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Modeling pressure transient due to valve closure in leaking viscoelastic pipelines

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The aim of the present study is to investigate the feasibility of using the analysis of pressure transients, generated by full closure of a downstream solenoid control ball valve, in leak detection and localization. A numerical model is developed to simulate pressure transients in leaking viscoelastic pipes. The model accounts for complex pipe characteristics, such as unsteady friction and viscoelastic behavior of pipe walls. The leak is treated as a flow through an orifice of prescribed size. An experimental setup is designed and constructed to provide reliable experimental data for transient flows in PVC (viscoelastic) pipelines to verify the numerical model. The pipeline is 60 m long and 25.4 mm internal diameter connecting two tanks. Leaks are simulated at different locations along the pipeline to study the effect of leak position. The pressure time history is recorded using pressure transducers located at five equidistance points along the pipeline and connected to Data Acquisition System. A downstream solenoid control ball valve used as a mean of generating pressure transients. Experiments are carried out for different pipeline flow rates corresponding to Reynolds number in the range from 2,100 to 55,000 and different leak quantities at different locations. The numerical model is experimentally verified to insure its capability of accounting for unsteady and viscoelastic complex phenomena and efficiently simulating pressure transients in the presence of a leak.

إن الهدف من الدراسة الحالية هو التحقق من ملائمة استخدام تحليل الضغوط العابرة المولدة من الإغلاق الكامل لصمام كروي، ذو ملف لولبي موجود في المجرى الهابط في كشف التسرب و تحديد موضعه. تم تطوير نموذج رقمي لمحاكاة الضغوط العابرة في المواسير ذات التسريب والمرونة اللزجة. هذا النموذج قادر علي التعامل مع موضوعات متخصصة مثل تأثير الاحتكاك غير المستقر والمرونة اللزجة لجدران الأنابيب على الضغوط العابرة كما تم التعامل مع التسرب على أنه تدفق خلال ثقب ذو مقياس موصف. تم إنشاء جهاز معملي قادر علي توفير نتائج معملية دقيقة للسريان العابر في المواسير ذات المرونة اللزجة للتحقق من صحة النموذج الرقمي وهو يتكون من خط أنابيب بطول ٦٠ م وقطر داخلي ٢٥,٤ مم يصل بين خزانين وتم محاكاة التسرب في أماكن مختلفة على طول خط الأنابيب لدراسة تأثير أماكن التسرب. تم تسجيل الضغط مع الزمن باستخدام أجهزة محولات الضغط الموجودة في خمسة أماكن علي أبعاد متساوية علي طول خط الأنابيب والموصلة بنظام اكتساب البيانات. أجريت التجارب علي تدفق سريان مختلف وبالتالي أرقام رينولدز مختلفة في المدى ٢١٠٠ إلي ٥٥٠٠٠ وكميات تسرب مختلفة. وبالتالي تم التحقق من قدرة النموذج الرقمي علي محاكاة السريان العابر في خطوط الأنابيب في وجود التسرب آخذا في الاعتبار تأثير الاحتكاك غير المستقر والمرونة اللزجة.

Keywords: Leak detection, Pressure transient, Unsteady friction, Viscoelastic pipes

1. Introduction

While pipelines are efficient and economic means of transporting hazardous fluids over long distance, the risks associated with accidental releases are high. Leaks in pipelines carrying fluid such as petrochemical products can cause serious pollution, injuries and fatalities, if they are not promptly detected and repaired. Several techniques have been implemented on many different pipelines with various levels of success, efficiency, complexity and cost. The optimum leak detection method should, quickly, accurately and economically, detect and locate the smallest leak. Also, it should not cause the cessation of pipeline operation. The oldest leakage detection method is that of passive control. In this method, a walker makes a visual inspection along the length of the pipeline and reports any leaks to the operating company.

Another traditional method is the static pressure pre-test in which pipelines are divided into sections by closing the appropriate valves. These sections are then pressurized to a pre-determined pressure and the pipeline is monitored over time. Any change in the pressure levels can then be associated with a leakage.

One of the earliest computer methods developed to detect the presence of leak in pipelines is the volume balance method. The principle behind the volume balance approach is the conservation of mass. That is, the amount of fluid that goes into the pipe over any time interval minus the amount that flows out of the pipe equals the change in fluid volume inside the pipe over the same time interval.

Another leak detection technique that has been widely employed is the use of pressure measurements to detect the depressurization that accompanies a leak. The principle behind the operation of single point pressure analysis is that the pressure in a pipeline will decline as a result of a leak. Further, certain statistical properties can be computed to determine if a pressure is declining in a significant manner. Single point pressure analysis requires that all events other than leaks that may cause a pressure to decline, such as operational changes to the pipeline, must be identified so that the leak detection can be inhibited until such time as the pipeline returns to a steady operation.

Pressure gradient analysis is one of the model-based techniques developed for detecting leaks in pipelines. This method is based on the principle that by simulating the hydraulics in real time using some measurements at the ends of a pipeline segment, a leak can be detected when the computed values (pressure and flow) at the end of the pipeline deviate from the measurement at the ends of the pipeline not used as boundary conditions. Leak detection systems, which are not model based, have attempted to work on the premise that a leak will cause a change in pressure or flow values at the end of the pipeline, and that by monitoring the change in the measurements, the leak can be detected.

The model compensating volume balance is an extension of the traditional volume balance approach. The method uses a simulation model to compensate for the transients in pipeline, thus enabling it to produce fast leak detection even in the presence of transients in the pipeline. This model is based on the comparison in real time between measurement generated flow balances and model generated packing rates.

Silva et al. [1] developed an on-line computational techniques used in the analysis of hydraulic transients caused by leakage. A computer program to be run on-line developed to simulate the leak, read and filter the pressure transducers data to display the pressure transient plots and to obtain leak location information.

Finding leaks is possible using inverse transient methods where the results of measurements are known but parameters (such as a friction factors and leaks) of the physical system are unknown. A transient in pipeline system occurs when a variation in pressure and velocity of the flow is caused by a change, for example, by a valve shutting or opening. The inverse transient approach provides an effective procedure for determining leaks and pipe friction factors for a water distribution system by initiating a transient event, measuring the transient pressures at the measurement location via a data acquisition system, and by using the inverse transient method to determine leak locations and magnitude of friction factors by minimizing the deviations between measured and numerical model pressure.

Vitkovsky et al. [2] used the Genetic Algorithm (GA) technique, applied it to the inverse transient to calibrate and detect leaks in a network. Satisfactory results have been gained for both leak detection and friction factors for the tested network based on GA technique.

Brunone [3] proposed a technique for leak detection in outfall pipes based on properties of transient pressure wave, simply by considering partial reflection of pressure waves that takes place at a leak. The location and discharge behavior of the leak could be determined. Transients were caused by valve opening installed at the inlet section. In order to verify the possibility of locating a leak, experimental and numerical results were shown to confirm the reliability and validity of the proposed technique.

This technique was used in pressurized pipe system, Brunone and Ferrante [4], where pressure transients were initiated by the closure of a downstream valve. The influence of size and shape of small leaks on the pressure signal were investigated. The numerical model did not account for the unsteady friction or the viscoelasticity of the pipe wall.

Transient flow caused by opening or closing a valve was analyzed in time domain by Mpesha et al. [5] using the Method of Characteristics, presented a procedure utilized pressure transients and transform the results into the frequency domain by using the fast Fourier transform. This method can be directly used to determine the location and magnitude of leaks by comparing the frequency response diagram of a system with leaks to the frequency response diagram for the same system if there are no leaks.

Studies covering the application of the Method Of Characteristics (MOC) to unsteady flow and water hammer problems were developed continuously over the last 50 years. Watters [6] provided the detailed theoretical basis for estimating the wave speed for different type of conduits. Also, Wylie and Streeter [7] summarized the various methods of solution for the water hammer problem, namely the method of characteristics, the rigid water column theory, the graphical method, the implicit method and the finite element method. They mentioned that for pressure transients, the method of characteristics is considered to be the numerical method by which other methods may be judged for accuracy and efficiency.

