisition of test signals
4- Wait for 10 seconds
5- Close exit valve to produce a water hammer
6- Wait for 70 seconds
7- Stop acquisition of test signals
8- Store data in an ASCII file

3.2 .Results and validation

The numerical and experimental results are presented and compared in this section. The numerical simulations were performed on data observed in experimental tests. The numerical section is constituted of 50mm internal diameter metal tubes extending through 757m between pressure sensor 1 and the water hammer valve. Such as in the experimental tests, ten solenoid valves distributed along the pipeline were considered and used to simulate the leak in the same position known in the tests the pressure values were obtained in four pressure sensors, the initial contour conditions were obtained by taking the pressure and flow values generated in the test and read in the first line of the output data file. The numerical cycle is as follows:

1-Set initial conditions and contour
2-Wait until data have stabilized
3-Open valve leakage simulation
4- Wait until data have stabilized
5-Start logging
6-Close exit valve to produce a water hammer
7- Wait until data have stabilized
8-Stop logging
9-Store data in an ASCII file.

The results for a transient event of 80s are shown in Figs. 2, 3, 4 and 5, at the point where the pressure sensors are located according to Tab. 1, considering the following cases: (i) experimental data, in Figs. 2 and 4; (ii) linear elastic model considering Brunone friction factor with variable damping coefficient $k_3 = 0.10$ in Figs. 3 and 5.

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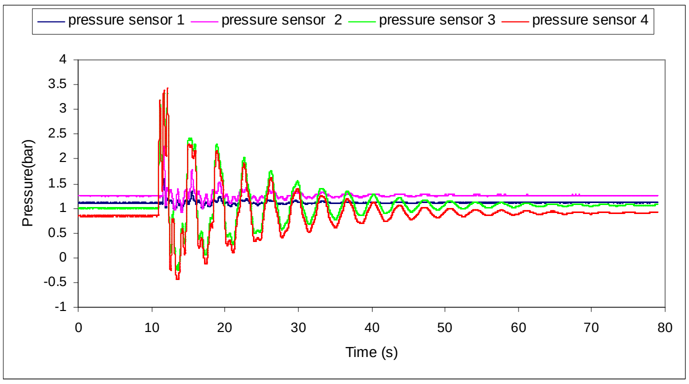

Figure 2. Experimental results in a pipeline without leak.

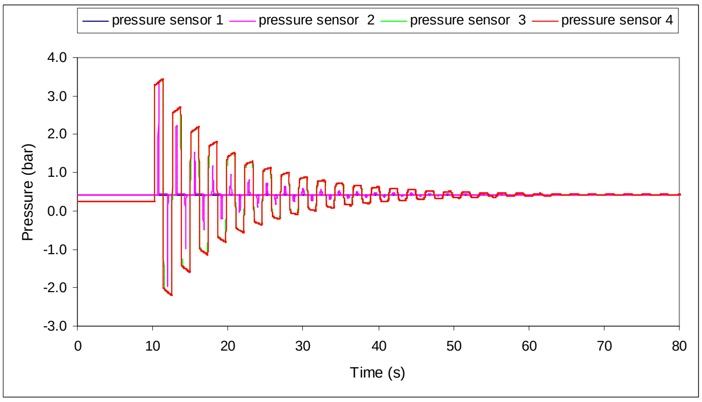

Figure 3. Numerical results in a pipeline without leak.

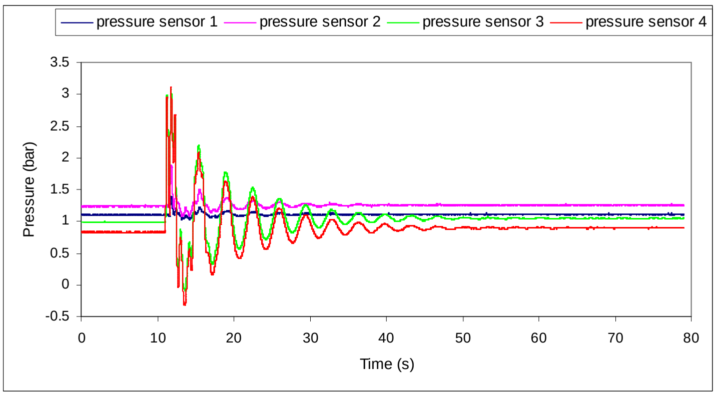

Figure 4. Experimental results in a pipeline with a leak in solenoid valve 1.

