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Pipeline leak diagnosis using transient analysis

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The aim of the present paper is to show the capability of using pressure transients, generated by full or partial closure of an upstream valve in leak detection and localization. The valve in this case could be located in the pumping station where all sensors and data acquisition systems could be installed. A numerical model based on the Method of Characteristics (MOC) is modified for modeling pressure transients due to upstream valve closure in the presence of leak and possible column separation. The model is capable of modeling complex phenomena, such as unsteady friction and viscoelastic behavior of the pipe walls. The column separation phenomenon is simulated through the discrete Vapor Cavity Model (DVCM). An experimental setup is constructed to provide reliable experimental data for transient flows in PVC (viscoelastic) pipes to verify the numerical model. The experimental apparatus comprises a 60 m long pipeline of 25.4 mm internal diameter connecting two water tanks. An upstream solenoid or manually operated ball valve is used to generate pressure transients by full or partial closure of the upstream valve. During experimental runs pressure time history at five equidistant locations along the pipeline is measured using pressure transducers connected to a Data Acquisition System. Finally, the numerical model is proved to be capable of simulating pressure transients in the presence of leak at different flow Reynolds numbers in range of 18000 to 56000. The model also proves to be sensitive to leak quantity and position of leak, and can reasonably locate the leak position.

الهدف من الدراسة الحالية هو التحقق من امكانية استخدام تحليل الضغوط العابرة المولدة من الإغلاق الكامل أو الجزئي لصمام موجود في المجرى الصاعد في كشف التسرب و تحديد موضعه. حيث أنه من الطبيعي وجود صمام في محطة المضخات في أول خط الانابيب ويمكن تركيب كل أجهزة القياس ونظام تخزين البيانات في المحطة ايضاً. تم تطوير نموذج رقمي مبني على طريقة الخصائص لمحاكاة الضغوط العابرة الناتجة عن غلق صمام المجرى الصاعد في وجود تسرب واحتمال انفصال عمود السائل. هذا النموذج قادر علي التعامل مع موضوعات متخصصة مثل تأثير الاحتكاك غير المستقر والمرونة اللزجة لجدران الأنابيب. تمت محاكاة ظاهرة انفصال عمود السائل بواسطة نموذج التجويف البخاري المنفصل. يتكون الجهاز المعملي من خط أنابيب بطول ٦٠ م وقطر داخلي ٢٥,٤ مم يصل بين خزانين. استخدم صمام كروي يدوي أو ذو ملف لولبي في المجرى الصاعد لخط الانابيب لتوليد الضغوط العابرة عن طريق غلق الصمام كلياً أو جزئياً. وفي اثناء التجربة، تم تسجيل تغير الضغط مع الزمن عند خمسة أماكن علي أبعاد متساوية علي طول خط الأنابيب بواسطة محولات الضغط الموجودة الموصلة بنظام تخزين البيانات على الحاسب الآلى. وقد ظهر من النتائج الرقمية والعملية أن وجود أى تسرب في الخط يؤدي إلى فقدان قيمة الضغط للموجة المارة نتيجة انعكاس جزء منها عند مكان التسرب. ومن ثم فقد ثبتت امكانية استخدام المتابعة والتسجيل والتحليل في اكتشاف وتحديد مكان اى تسرب في الخط. ,اخيراً تم التحقق من قدرة النموذج الرقمي علي محاكاة السريان العابر في خطوط الأنابيب في وجود كميات تسرب مختلفة وعند أرقام رينولدز مختلفة في المدى ١٨٠٠٠ إلي ٥٦٠٠٠. وبالتالي يمكن استخدام النموذج الرقمي لاكتشاف وتحديد مكان التسرب بدقة عالية.

Keywords: Pipeline, Leak detection, Transient, Pressure wave, Column separation

1. Introduction

The last two centuries have witnessed dramatic changes in society and growth of large-scale industrial activities. One of the main reasons for these changes was the discovery of petroleum and the emergence of a massive range of products and processes reliant on oil.

An obvious result of this dependence is that oil is now transported from its source to the consumer by a variety of different transportation methods. However, despite the developments in sea-going tankers, the main methods of transportation, at least over short to moderate distance, is probably still by pipelines and these generally have an unmatched safety record when compared with other methods. In addition to their safety, pipelines have the advantage of offering continuous monitoring and control of the transported medium. Leaks in pipelines carrying hazardous fluids can cause serious pollution and injures. Moreover, water pipeline rupture not only causes large amount of water loss, but also may affect the water quality. Therefore, Leak detection and localization are obviously important from an environmental as well as an economic point of view and pipeline leaks should promptly be detected, located and repaired.

Large leaks yield to significant changes in pressure gradients and differences in flow rates at measurement points and therefore are easy to detect. On the other hand, small leaks are more difficult to detect because changes in the usual process parameters are small. However, small leaks of the dangerous fluid may have a bad impact on the surrounding environment. The early detection of such small leaks is then the main goal of any leak detection system.

In practice, several methods are currently available, these methods vary from very simple techniques to more complex and expensive methods. These methods such as visual inspection, acoustic, emission, fiber optics, volume balance, steady-state pressure monitoring and hydraulic transient analysis.

Whaley et al. [3] presented an overview of the various computer based methods for performing leak detection on pipelines in real time, as single point pressure analysis, pressure gradient analysis and model compensated volume balance techniques. In addition, the strengths and weaknesses of each of the methods are discussed.

The performance of a statistical pipeline leak detection system called ATMOS PIPE designed by Zhang [4] was tested by Zhang et al. [5-6]. This statistical method does not use mathematical models to calculate flow or pressure in pipe line but it detect changes in relationship between flow and pressure using available measured data. Real-time applications and field tests show that it is cost effective and has a very low false alarm rate and leaks with size from 0.5% to 55% were detected on liquid propylene, ethylene gas and natural gas liquid pipelines.