Kaplan et al. [8] showed that transients arising in long oil pipelines could be adequately simulated by the method of characteristics, which completely considers attenuation. On the other hand, Bergant and Simpson [9] demonstrated the numerical inaccuracies that could arise from applying the standard MOC when a solution is needed at the boundaries such as valves, orifices and pumps.

Warda et al. [10-11] modified the MOC for accurate and efficient modeling of complex phenomena such as unsteady friction, viscoelasticity of the pipe walls. They showed that the numerical results are in reasonable agreement with the experimental results.

The present study is concerned with studying the effect of a leak on the pressure transient, caused by a full downstream valve closure, within fluids flowing in pipes both experimentally and numerically. The numerical model developed by Warda et al. [10-11] is modified to study the effect of a leak on pressure transients, due to full valve closure, in pipelines. The model account for viscoelastic behavior of the pipe wall and unsteady friction. The leak is considered as a boundary condition and is treated as an orifice of a given size.

In the next sections, the governing equations and the new laboratory setup are presented. Then, the numerical and experimental results are discussed

2. Mathematical formulation

In the present work a numerical model, based on the standard MOC, is developed for modeling the effect of a possible leak on pressure transients in viscoelastic pipes. The model accounts for complex pipe characteristics, such as unsteady friction and viscoelastic behavior of pipe walls.

The basic governing conservation equations for 1-D, unsteady, incompressible flow are given by:

Continuity eq.:

$$\frac{1}{\rho}\frac{dP}{dt} + a^2\frac{\partial V}{\partial s} = 0 . \tag{1}$$

Euler (Momentum) eq.:

$$\frac{dV}{dt} + \frac{1}{\rho}\frac{\partial P}{\partial s} + g\frac{dz}{ds} + \frac{f}{2D}V|V| = 0 . \tag{2}$$

Some manipulations to these equations are performed to replace the two original partial differential equations with two ordinary differential equations, Watters [6],

$$\frac{dV}{dt} + \frac{g}{a}\frac{dH}{dt} - \frac{g}{a}V\frac{dz}{ds} + \frac{f}{2D}V|V| = 0 ,$$

only when

$$\frac{ds}{dt} = V + a\ , \qquad (3)$$

and

$$\frac{dV}{dt} - \frac{g}{a}\frac{dH}{dt} + \frac{g}{a}V\frac{dz}{ds} + \frac{f}{2D}V|V| = 0\ ,$$

only when

$$\frac{ds}{dt} = V - a\ , \qquad (4)$$

where the Pressure (P) is replaced by ρg (H-z). Eq. (3) is known as the C^+ characteristic equation and eq. (4) is known as the C^- characteristic equation.

Since the characteristic equations are obtained, the head and velocity values could be easily obtained at the intersection point of the C^+ and C^- characteristic lines by solving the two equations.

The ordinary differential eqs. (3 and 4) can now be expressed in finite difference form along the C^+ and C^- characteristic lines, as follows:

$$C^+\ V_P - V_L + \frac{g}{a}(H_P - H_L) - \frac{g\Delta t}{a}V_L\frac{dz}{ds} + gh_{fL}\Delta t = 0\ . \qquad (5)$$

$$C^-: V_P - V_R - \frac{g}{a}(H_P - H_R) + \frac{g\Delta t}{a}V_R\frac{dz}{ds} + gh_{fR}\Delta t = 0. \qquad (6)$$

The unsteady friction terms (h_{fL} and h_{fR}) are accurately modeled by the general model developed by Warda et al. [10], which is a modified version of Vardy et al.'s model [12-13] for turbulent flow in which an adjustment is introduced to account also for laminar flows. The unsteady friction terms are expressed as:

$$h_{fL}(K\Delta t) = \frac{fV_L(i,K\Delta t)|V_L(i,K\Delta t)|}{2gD} + \frac{16\nu}{gD^2}\sum_{J=1}^{K}[V_L(i,(K-J+1)\Delta t) - V_L(i,(K-J)\Delta t)]\,W\left[\left(J-\frac{1}{2}\right)\Delta t\right]. \qquad (7)$$

$$h_{fR}(K\Delta\Delta) = \frac{fV_R(i,K\Delta,)|\,V_R(i,K\Delta,)|}{2gD} + \frac{16\upsilon}{gD^2}\sum_{J=1}^{K}[V_R(i,(K-J+1)\Delta t) - V_R(i,(K-J)\Delta t)]\,W\left[\left(J-\frac{1}{2}\right)\Delta t\right]. \qquad (8)$$

The weighting function $\overline{W}(\tau)$ could be calculated from the following equation at an intermediate time $\left(J-\frac{1}{2}\right)\Delta t$.

$$\overline{W}(\tau) = W(t) = \left(\frac{1}{2\sqrt{\pi\tau}}\right)e^{-\tau/C^*}. \qquad (9)$$

Where

$\tau = \frac{4\nu}{D^2}t$ is the (dimensionless time),
D is the pipe diameter,
ν is the fluid kinematic viscosity,
I is the Grid point location in x-Direction,
K is the time level,

c^* is the shear decay coefficient $= \frac{7.41}{R_N^b}$, (10)

and the exponent, b, is given by:

$$b = \log_{10}\left(\frac{14.3}{R_N^{0.05}}\right). \qquad (11)$$

For laminar flow, the value of the shear decay coefficient (c^*) takes a constant value irrespective of Reynolds Number; Warda et al. [10] suggested a modified value of C^*=0.0215

The viscoelasticity of the pipe walls are modeled using a Kelvin-Voigt model with only one element, Wahba [14]. The following characteristic equations are obtained in which the dominant effect of the viscoelastic nature is clearly recognized.

two tanks. It consists of 6 m pipe segments coupled together by special flange arrangement to eliminate any effect on pressure transients due to wave reflections at pipe connections. The pipeline is assembled in two loops with three bends located at a distance of 13.5, 28.5 and 43.5 m from the upstream tank with a radius of curvature equals to 1.5, 1.37, and 1.45 m, respectively to minimize any bend effect on pressure transients, as proposed by Wiggert et al. [16]. The pipeline is firmly fixed by rigid supports to eliminate the fluid-structure interaction effects. The pipeline flow rate is controlled by means of a downstream manually operated ball valve.

The upstream tank is a vertical standing, cylindrically shaped, pressurized air vessel of $0.7 m^3$ capacity. A minimum air volume of $0.3 m^3$ is maintained in the tank to ensure that it serves as a reservoir. The tank is equipped with a safety exhaust valve, pressure gauge, manhole and sight glass for visual observation of water level. The tank is either connected to an 11 m elevated tank as a source of constant pressure, or directly connected to a centrifugal pump which acts as a source of relatively high pressure up to 5 bar. The elevated tank is $9 m^3$ capacity installed on the roof of the laboratory and connected to the ground pressurized tank via a 10 cm diameter vertical pipe. The water is continuously supplied to the elevated tank by a centrifugal pump and its level is kept constant by means of an overflow pipe connected to the side of the tank.

The downstream tank is an open PVC rectangular tank of $0.29 m^3$ capacity. The water level in the tank is kept constant and equals 20 cm by means of an overflow pipe connected to the side of the tank. The tank contains a sight glass to measure the change in water volume in the tank, and hence determine the pipe flow rate.

Leaks are simulated at different locations along the pipeline to study the effect of leak position. A gate valve is used to control the leak flow rate from the pipeline to the atmosphere and the leak flow rate is measured using a calibrated tank and a stopwatch.