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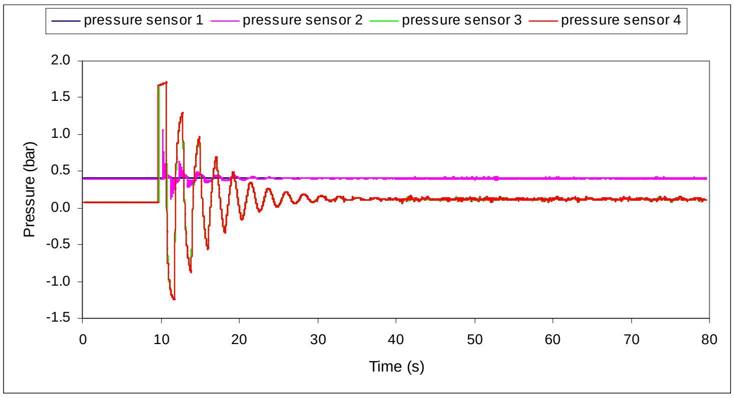

Figure 5. Numerical results in a pipeline with a leak in solenoid valve 1.

Figures 6 and 7 show the results of the experimental tests and computational simulation, for the computational model considering a variable factor friction and constant factor friction equal to 0.1 and 0.2 The Fourier transform filter was utilized to extract the average value from the signal.

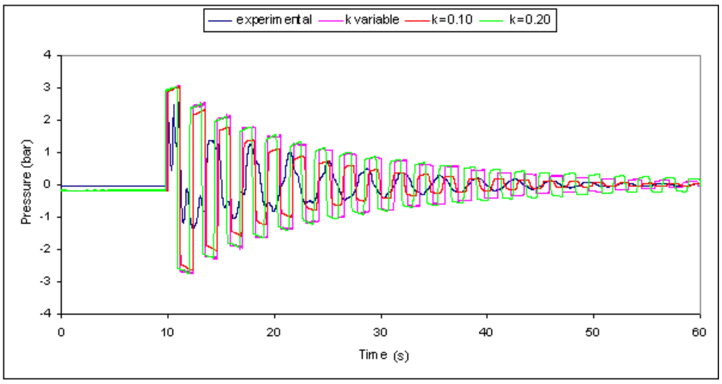

Figure 6. Comparison between numerical and experimental results in the pipeline without leak.

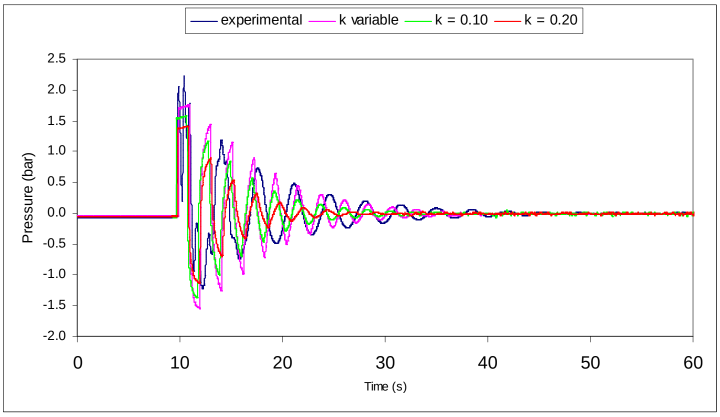

Figure 7. Comparison of numerical and experimental results in the pipeline with a leak in solenoid valve 1.

The numerical results presented a good agreement with the attenuation parameter of the experimental tests confirming that the numerical model captured the correct physics of the propagation phenomena.

Analyzing the transient flow caused by closing the valve, it was observed that the attenuation of pressure pulses in the case of leakage is higher compared to the system without leaks, and the stabilization of the flow is faster in systems with leaks. The differences in the frequency of waves between the numerical and experimental results are due to spurious frequencies found in the experimental results caused by the resonance of the pipe and other factors that are assumed in the development of the equations of water hammer. In the figures comparing the experimental and

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numerical results where the Fourier transform was applied, different values of K_3 were assessed. It was possible to observe that the pressure variation presents a higher attenuation as the damping coefficient increases.

The results obtained via hydraulic simulator were used in the numerical model suited to the simulation of leak detection technique.