Another technique was used for leak detection, which makes use of the acoustic energy released by the fluid escaping through the leakage area in the pipe wall. Watanabe et al. [7] described an acoustic method to detect and locate very small leaks in a closed gas pipe or closed empty liquid pipe. The proposed method locates small leaks by using the acoustic noise generated by flow in or out of the pipe through a hole in the closed single pipeline. An increase or decrease in the pressure of the gas in the closed pipe leads to turbulent flow through the small leak that in turn generates acoustic noise with a broadband spectrum.

Belsito et al. [8] developed a leak detection system for pipelines by using Artificial Neural Networks (ANN) for leak sizing and localization and by processing the field data. Adequate preprocessing of the data was performed by using a computer code in conjunction with the ANN to compensate for the operational variations and prevent spurious alarms. The package detects leaks as small as 1% of the inlet flow rate and correctly predicts the leaking segment of pipeline with a probability of success that was greater than 50% for the smallest leak. Also, Adam and Kassem [9] investigated the suitability of ANN for pipeline leak detection, the neural network was trained using a combination of pressure and flow rate data. The ANN package predicted the leaking pipe segment and leakage location with a high rate of success. Kassem and Adam [10] examined the use of genetic algorithm optimization techniques to optimize the neural network. The neural networks examined in that study did not use the sensor reading directly as in conventional neural networks but combined it using polynomial type laws to produce hybrid inputs. The resulting networks show superior performance and use fewer numbers of neurons.

Brunone and Ferrante [11] investigated the possibility of leak detection and estimation in a polyethylene pipeline by numerically and experimentally studying the unsteady pressure wave initiated by a closure of downstream valve. The time-history of the pressure signal acquired during a transient at one measurement section was analyzed in the time domain. The location of the leak was determined by measuring the period of time which the pressure wave takes to travel from the measurement section to the leak and vice versa. The numerical model did not account for the unsteady friction or the viscoelasticity of the pipe wall. Brunone [12] used this technique, for leak detection in outfall pipes based on properties of transient pressure wave 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.

The same technique is used by Warda et al. [1, 2] to investigate the feasibility of using pressure transients, generated by full closure of solenoid operated ball valve located downstream the pipe [1] or by using a controlled partial closure of the valve as a mean of generating pressure transients [2]. A numerical model based on the Method Of Characteristics (MOC), modified for modeling pressure transients due to full or partial closure of downstream valve in the presence of leak. The model accounts for unsteady friction and viscoelastic behavior of pipe walls. 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.

The present study investigate the feasibility of locating the control valve upstream of the piping system in the pumping station. In this case pressure transient propagation in viscoelastic pipes due to full or partial closure is investigated and tested numerically and experimentally in locating possible leaks.

2. Mathematical formulation

In the present study, the numerical model developed by warda et al. [1, 2] is modified to deal with probable upstream column separation using the Discrete Vapor Cavity Model (DVCM).

The transient flow analysis technique utilized in the numerical model is the method of characteristics; in which the Continuity and Euler (Momentum) Equations are modified to account for the viscoelastic behavior and unsteady friction, and then solved together. The complete derivation of these equations can be found in warda et al. [1, 2].

$$C^{+}: v_P - v_L + \frac{g}{a}(H_P - H_L) + g\,h_{fL}\Delta t + \frac{2a\Delta t}{\tau_1}\left(\frac{\rho g H_L D\lambda}{2eE_1} - \varepsilon_{1L}^{t-\Delta t}\right) = 0 . \tag{1}$$

$$C^{-}: v_P - v_R - \frac{g}{a}(H_P - H_R) + g\,h_{fR}\Delta t + \frac{2a\Delta t}{\tau_1}\left(\frac{\rho g H_R D\lambda}{2eE_1} - \varepsilon_{1R}^{t-\Delta t}\right) = 0 . \tag{2}$$

The viscoelasticity of the pipe walls is modeled using a Kelvin-Voigt model with only one element. The above characteristic equations are obtained in which the dominate effect of this viscoelastic nature is clearly recognized.

The unsteady friction terms (h_{fL} and h_{fR}) are expressed as:

$$h_{fL}(K\Delta t) = \frac{f v_L(i,K\Delta t)\left|v_L(i,K\Delta t)\right|}{4gR} + \frac{4\nu}{gR^2}\sum_{J=1}^{K}\begin{bmatrix} v_L(i,(K-J+1)\Delta t) - \\ v_L(i,(K-J)\Delta t) \end{bmatrix} W\left[\left(J-\frac{1}{2}\right)\Delta t\right], \tag{3}$$

$$h_{fR}(K\Delta t) = \frac{f v_R(i,K\Delta t)\left|v_R(i,K\Delta t)\right|}{4gR} + \frac{4\nu}{gR^2}\sum_{J=1}^{K}\begin{bmatrix} v_R(i,(K-J+1)\Delta t) - \\ v_R(i,(K-J)\Delta t) \end{bmatrix} W\left[\left(J-\frac{1}{2}\right)\Delta t\right]. \tag{4}$$

$$\overline{W}(\tau) = W(t) = \left(\frac{1}{2\sqrt{\pi\tau}}\right)e^{-\tau/C^{*}} . \tag{5}$$

Where,

C^{*} is the shear decay coefficient $= \dfrac{7.41}{R_N^b}$. (6)

In addition, the exponent, b, is given by:

$$b = \log_{10}\left(\frac{14.3}{R_N^{0.05}}\right). \quad (7)$$

For laminar flow, the value of the shear decay coefficient (C^*) takes a constant value irrespective of Reynolds Number; C^*=0.0215.

In order to account for a possible column separation, the DVCM is used. Swaffield and Boldy [13] presented the historical development of the work dealing with column separation phenomena. In their presentation, they mentioned that the earliest work dealing with column separation was introduced by Le Conte (1937) who considered column separation upstream of a closed valve and pointed out the importance of the interface velocity in the determination of the cavity collapse pressure rise.