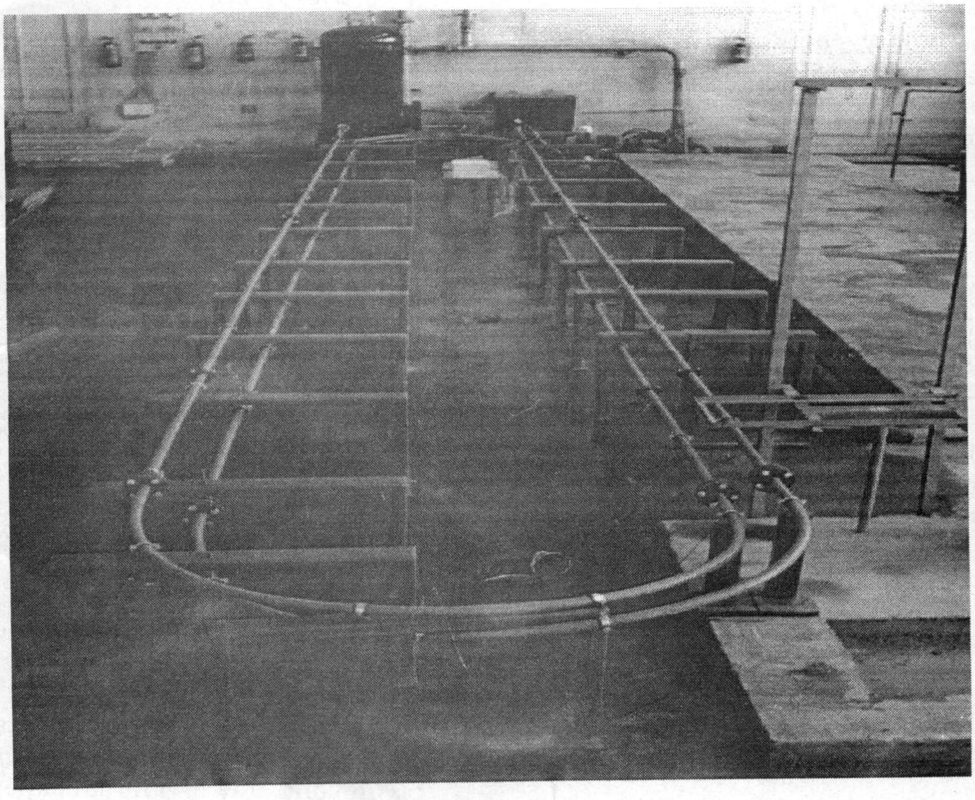

Fig. 1. Experimental setup.

C^+:

$$V_P - V_L + \frac{g}{a}(H_P - H_L) - \frac{g\Delta t}{a} v_L \frac{dz}{ds} + g\, h_{fL} \Delta t + \frac{2a\Delta t}{\tau_1}\left(\frac{\rho g H_L D\,\lambda}{2\,e\,E_1} - \varepsilon_{1L}^{t-\Delta t}\right) = 0. \quad (12)$$

C^-:

$$V_P - V_R + \frac{g}{a}(H_P - H_R) + \frac{g\Delta t}{a} v_R \frac{dz}{ds} + g\, h_{fR} \Delta t + \frac{2a\Delta t}{\tau_1}\left(\frac{\rho g H_R D\,\lambda}{2\,e\,E_1} - \varepsilon_{1R}^{t-\Delta t}\right) = 0. \quad (13)$$

Where the values of the retarded strains ε_{1L}^{t} and ε_{1R}^{t} are computed at each time step from the following equations:

$$\frac{\varepsilon_{1L}^{t} - \varepsilon_{1L}^{t-\Delta t}}{\Delta t} = \frac{1}{\tau_1}\left(\frac{\rho g H_L D\,\lambda}{2\,e\,E_1} - \varepsilon_{1L}^{t-\Delta t}\right). \quad (14)$$

$$\frac{\varepsilon_{1R}^{t} - \varepsilon_{1R}^{t-\Delta t}}{\Delta t} = \frac{1}{\tau_1}\left(\frac{\rho g H_R D\,\lambda}{2\,e\,E_1} - \varepsilon_{1R}^{t-\Delta t}\right). \quad (15)$$

The boundary conditions at each end of the pipe are comprised of externally imposed conditions of velocity and/or pressure head. These conditions, along with the characteristic equation available at this boundary, are sufficient for modeling that boundary within the frame of the method of characteristics.

When the upstream or downstream end of the pipe is connected to a tank, the head at that end is assumed to remain constant at all times (neglecting velocity head) and equal to tank pressure head.
$H_P = H_o$.

Knowing the head at the upstream or downstream end of the pipe, the velocity could be obtained using the C^+, C^- equation.
In case of downstream tank

$$V_P = V_L - \frac{g}{a}\left(H_p - H_L\right) + \frac{g\Delta t}{a} V_L \frac{dz}{ds} - g\, h_{fL} \Delta t - \frac{2a\Delta t}{\tau_1}\left(\frac{\rho g H_L D\,\lambda}{2\,e\,E_1} - \varepsilon_{1L}^{t-\Delta t}\right). \quad (16)$$

In this study, pressure transients are generated from a rapidly closing solenoid ball valve; the valve will be located at the downstream end of the pipeline adjacent to the downstream tank.

The modeling of this boundary condition is performed by applying the following Energy eq. (17), across the downstream valve

$$H_p = H_{down} + K_L \frac{V_p^{\,2}}{2g}. \quad (17)$$

The above energy equation is solved together with the C^+ eq. (12) to obtain the velocity at the valve, Rashad [15]. The real values of K_L for the solenoid valve are obtained in this study by applying the energy equation at each time step and is embedded into the model.

The leak through the pipe is modeled as a flow through an orifice of a prescribed size and the leak flow rate can then be calculated from the following equation

$$q = K_{orifice}\sqrt{H_{Leak}}. \quad (18)$$

Where H_{Leak} is the pressure head at the leak point and $K_{orifice}$ is a constant representing the characteristic of the orifice.

In the present work, the measured steady leak flow rate is implemented in eq. (18) and the orifice constant, $K_{orifice}$, is calculated. The calculated $K_{orifice}$ is assumed to be constant throughout the unsteady process and hence the unsteady leak flow rate at any instant, t, could be obtained knowing the pressure in the pipe at the location of leak.

3. Experimental setup

An experimental setup is design and constructed to be capable of providing reliable experimental data in order to verify the transient model and to investigate the effect of leak on pressure transient. The experimental setup, shown in fig. 1, is constructed in the Fluid Mechanics Laboratory at the Faculty of Engineering, Alexandria University. The setup consists of 25.4 mm inside diameter PVC pipe, 60 m long and 4 mm thickness, connecting

Fast closing solenoid ball valve, having a closure time of 30 milliseconds approximately, is used as a mean of generating pressure transients. Fast valve closure is essential to generate a sharp wave front and to avoid wave interaction between the original wave and its reflection from the downstream tank or from any possible leak. This pressure wave interaction restricts the accuracy of leak detection and localization using pressure transient. Hence the complete closure of the valve should be accomplished before the return of the reflected wave. The valves is installed at the downstream end of the pipe; to investigate the effect of downstream valve closure.

The pressure is continuously monitored and recorded during each experimental run using piezoelectric pressure transducers located at six equidistant points along the pipeline, including both ends of the pipeline. The technical data for each transducer are shown in table 1.

The pressure signals are recorded from the transducers by a Data Acquisition System (DAS). Fig. 2 shows a diagrammatic sketch of the pressure transducers locations and possible leak positions. In order to perform a precise capturing of the data, the solenoid valve is connected to the DAS and a pre-triggering program is designed to allow collection of steady state data for a certain time before energizing the solenoid valve.