4. EXPERIMENTAL AND NUMERICAL RESULTS ABOUT ATTENUATION COEFFICIENT OF AN ACOUSTIC WAVE

Numerical results on measuring the attenuation coefficient for acoustic waves propagating in long oil and petroleum product pipelines are also presented. A comparison of experimental and numerical results is performed using the experimental data obtained by Glikman and Barabanov (2009) long oil pipeline (Table 1). On numerical tests, leaks were simulated in different positions along the pipe and the leak detection technique, based on active acoustic inspection of the pipeline, was applied for the inspection in the pipeline.

Table 1. Tests on an oil pipeline along with the following specifications:

Length of pipeline	**290 km;**
Diameter of pipe	**1m;**
Density	**872.3 kg/m^3;**
Speed	**0,442 m/s;**
Viscosity	**0,01836 Pa.s;**
Celerity	**1.040 m/s.**

The acoustic inspection pulses corresponded to water hammers generated by closing a fast action valve placed at the beginning of the pipeline. A series of tests was carried out, which consisted in simulating leaks in different positions. The propagation of pressure wave generated by the disturbance is observed along the pipeline at points where sensors are located and the amplitude of the pressure wave obtained in these points versus the coordinates points are approximated by an exponential curve given by $\Delta P = \Delta P_0 \exp(-\alpha x)$. Since $\Delta P = P_{end} - P_{begin}$ is the pressure drop between the beginning and end of the wave front. The pressure difference is considered magnitude of disturbance, i.e. the wave amplitude. The magnitude of the pressure drop (the wave amplitude) at each of the sensors versus the sensor coordinate was plotted. The zero coordinate was taken to be the coordinate at which the perturbation arose.

As a result for the experimental and numerical tests, the values of two coefficients were obtained: ΔP_0 (the initial (preset) perturbation at the point $x = 0$) and α (the attenuation coefficient). The Fig.8 presents the approximating exponential curve. As can be seen from the plots, the numerical and experimental tests confirm the assumption that the perturbation in the pipe attenuates according to the exponential law with a good approximation.

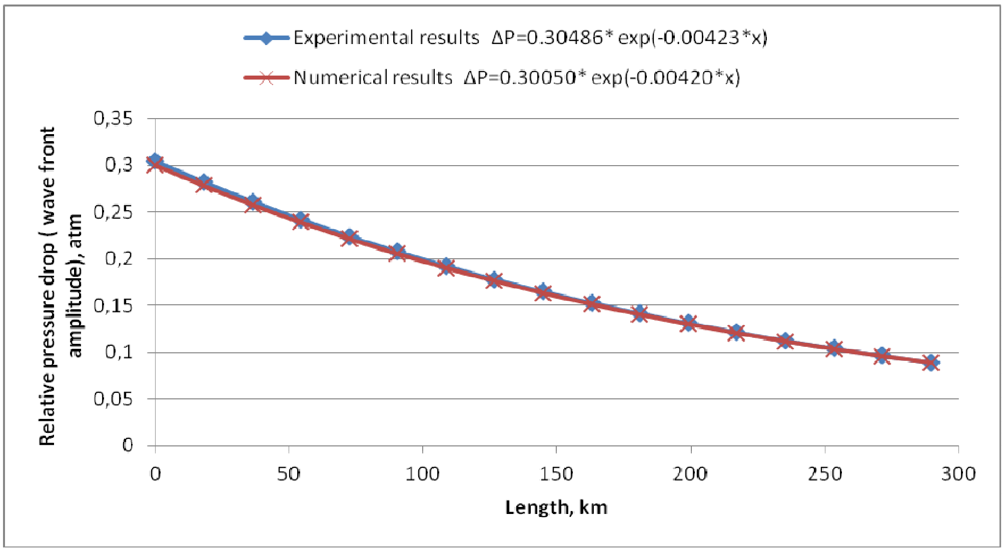

Figure 8. Variation of the perturbation amplitude along pipeline: experimental results and numerical results.

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In order to obtain a theoretical equation for the approximation of the attenuation coefficient of the acoustic wave, Glikman and Barabanov (2009) carried out tests on four long pipelines and proposed an approach to the attenuation coefficient dependent on the dimensionless parameters of the flow.