Streeter introduced the DVCM for simulating column separation, as reported by Simpson and Bergant [14]. The model allows vapor cavities to form at computing sections in the method of characteristics. Streeter incorporated this model with the normal rectangular grid of the method of characteristics. A constant wave speed for the liquid between computational sections is assumed.

Safwat and van der Polder [15] modified the DVCM, allowing discrete vapor cavities to form at predetermined locations (valves and high points). The modified DVCM eliminated the unrealistic pressures that occurred in the standard DVCM.

Simpson and Wylie [16] investigated water hammer pressures in a pipeline due to the collapse of a vapor cavity adjacent to a valve. A water hammer event is initiated by the closure of a valve in a simple reservoir-valve system connected by a hypothetical frictionless pipe. They mentioned that short-duration pressure pulses result from the superposition of the valve-closure water hammer wave and the wave generated by the collapse of the vapor cavity.

The DVCM model allows vapor cavities to form at the computational sections in the MOC. The pressure at that section is then set equal to the liquid vapor pressure at the working temperature and a vapor cavity is assumed to occur. The model performs the following steps when the pressure at a computational section drops below the vapor pressure of the liquid, where the solution by the method of characteristics is no longer valid:

The pressure at that section is set equal to the vapor pressure and a vapor cavity is assumed to occur.

$$H_p = H_v . \quad (8)$$

The C^+ and the C^- equations are utilized to compute the velocity upstream of the cavity (V_{pu}) and the velocity downstream of the cavity (V_{pd}).

$$C^+ : V_{Pu} - V_L + \frac{g}{a}(H_P - H_L) - \frac{g\,\Delta t}{a} V_L \frac{dz}{ds} + g\,h_{fL}\Delta t$$
$$+ \frac{2a\Delta t}{\tau_1}\left(\frac{\rho g H_L D\,\lambda}{2\,e\,E_1} - \varepsilon_{1L}^{t-\Delta t}\right) = 0 . \quad (9)$$

$$C^- : V_{Pd} - V_R - \frac{g}{a}(H_P - H_R) + \frac{g\,\Delta t}{a} V_R \frac{dz}{ds} + g\,h_{fR}\Delta t$$
$$+ \frac{2a\Delta t}{\tau_1}\left(\frac{\rho g H_R D\,\lambda}{2\,e\,E_1} - \varepsilon_{1R}^{t-\Delta t}\right) = 0 . \quad (10)$$

The vapor cavity volume is then calculated from the continuity equation:

$$\forall_v = \int A\left(V_{pd} - V_{pu}\right)dt, \quad (11)$$

where,
A is the pipe cross sectional area, and
$\forall_v$ is the vapor cavity volume.

As long as the cavity size is positive, vapor pressure persists. As soon as the cavity size becomes zero or negative, the following is performed by the model:

1. The volume of the cavity is set equal to zero.
2. The head H_P is calculated from the C^+ and C^- characteristics.
3. Proceed as usual with method of characteristics

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 where $H_P = H_o$.

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

In this study, an upstream fully or partially closing solenoid ball valve will be the cause for generating pressure transients within the system.

The modeling of this boundary condition is performed by applying the following energy equation across the upstream valve

$$H_P = H_{Res} - k_L \frac{V_P^2}{2g} , \quad (12)$$

where,

H_p is the pressure head at the valve at time (t) from the beginning of simulation,.

H_{Res} is the pressure head at the upstream reservoir, and

K_L is the valve loss coefficient at time (t) from the beginning of simulation.

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 are embedded into the model.

When a leak exists in a pipeline, it is treated as a flow through an orifice and the leak flow rate is calculated from the following equation

$$q = K_{orifice}\sqrt{H_{Leak}} , \quad (13)$$

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. (13) and the orifice constant, $K_{orifice}$, is calculated. The calculated value is assumed constant throughout the unsteady process and hence by knowing the pressure at leak position at any instant, t, the unsteady leak flow rate is obtained.

3. Experimental setup

In order to verify the transient numerical model and to investigate the effect of leak on pressure transients, an experimental setup is designed and constructed to provide reliable experimental data; the experimental setup is constructed in the fluid mechanics laboratory at the Faculty of Engineering, Alexandria University. The setup consists of the following main components, as shown in fig. 1.

- Overhead tank
- Upstream and downstream tanks
- PVC pipe
- Solenoid operated quick actuating valve
- Data acquisition system

The capacity of the overhead tank is 9 m^3. The tank is installed on the roof of the laboratory and maintains a maximum head of 11m, above the pipe centerline. A centrifugal pump continuously feeds the tank with water. An overflow vertical pipe is connected to the tank to ensure that the water head in the tank is maintained constant at 11 m.

The upstream tank, as shown in fig. 2, 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 to visualize water level in the tank. This tank is connected to an 11 m elevated tank (Elevated tank feed system), as a source of constant pressure, or directly connected to a centrifugal pump (pump feed system), which acts as a source of relatively high pressure up to 5 bar. This tank is connected via a 10 cm diameter vertical pipe to the overhead 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 any changes in water volume in the tank, and hence determine the pipe flow rate.

The setup consists of a 25.4 mm inside diameter, horizontal PVC pipeline. The pipe is 60 m long and 4 mm thickness, connecting the upstream and downstream tanks. It consists of 6 m pipe segments coupled by special flange arrangement, shown in fig. 3, to eliminate any pressure transients due to wave reflections at pipe connections. The pipeline is assembled in two loops, as shown in fig .1, with three large bends to minimize any bend effect on pressure transients. The pipeline is firmly fixed by rigid supports, as shown in fig. 4; to eliminate fluid-structure interaction effect. The pipeline flow rate is controlled by means of a downstream manual ball valve.

A PVC pipe is used since the low value of the wave speed in the PVC pipe enables the completion of the valve closure event before the arrival of the reflected pressure wave.