4. Results and discussion

A cost-effective and reliable technique for leak detection and localization is proposed based on the well-known properties of transient pressure wave. When a

Table 1
Technical data of the pressure transducers

Location	Type	Range	Sensitivity	Linearity	Uncertainty
0	PCB	0-5000 psi	134 mV/MPa	0.1% FS	1%
0.2L	PCB	0-5000 psi	129.5 mV/MPa	0.1% FS	1%
0.4L	PCB	0-5000 psi	136.5 mV/MPa	0.7% FS	1%
0.6L	PCB	0-5000 psi	132.5 mV/MPa	0.1% FS	1%
0.8L	Kistler	0-200 bar	-5.12 pC/bar	0.3% FS	0.3%
L	Kistler	0-200 bar	-5.92 pC/bar	0.4% FS	0.3%

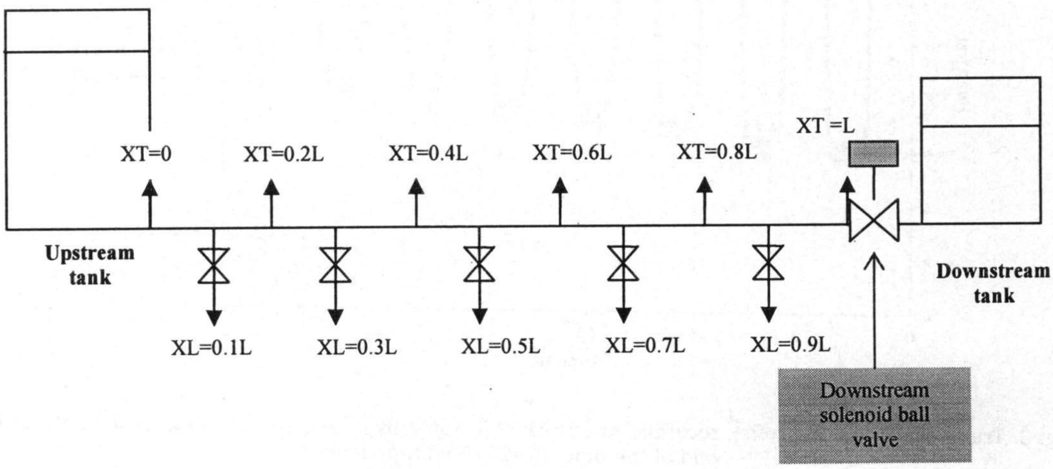

Fig. 2. Schematic diagram of the pipeline with different transducers location (XT) and different possible leak positions (XL).

pressure wave arrives at the leak position, a part of it is transmitted and the other part is reflected back, with the reflection phenomenon depending on the characteristics of the leak. Therefore, the pressure signal conveys information about the state of the system: not only the presence of a leakage, but also its location and size.

In order to check the accuracy, the minimum detectable leak, sensitivity of the model and the feasibility of using this technique, a series of experimental and numerical tests are carried out to study the effect of leak flow ratio, leak positions, changing Reynolds number and transducer positions on the characteristics of pressure transient. The series of tests are carried out for downstream solenoid full valve closure.

In order to test the capability of the numerical model, comparison is made between numerical and experimental results.

Fig. 3 shows the experimental and numerical results of pressure transients recorded directly upstream of a suddenly closed valve, located downstream of the pipe without leak for low Reynolds number (R_N= 2115) to avoid column separation upstream of the valve.

The same case is repeated for the same flow R_N = 2115 and simulating leak in the middle of the pipe (XL = 0.5L) where "XL" is the location of the leak measured from the beginning of the pipe (at the upstream tank).

The quantity of leak flow ratio (q/Q) is about 8%, where "Q" is the steady-state pipe flow rate and "q" is the leak flow rate. The comparison between numerical and experimental results is illustrated in fig. 4.

Figs. 3 and 4 prove that the numerical model is capable of accurately predicting transient laminar flow in both cases with and without leak.

Figs. 5 and 6 show the same comparison but using a pump, to raise the whole system pressure with turbulent flow, to avoid cavity formation and column separation. The pressure is recorded directly upstream of the valve (XT = L). Fig. 6 demonstrates that with a leak flow ratio of q/Q = 49% at the middle of the pipe, the model is still capable of accurately predicting pressure transients due to downstream valve closure at high R_N without column separation.

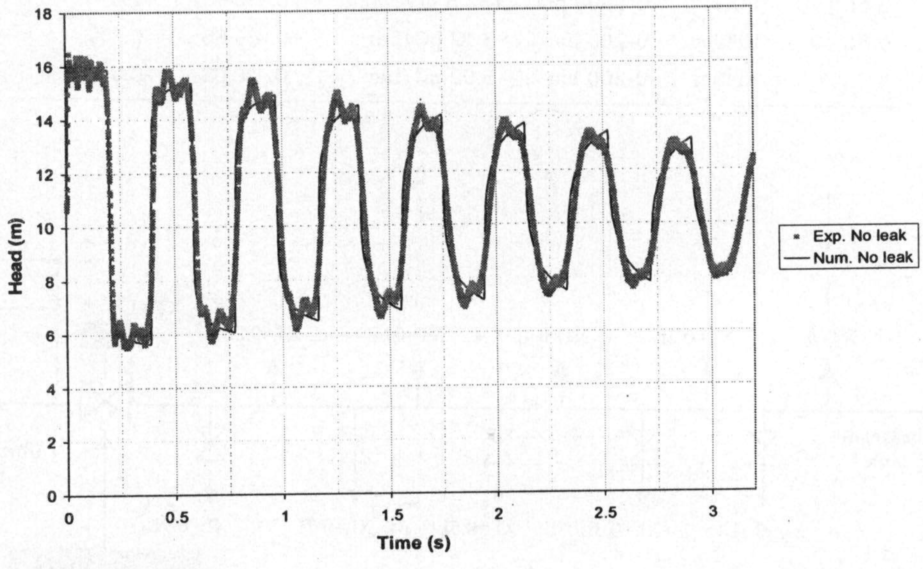

Fig. 3. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=2115 with no leak.

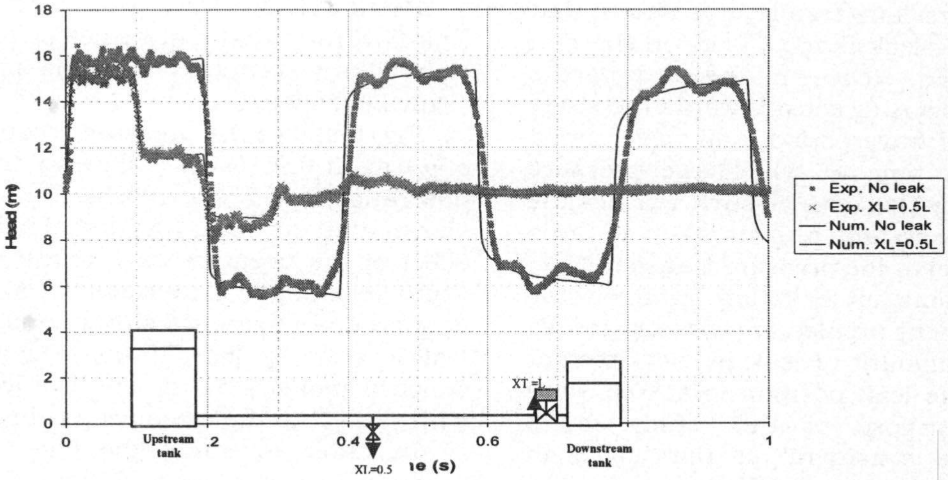

Fig. 4. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=2115 with leak of q/Q = 8%, at XL=0.5L.

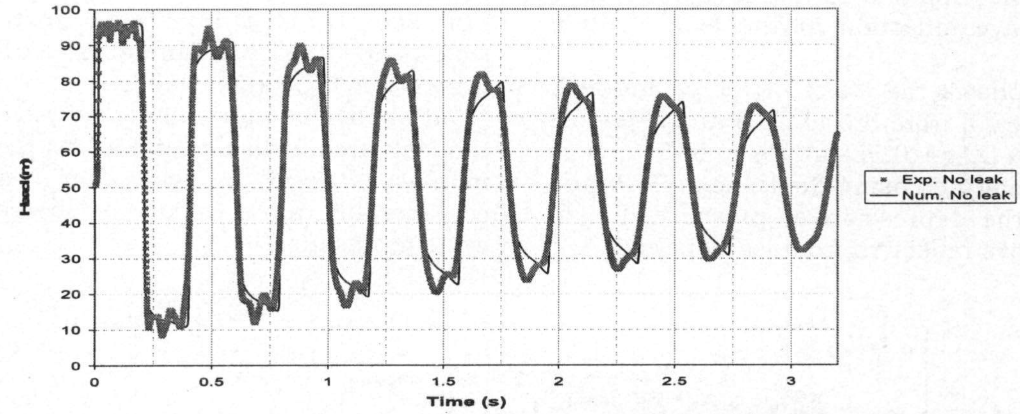

Fig. 5. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=17714 with no leak.