The attenuation of wave processes in a turbulent flow is mainly due to viscous friction forces. The ratio of friction forces to inertial forces of the flow is characterized by the Reynolds number. Using the processed data of experiments and the results obtained in this work, the attenuation coefficient α versus the dimensionless parameter Re (Fig. 9) can be plotted.

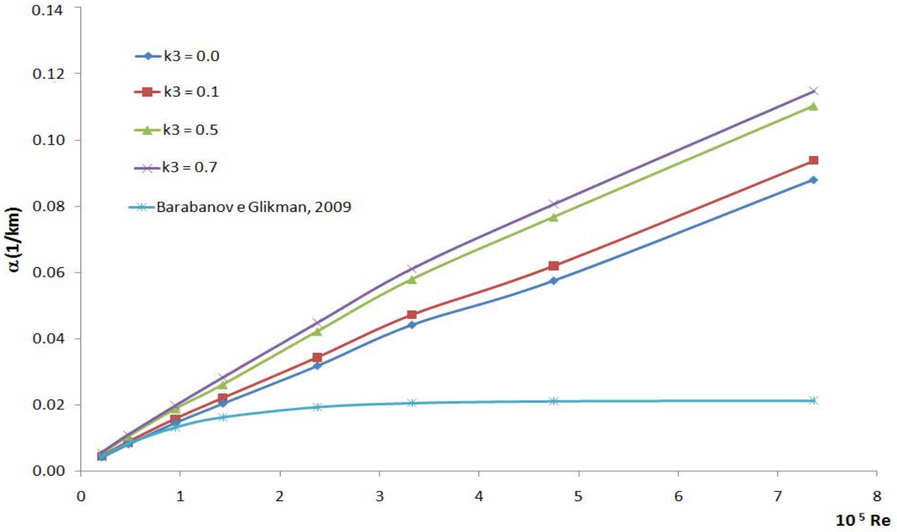

Figure 9. Comparison of numerical and experimental results, dependence of the attenuation coefficient on the Reynolds number

When the Reynolds number tends to zero, the flow becomes laminar and the attenuation coefficient of the wave can be calculated by Eq. (13):

$$\lambda\ |u|/\ 2D = \lambda_0|u_0|\ /2D = 2a = const \tag{13}$$

where D is the diameter of the pipe; λ_0 and λ are the coefficients of friction before and after perturbation, respectively; u is the velocity after perturbation at the point x; and u_0 is the velocity before perturbation at the point x.

Under the assumption that, for a laminar flow, the friction law is expressed by the Stokes formula $f = 64/Re$, the attenuation coefficient in the domain of validity of the Stokes formula is given by the Eq. (14)

$$\alpha_0 = 32\eta/\rho\, a\, D^2 \tag{14}$$

where η is the dynamic viscosity, ρ the density, and a the celerity. Thus, the dependence of the attenuation coefficient on the Reynolds number takes the form:

$$\alpha = \alpha_0 + \frac{2,1}{10^5}\left[1 - \exp(-Re/10^5)\right] \tag{15}$$

In Fig.9 it can be seen that a better approximation between numerical and theoretical results for low values of Reynolds, which is also verified by Barabanov and Glikman, between experimental and theoretical results. In the region of high Reynolds number, the results show a qualitative behavior consistent with the theoretical analysis. The theoretical curve given by equation (Barabanov and Glikman, 2009) has greater attenuation than the calculated by numerical model due to viscous friction, but the equation presents an approximation for the coefficient of attenuation dependent on the parameters dimensionless flow, i.e. α is proportional to fv_0.

In order to evaluate the behavior of the attenuation coefficient in pipeline with a pre-existing leak, numerical simulations were performed using experimental data from the pipe studied by Barabanov and Glikman (2009) considering leaks in different positions along the pipe. Each test considered the pipe without leakage or with only one pre-existing leakage.

The Fig. 10 presents the fitted curve of the variation of the disturbance along the pipeline considering a pre-existing leak in position *197.14 km*. The curve shows two attenuation coefficients, the first before the leak and the second after the leak. The attenuation coefficient obtained by adjusting the curve using exponential fitting in this case is called

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apparent attenuation coefficient (α*) since the adjustment curve is enclosed between the observed points. For this case the value of the attenuation coefficient was obtained from α* = 0,00547.