Leaks are simulated at different locations along the pipeline, as shown in figs. 5 and 6, to investigate the effect of leak position on pressure transients. A gate valve is used to control the leak flow rate from the pipeline and the leak flow rate is measured using a calibrated tank and a stopwatch.

A quick operated solenoid ball valve is used (Omal -ART. 420, 2-way full-bore stainless steel ball valve with double acting pneumatic actuator and 5/2 Parker solenoid valve, with maximum pressure 10 bar) and shown in fig. 7. The closure time of the valve is approximately 30 milliseconds and is used in generating pressure transients after closure. Fast valve closure is essential to generate sharp wave fronts and ensure complete valve closure before the return of the reflected wave. The valve is installed upstream of the pipe and closer to the tank.

In addition, the closure pattern needs to be repeatable (in order to duplicate experiments for the same initial steady state condition). Therefore a precision pressure

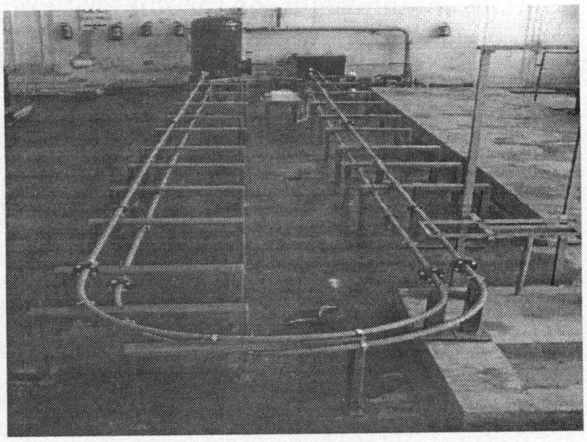


Fig. 1. Experimental setup.

Fig. 2. Upstream tank.

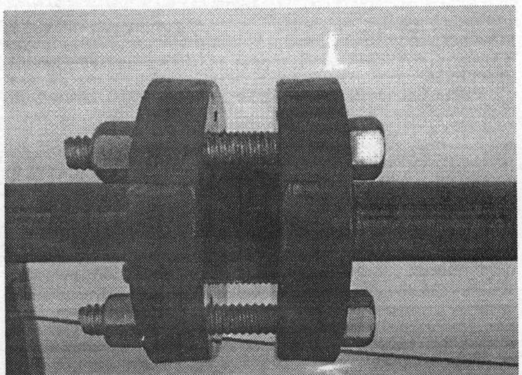


Fig. 3. Flange arrangement of the PVC pipeline.

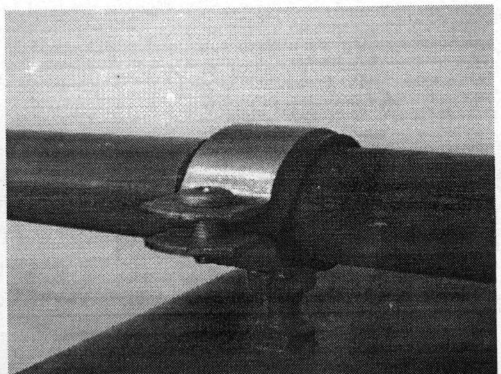


Fig. 4. Pipeline fixation.

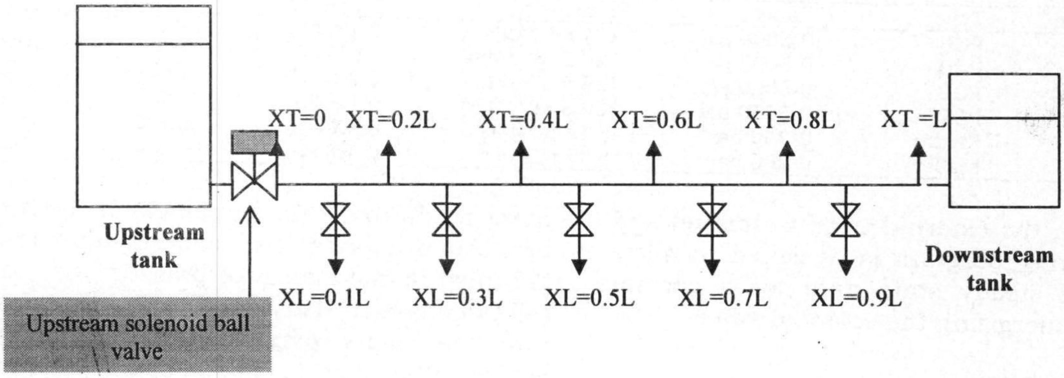


Fig. 5. A schematic diagram of the pipeline with different transducers location (XT) and different possible leak positions (XL).

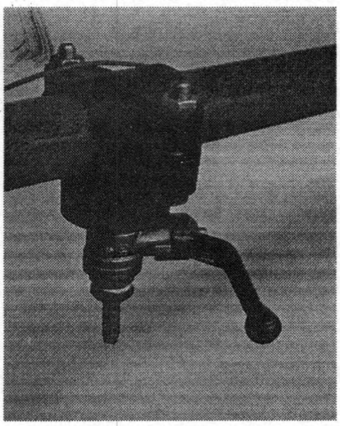


Fig. 6. A ball valve simulating the leak.

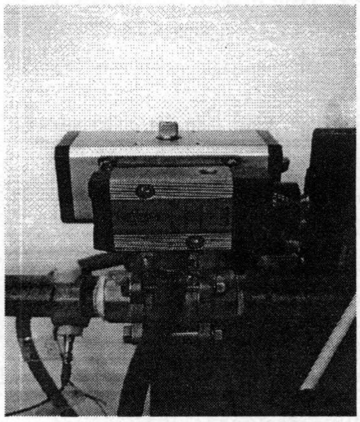


Fig. 7. Fast closing valve.

regulator (Type BOSCH, G1/4 with maximum pressure 16 bar) is used to regulate the inlet pressure to the solenoid valve and is set at 6 bar.