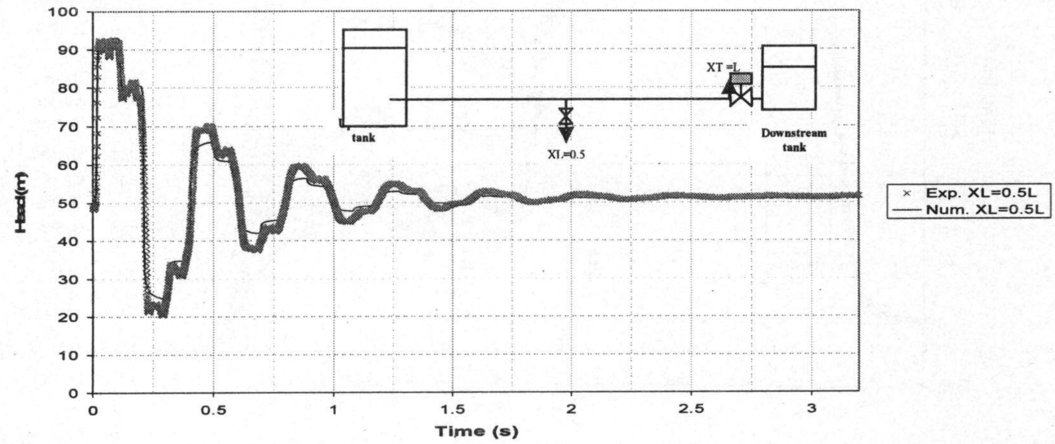

Fig. 6. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=17714 with leak. of q/Q = 49% , at XL=0.5L.

From the previous results, it is shown that the effect of the leak is most clear in the first half wave period. Hence, in the next results special emphasis is directed towards the study of the first half wave period (half wave period represents the time at which the pressure wave, caused by the valve closure, reaches the terminal reservoir and returns back towards the closed valve) of the pressure transient.

The variations of leak flow ratio on the pressure transient profiles are investigated by changing the amount of leak in two different cases where the leak position is at (0.5L and 0.9L). The purpose of this study is to investigate the sensitivity of the model in predicting transients at different leak flow ratios and also the threshold of minimum leak flows that could be detected.

It is clear that as the amount of leak is increased the drop of recorded pressure due to negative wave reflection at the leak location increases.

Fig. 7 shows the effect of increasing leak flow ratio (q/Q) from 3% to 20% at the middle of the pipe (XL = 0.5L) at R_N = 55666. It is apparent that increasing the leakage flow ratio increases the depression of pressure due to negative wave reflection from leak opening.

Results show that the lowest individual leak flow ratio that can be detected is 3% and leak at any location along the pipeline can easily be detected.

Fig. 8 shows the pressure recorded in case of a leak at 0.9L (XL = 0.9L) with different leak flow ratios from 1% to 12% at R_N = 55666. It is shown that as leak flow ratio increases the effect of the negative wave reflected from the leak opening increases. However, the depression of pressure starts earlier since the leak location is closer to the measuring point, which demonstrates the effect of leak location with respect to the measuring point.

In order to study the effect of system pressure a pump feed system is used as a source of high pressure up to 60 m and the pipe flow is controlled using a downstream valve. Fig. 9 shows leak at the middle of the pipe (XL = 0.5L) with different leak flow ratios from 26% to 71% while Fig. 10. represents the leak at XL = 0.9L with different leak flow ratios from 6% to 67% at R_N= 17714.

It should be maintained that, even though the leak area in figs. 9 and 10, is the same as in figs. 7 and 8, leak flow ratios vary considerably as a result of increasing the system pressure.

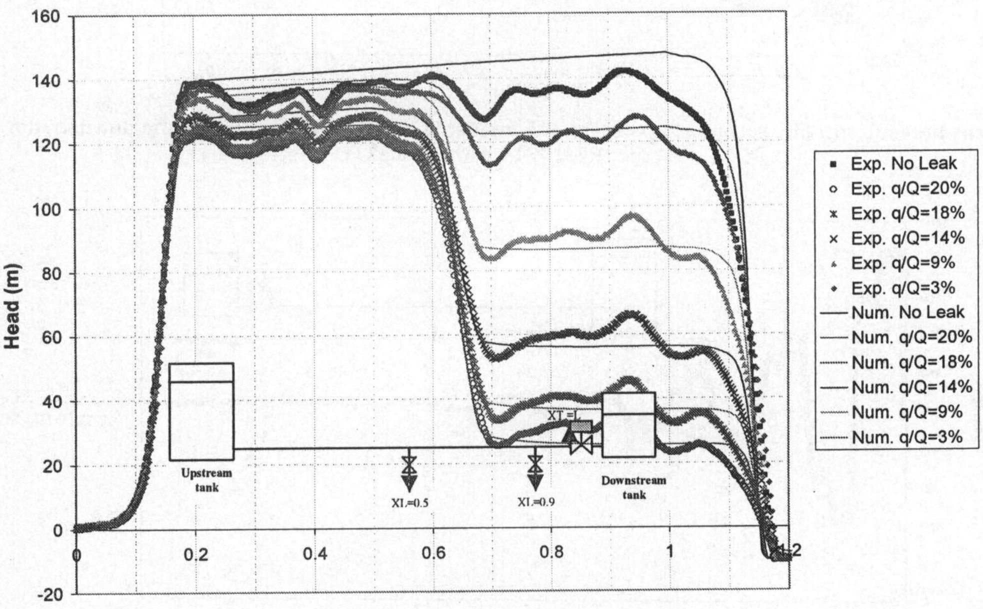

Fig. 7. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=55666 with leak at XL=0.5L and different leak flow ratios.

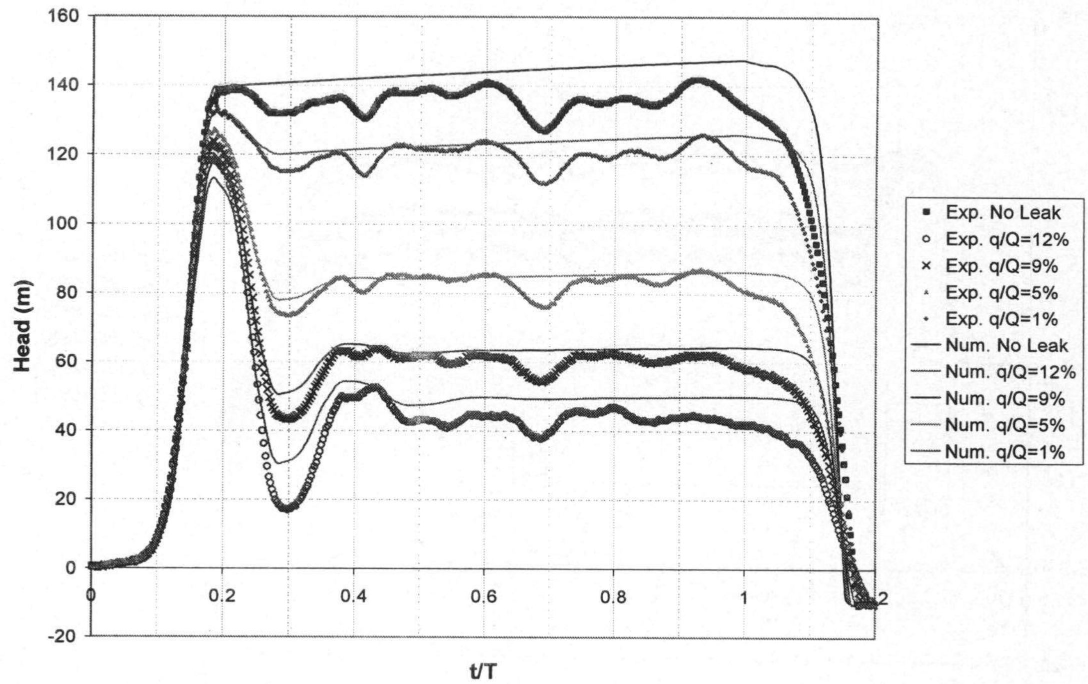

Fig. 8. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=55666 with leak at XL=0.9L and different leak flow ratios.