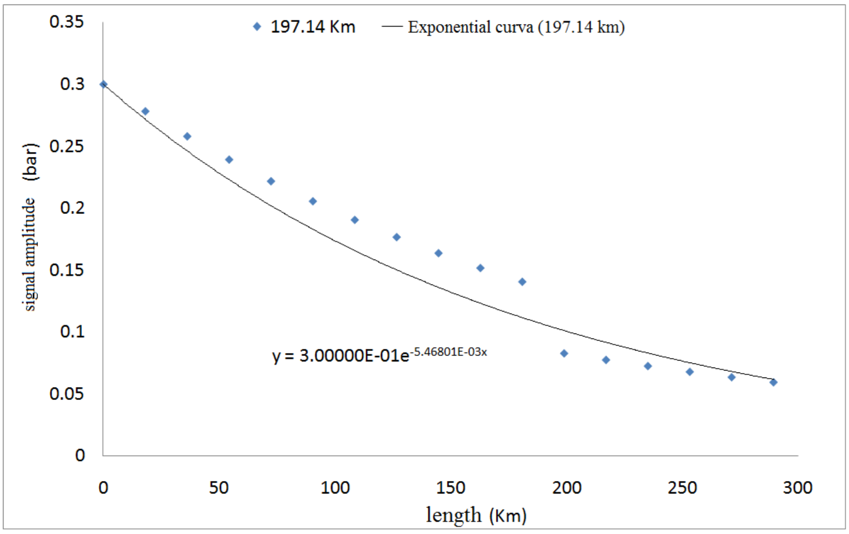

Figure 10. Obtaining the apparent attenuation coefficient.

In Fig. 11 the behavior of the apparent attenuation coefficient for all numerical tests performed can be observed. The test for the pipe without leak presents pipe natural attenuation, the value of the attenuation coefficient in this case *is* α = *0.00416*. In all simulations with pre-existing leakage was obtained from a coefficient of apparent attenuation greater than the case without leakage. It can also be seen that the attenuation is increased as the leak is near the position where the acoustic pulse is introduced, which in this case was at the beginning of the pipeline (point x = 0).

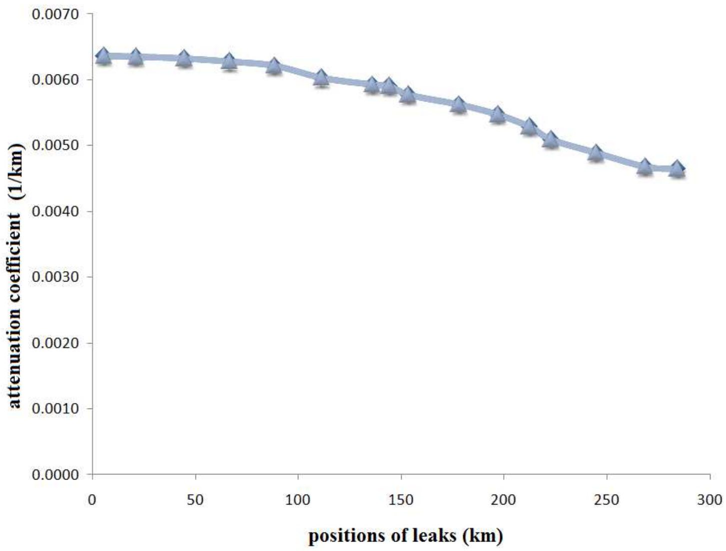

Figure 11. Behavior apparent attenuation coefficient depending on the position of the leak.

The results using the attenuation coefficient are a good indicator for leaks detection, and provide an estimate of its location. The location of the leak may be obtained by performing numerical tests searching for apparent attenuation curves for different leaks diameter values; the intensity of the leakage can be recorded, for example, using the mass balance. Obtaining the measurement of the diameter of the leak its location is possible. That is, the attenuation coefficient is a variable that can be used as a parameter for detection and location of leaks. The curve seen in Fig. 11 obtained by numerical tests represents an important and unprecedented contribution for leak detecting methodology.

5. CONCLUSIONS

The development and validation of the simulator for transient hydraulic analysis in the numerical model suitable for the simulation of a leak detection technique have been presented. The results confirmed that the numerical model captures the correct physics of the propagation phenomena. Furthermore, the attenuation coefficient proved to be a good indicator for leak detection, and also to provide a good estimate of its location. Particularly, a good agreement was found between the experimental and numerical attenuation parameters, which validates the model developed as an on-line predictor to be used in a LDS system.

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