The pressure time history is continuously monitored and recorded during each experimental run using

- Piezoelectric Pressure Transducers
- PCI-DAS1200 Board
- HP VEE Lab software installed in the personal Computer.

Fig. 5 shows a diagrammatic sketch of the pressure transducers locations, located at six equidistant points along the pipeline, including both ends of the pipeline. Two types of pressure transducers are used: Kistler and PCB. The Kistler piezoelectric pressure transducers, model 603B, connected to the Kistler amplifiers, model 5011, have linearity of 0.05% FS and accuracy of 3%. The PCB pressure transducers are ICP pressure sensors, model 111A22, connected to signal conditioner, model 442B06.

The technical data for each transducer are shown in table 1.

The data acquisition board used is a Computer Boards-PCI-DAS1200 type. The board is a multifunction measurement and control board designed to operate in computers with PCI bus accessory slots. The board is completely plug and play; i.e. there are no switches or jumpers on the board.

In order to perform a precise capturing of the data, the solenoid valve is connected to the

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%

DAS through the external trigger channel and a pre-triggering program is designed to allow collection of steady state data for a certain time before energizing the solenoid valve.

3. Results and discussion

3.1. Full closure of upstream valve

In this study, the effect of sudden closure of an upstream valve on pressure transients in the presence of leak is investigated experimentally or numerically. 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 location and transducer position on the characteristics of pressure transient.

In order to test the capability of the numerical model in simulating the behavior of pressure transients in the presence of leak, comparison is made between numerical and experimental results. Fig. 8 shows the experimental and numerical pressure profiles recorded directly downstream of a valve located upstream of the pipe, due to sudden closure. It shows some slight disagreement in the frequency of repeated pressure rise while the extent of pressure rise is maintained. The disagreement in frequency may be attributed to the pressure rise due to cavity collapse and the air release phenomenon, which usually accompanies column separation. Air release is well known to effectively decrease the wave speed. Unfortunately, the DVCM does not account for the air release phenomenon. The air release could be effectively simulated if the DGCM is applied instead of the DVCM.

Same comparison is illustrated in fig. 9. But in case of leak in the middle of the pipe (XL = 0.5L) with a leak flow ratio q/Q = 11%, there tends to be no agreement in frequency, between numerical and experimental results, and also in the extent of pressure rise due to cavity collapse. Also from fig. 9, it is apparent that the cavity persists for a shorter time before collapse and reopens again. This is due to the fact that, as the pressure wave arrives at the leak position then it is partially transmitted and the rest is reflected back.

In order to determine the validity constrains of the numerical model, the cavity formation and column separation at high Reynolds number is avoided using a pump feed system, so that the whole system pressure is elevated to avoid cavity formation. However, this high pressure may affect the pipe and also causes high leak flow ratios even for small crakes (orifices) size. Hence, the following results were taken at elevated system pressure by partially closing the downstream valve to control the system pressure and R_N.

It is apparent from fig. 10, in case of no leak, that by suddenly closing the upstream valve and recording the pressure transient, directly downstream of the valve, pressure drop occurs and a negative pressure wave is traveled along the pipe with wave speed (a). When the pressure wave reaches the downstream tank at (L/a) seconds, negative wave is reflected at the partially closed valve back to the upstream valve. At the instant this wave reaches the upstream valve at (2L/a) seconds the pressure wave is reflected back with the same sign to the downstream tank at (3L/a) seconds and is reflected backward with a positive sign until it reaches the valve at (4L/a) seconds. But in case of leak in the middle of the pipe (XL = 0.5L),as shown in Fig. 11, at the measurement section, by analyzing the pressure signal it shows that the presence of leak, if a pressure wave comes into the measurement section before the expected time for the arrival of the reflected wave. This is because part of the pressure wave propagating along the pipe is reflected back at a leak with change of sign, where as the remaining part passes the leak.

Figs. 10 and 11 show the same comparison between experimental and numerical pressure profiles recorded directly downstream of a valve located upstream of the pipe, due to sudden closure, with and without leak (R_N= 18832, leak flow ratio q/Q = 25%). It shows a reasonable degree of agreement between predicted and measured pressure in case of pipe with or without leak, and the small fluctuations of pressure appear to be due to bends in the system.

From the previous results it is apparent that the effect of leak is clearly observed in the first half wave period. Hence, 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.

In order to investigate the threshold of minimum leak flows that could be detected (experimentally), the amount of leak flow ratio in two different cases (where the leak position at (0.1L and 0.5L) is varied). Figs. 12 and 13, at R_N = 18832, show the pressure transient recorded directly downstream the valve. It is obvious that as the amount of leak increases, the rise of recorded pressure due to positive wave reflection from the leak location increases and the pressure drop behind the valve due to sudden valve closure increases until the drop in pressure due to sudden valve closure reaches vapor pressure, where column separation starts and leak location cannot be detected.