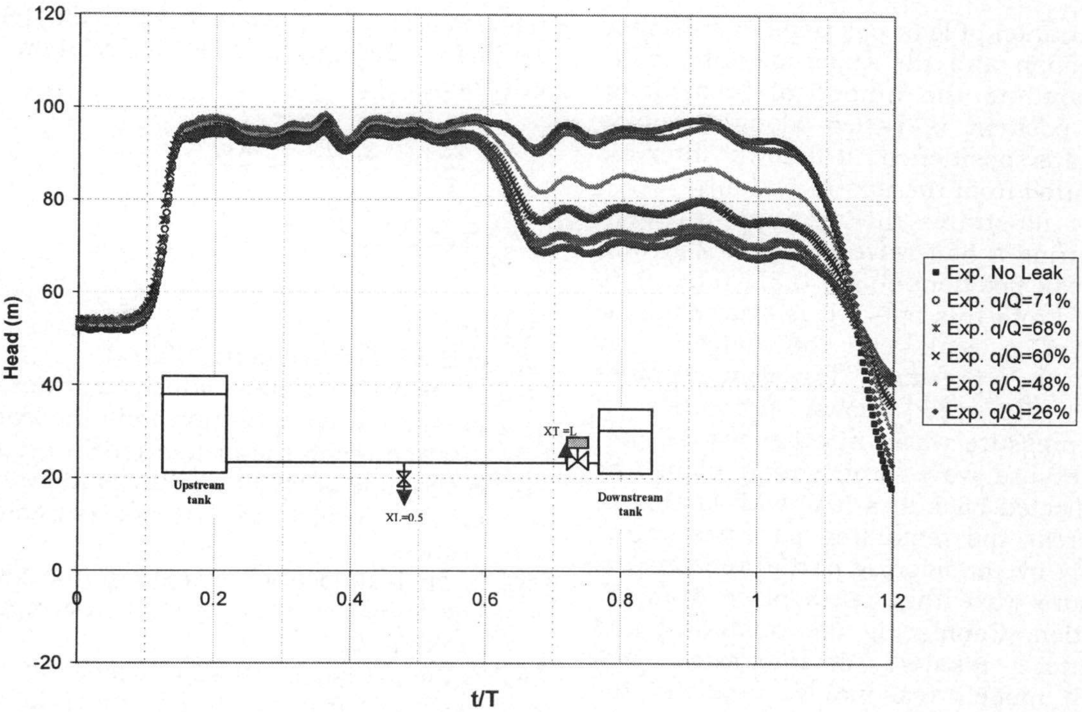

Fig. 9. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=17714 with leak at XL=0.5L and different leak flow ratios (at higher system pressure).

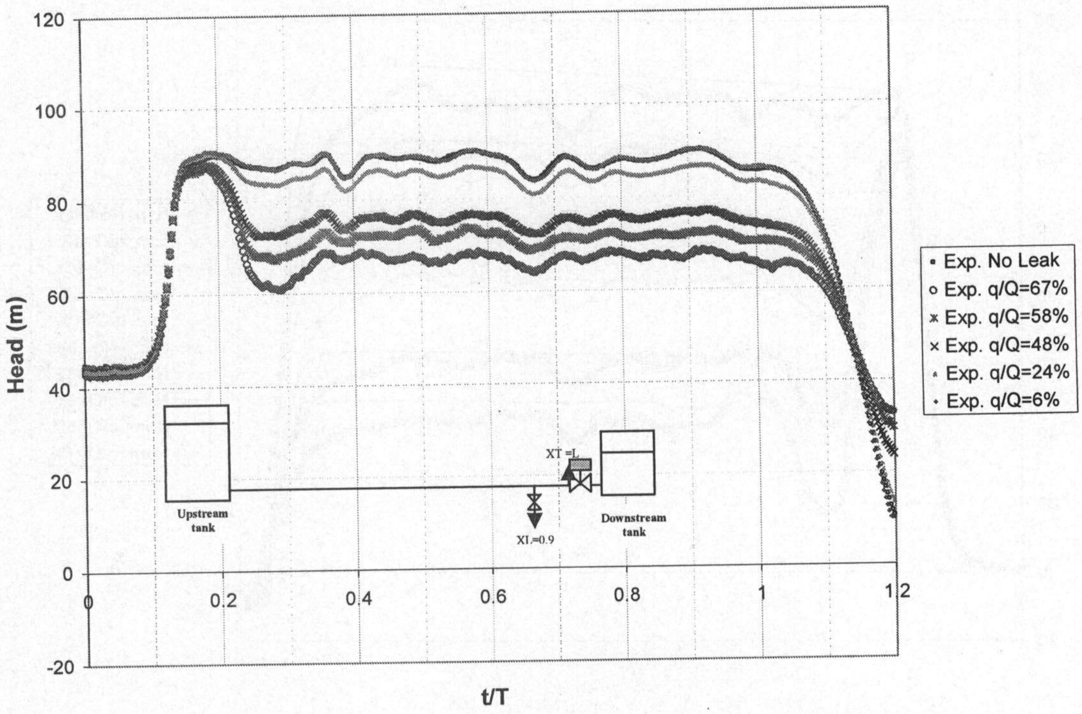

Fig. 10. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=17714 with leak at XL=0.9L and different leak flow ratios (at higher system pressure).

The variation of leak positions is presented in this section and the experimental results are compared to the numerical predictions. The leak position is varied along the pipe through taps positioned at known intervals (XL) measured from the upstream tank.

Fig. 11 illustrates the pressure transient profiles during a half wave period (2L/a) with different leak positions (0.1L, 0.3L, 0.5L, 0.7L and 0.9L). From this figure it is clear that the presence of a leak can be detected by analyzing the pressure transient profiles based on the well known properties of transient pressure wave. In other words, part of the pressure wave propagation along the pipe is reflected back at a leak with change of sign, whereas the remaining part passes the leak simply by considering partial reflection of the pressure wave that takes place from the leak position. Comparing the numerical and experimental results demonstrate that numerical model reasonably predicts the pattern of pressure transient profiles at different leak locations.

The location of the leak can approximately be estimated through the following relation (Brunone [3]).

$$a = \frac{2L}{T} = \frac{2(XT - XL)}{t_r - t_c}$$

$$\frac{t_r - t_c}{T} = \frac{XT - XL}{L}. \qquad (19)$$

Where

- T is the half wave period (2L/a),
- t_r is the arrival time at which the transient pressure wave reflection from the leak location reach the measurement section,
- t_c is the time at which the pressure wave due to valve closure reach the measurement section,
- XL is the leak location measured from the beginning of the pipe (at the upstream tank), and
- XT is the pressure transducer position measured from the beginning of the pipe (at the upstream tank).

It is clear that the precision in locating the leak strictly depends on the accuracy in evaluating the time at which the pressure waves reach the measurement section. It is clear from fig. 11 that the accuracy in predicting the wave arrival time is affected by the curved shape of the waveform especially at the initiation and the end of the wave front. So, instead of using the wave arrival time, the time, at which the maximum wave pressure gradient (dp/dt) occurs, is implemented in eq. 19. Table 2 shows a comparison between the actual and predicted leak locations. The estimated leak location is affected by wave front shape, pressure attenuation and time measurement. Also, the fluid-structure interaction and the wave interaction between the wave reflected from the leak and that from the bends or other discontinuities may reflect on the accuracy of prediction. The discrepancies between the actual and estimated leak locations may also originate from the uncertainties and signal to noise ratio in measurements.