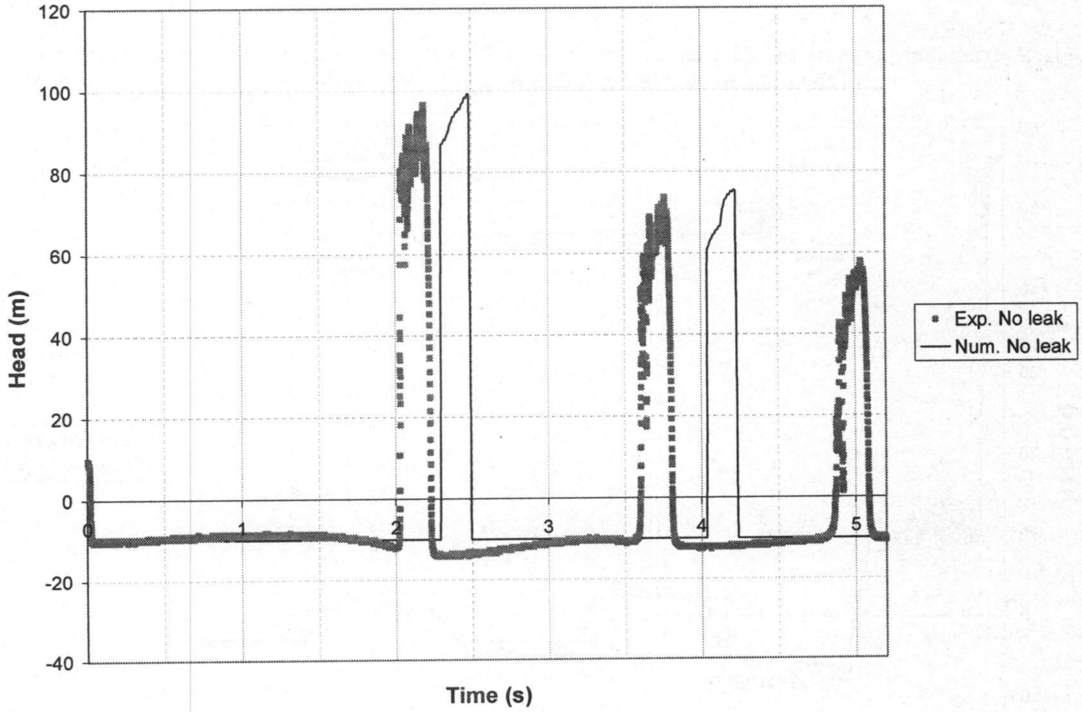


Fig. 8. Transient pressure profile, recorded downstream of a suddenly closed valve located upstream of the pipe, R_N=55666 with no leak.

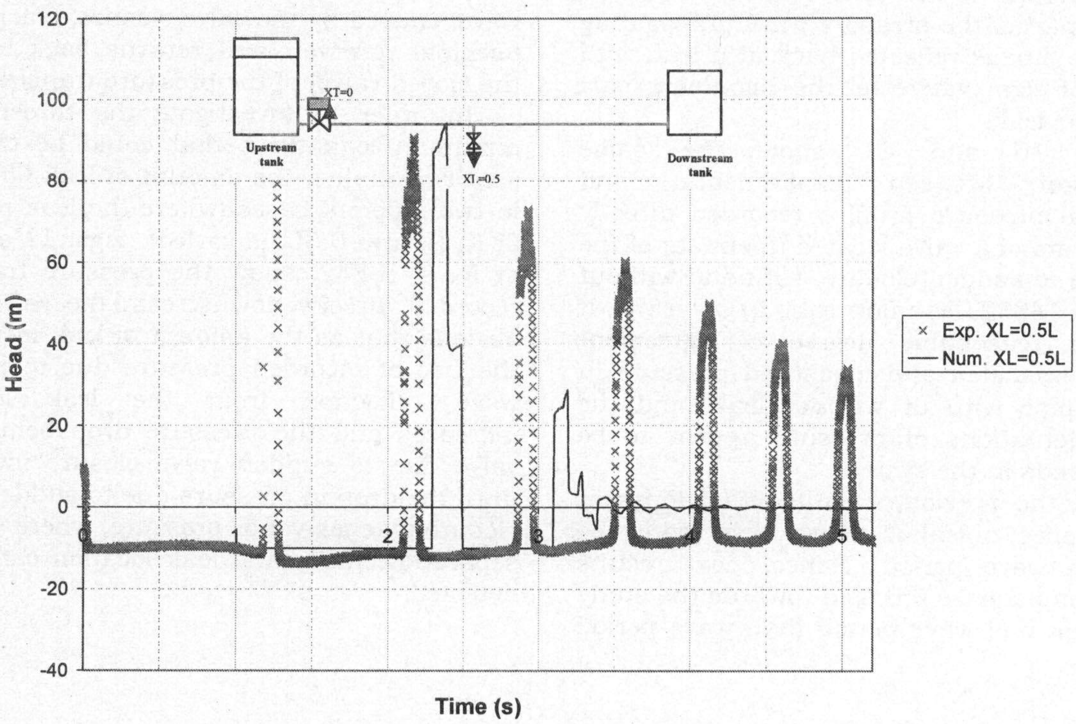


Fig. 9. Transient pressure profile, recorded downstream of a suddenly closed valve located upstream of the pipe, R_N=55666 with leak of q/Q = 11% , at XL=0.5L.