The capability of using the pressure transient analysis in leak localization is also tested at different flow Reynolds number (from 9386 to 55666). Transient pressure profiles recorded immediately upstream of the valve for leaks at only two locations (0.5L and 0.9L) are illustrated in fig. 12. It is clear that as Reynolds number decreases the pressure transients for the pipe without leak decreases and the negative wave reflected from leak decreases. Also, when the leak at 0.9L, two waves are noticed the first one is the negative wave reflected from the leak position and the

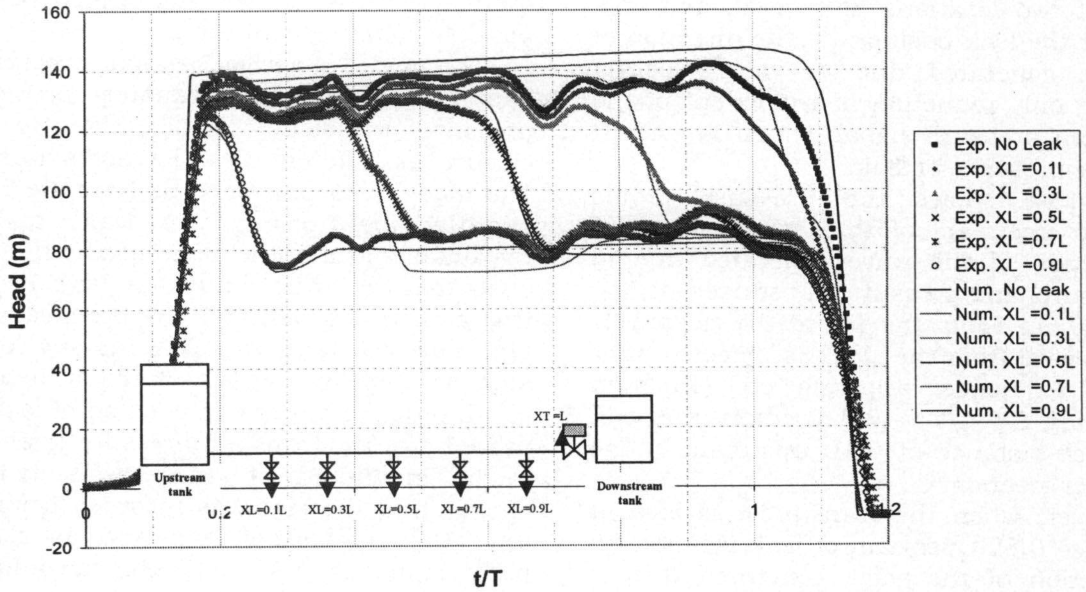

Fig.11. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=55666 with different leak positions.

Table 2
Comparison between actual and predicted leak locations

Actual location (m)	Predicted location (m)	Error (m)	Error (%)
6 m (0.1L)	6.6 m (0.11L)	0.6 m	1%
18m (0.3L)	17.4m (0.29L)	- 0.6m	-1%
30m (0.5L)	30.12m (0.503L)	0.12m	0.2%
42m (0.7L)	41.64m (0.694L)	-0.36m	0.4%
54m (0.9L)	53.82m (0.897L)	-0.18m	-0.3%

second is a positive wave reflection from the first one as it had reached the leak position. In addition, fig 12 shows that the model can reasonably simulate the transient pressure history in all cases with different R_N.

In order to detect the location of the leak, the pressure transient should be monitored at different stations along the pipe. This is because pressure transient profile clearly depends on the position of leak and also the location of pressure measurement stations. Therefore, the effect of the location of the transducer with respect to the location of leak is investigated and the results, of one case only, are presented in which the leak is located in the middle of the pipe.

Figs. 13a-e illustrate the pressure signal recorded at five different locations simultaneously. Figs. 13-a and 13-b show the results at two locations XT = 0.2L and XT= 0.4L after the leak position (in the direction of the wave generated due to valve closure) indicating only reduction in the extent of the transmitted pressure signal, which is evident due to the presence of leak.

Fig. 13-c shows the pressure profile monitored upstream of the leak position (in the direction of the wave generated due to valve closure) and pressure transducer located at XT = 0.6L. From the figure the negatively reflected wave from the leak is detected after $t_r/T \approx 0.4$. Hence, applying eq. (19) and substituting for $t_c/T \approx 0.3$ predicts the leak location at distance of 0.1L upstream of the transducer location.

However, when the transducer is located at distance 0.8L upstream of leak location (in the direction of the wave generated due to valve closure), two negative waves are reflected as shown in fig. 13-d. The first is the negative wave reflected from the leak position and the other is its reflection as it had reached the closed valve. From the figure the location of leak can be also predicted, by substituting for $t_c/T \approx 0.2$.

Fig. 13-e demonstrates clearly that in case the transducer is located immediately upstream of the downstream valve only one negative wave reflection is recorded indicating that the leak is located at the middle of the pipe.

5. Conclusions

The feasibility of using pressure transients, generated by full closure of a downstream solenoid ball valve, in leak detection and localization is investigated both numerically and experimentally. The location of leak is determined by measuring the period of time, which the pressure wave takes to travel from the measurement section to the leak location and vice versa.

A numerical model based on the MOC, developed for modeling pressure transients due to sudden closure of downstream valve, is adapted to account for the presence of leaks in pipelines. The model accounts for unsteady friction, viscoelastic behavior of pipe walls and possible column separation.

The model is verified against experimental data and proved to adequately predict the pressure transient profiles due to valve closure at different flow Reynolds numbers. The model also proves to be sensitive to leak quantity and position of leak, and can reasonably locate the leak position. Results show that the lowest individual leak discharge that can be detected is 1% of the steady-state pipe flow rate and that leak at any location along the pipeline can reasonably be detected.

In order to detect the position of leak, it is proved that the transient pressure profiles has to be monitored at different locations, to ensure that the signal is recorded before and after the position of leak and as close as possible to it in order to be able to confirm the occurrence of leak and to locate its exact position.

The main drawback of using the full closure of a downstream is the very high pressure rise that may reach 14 times the operating pressure which could be damaging to the pipe installation. Also, full valve closure results in complete disruption of the pipe flow.

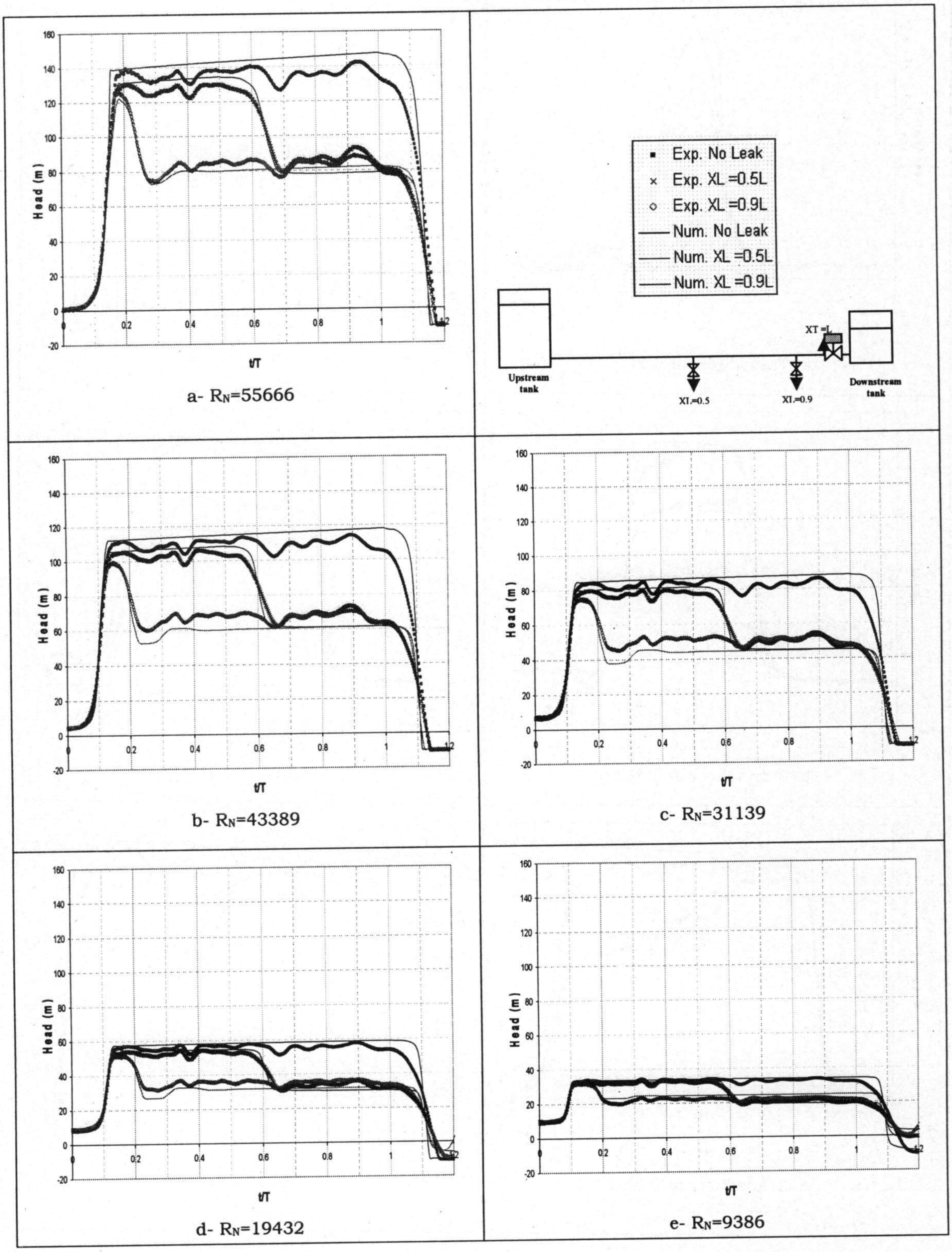

Fig. 12. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, for different R_N with two leaks at XL = 0.5L and XL=0.9L.

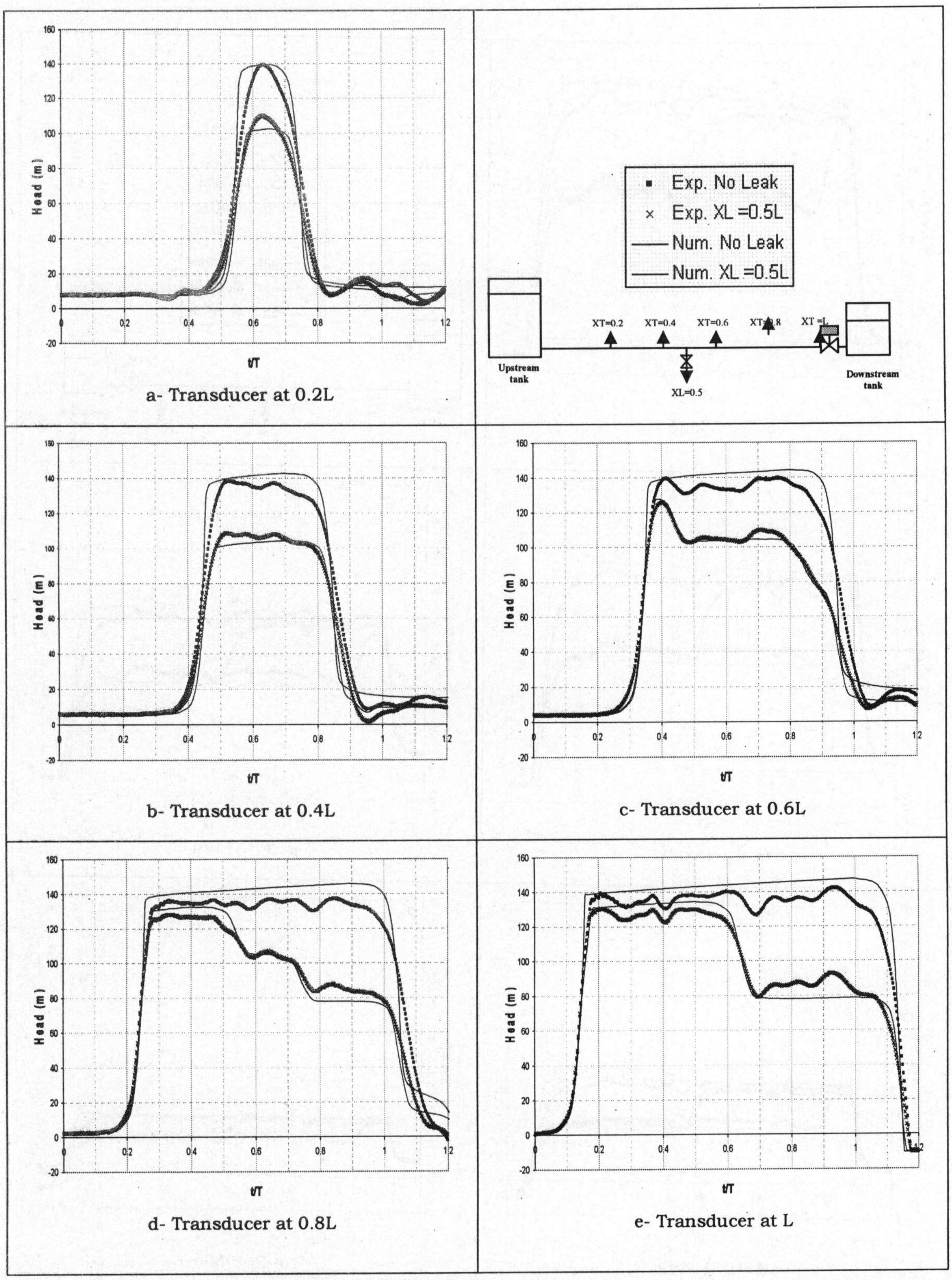

Fig. 13. Transient pressure profile, recorded upstream of a suddenly closed valve located at the downstream end of the pipe, R_N=55666 with leak of q/Q=11% at XL=0.5L.

Nomenclature

A is the flow cross sectional area (m^2),
A is the wave speed in a fluid contained within an elastic conduit (m/s),
C^+ is the characteristic curve, transmitting information downstream,
C^- is the characteristic curve, transmitting information upstream,
D is the pipe diameter (m),
E_j is the modulus of Elasticity of the *j*th Kelvin-Voigt element (N/m^2),
e is the pipe wall thickness (m),
f is the Darcy-Weisbach friction factor,
g is the acceleration due to gravity (m/s^2),
H is the local flow head (m),
H_{down} is the head of the downstream reservoir (m),
H_{Leak} is the head at the leak location (m),
h_f is the friction head loss per unit length,
K_L is the valve loss coefficient,
$K_{orifice}$ is a constant represents the characteristic of the orifice,
L is the total length of the pipe (m),
Q is the steady-state pipe flow rate (m^3/s),
q is the leak flow rate (m^3/s),
R_N is the Reynolds Number,
s is the distance along the pipe (m),
T is the half wave period (2L/a) (s),
t is the time (s),
t_r is the arrival time at which the transient pressure wave reflection from the leak location reach the measurement section (s),
t_c is the time at which the pressure wave due to valve closure reach the measurement section (s),
V is the flow mean velocity (m/s),
$W(\,)$ is the weighting function for the unsteady friction models,
XL is the leak distance from the upstream tank (m),
XT is the transducer location from the upstream tank (m),
Δt is the time step in method of characteristics solution.,
ε_j is the strain of the *j*th Kelvin-Voigt element,
λ is the constraint coefficient in the wave speed formula, also used as the multiplier in the solution by the method of characteristics,
ν is the fluid kinematic viscosity (m^2/s),
ρ is the fluid density (kg/m^3),
τ is the dimensionless time in the unsteady friction models, and
τ_j is the retardation time of the *j*th Kelvin-Voigt element, ($\tau_j = \frac{\eta_j}{E_j}$) (s),

Subscripts

d is the refers to the downstream point,
L is the known condition downstream at time (t-Δt) to be used in the C^- characteristic equation,
P is the node to be calculated at time (t),
R is the known condition upstream at time (t-Δt) to be used in the C^+ characteristic equation,
u refers to the upstream point,

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