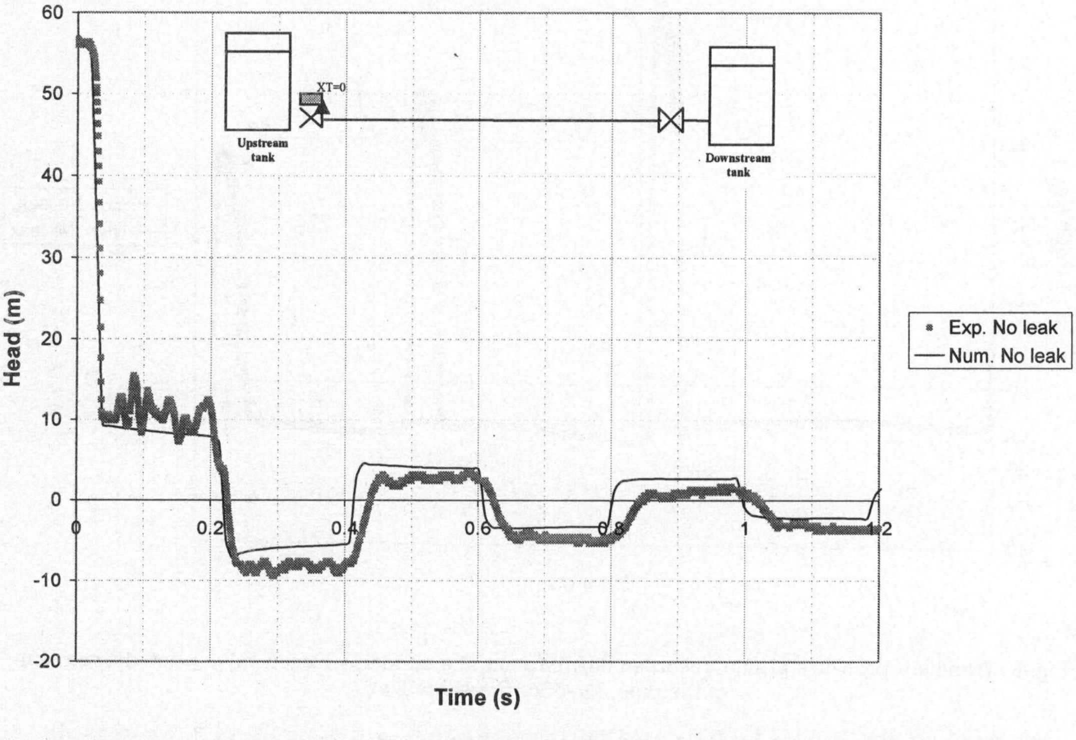


Fig. 10. Transient pressure profile, recorded downstream of a suddenly closed valve located upstream of the pipe, R_N=18832 with no leak.

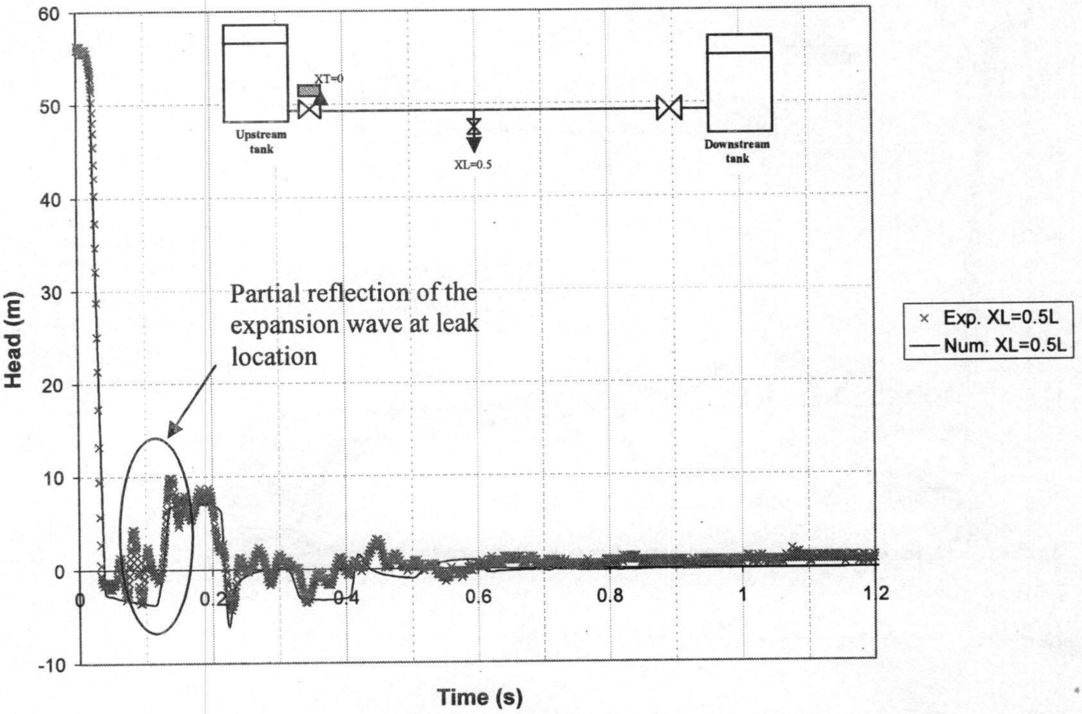


Fig. 11. Transient pressure profile, recorded downstream of a suddenly closed valve located upstream of the pipe, R_N=18832 with leak of q/Q = 25% , at XL=0.5L.

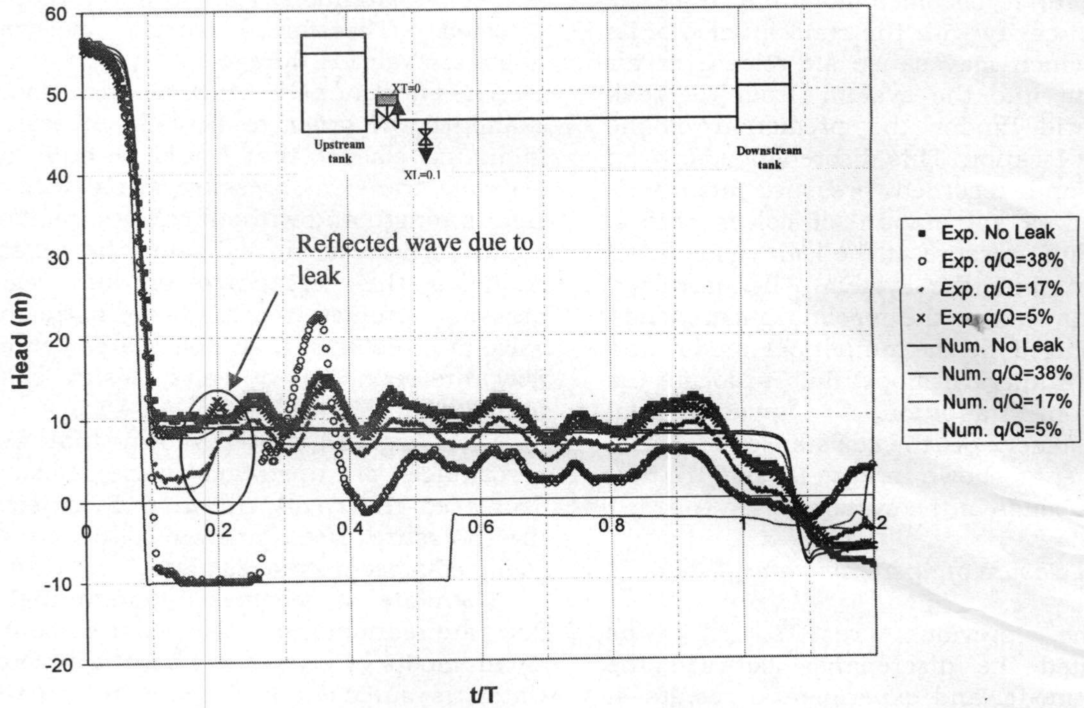


Fig. 12. Transient pressure profile, recorded downstream of a suddenly closed valve located upstream of the pipe, R_N=18832 with leak at XL=0.1 L and different leak flow ratios (at higher system pressure).

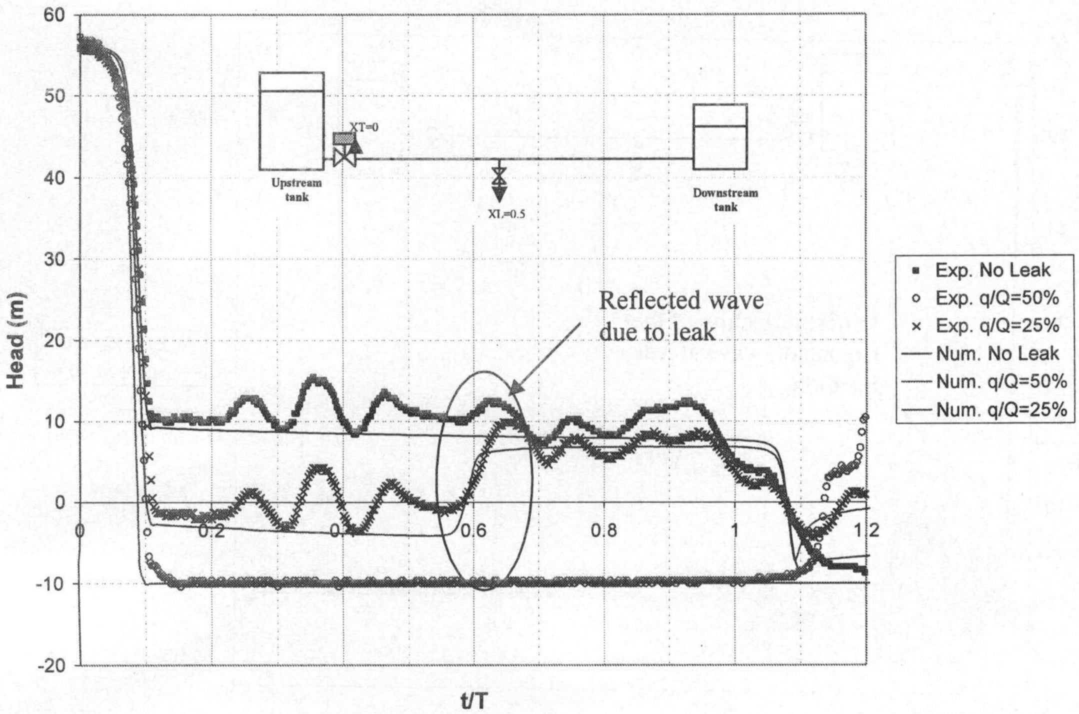


Fig. 13. Transient pressure profile, recorded downstream of a suddenly closed valve located upstream of the pipe, R_N=18832 with leak at XL=0.5 L and different leak flow ratios (at higher system pressure).

Therefore, it becomes apparent that the presence of cavity with the consequence of its collapse, which may cause air release or air entrainment into the system, from the leak position, will hinder the prediction of the actual leak location. This discrepancy between predicted and recorded pressure history is emphasized as the amount of leak increases, then vacuum pressure at the leak yields to air entrainment into the system. The entrained air from the leak to the pipeline phenomenon is not modeled in the numerical model and hence the numerical model fails to locate the leak position. In addition, it is apparent from the consistency of the existence of small fluctuations, as shown in figs. 12 and 13, that it is due to bends in the system.

3.2. Partial closure of upstream valve

In the previous results, it was demonstrated the discrepancy between the numerical model and experimental results in predicting the behavior of transient pressure waves; this is attributed to the formation of cavity and column separation and possible air release. In addition, leak location cannot be detected. Therefore, partial closure of upstream valve is thought.

The effect of percentage of valve closure is examined, in order to be able to select the minimum closure that would be sufficient to generate transient pressure signal with sufficient strength and without cavity formation.

In order to investigate the effect of changing the percentage of valve closure, pressure profiles recorded downstream the valve at a distance 0.2L and the percentage of flow rate reduction by valve closure changed from 20% to 100%

From fig. 14, it is shown that as the percentage of upstream valve closure is decreased the cavity duration decreases and the pressure rise generated due to vapor cavity collapse decreases also.

Therefore, it becomes apparent that with flow rate reduction by valve closure about 20% small shoots of pressure, about few meters of water, is sufficient and therefore, no risk of damaging the pipeline.

The effect of leak quantity on pressure transient profiles recorded at XT= 0.2L is illustrated in fig. 15. To give an impression of the threshold of leak below which the certainty of the localization of leak position will be doubtful at 20% partial closure.

From the figure, it is apparent that as the amount of leak increases the pressure depression due to partial valve closure increases, due to the increased of pipe flow rate when the amount of leak increases. Meanwhile, the rise of recorded pressure due to wave reflection from leak location increases.

From the figure, it is apparent that at relatively very small leak flow ratio (approximately 3%) the change in transient pressure profile is evident. The position of leak is changed along the pipe to investigate the effect of leak location on pressure transient. The results of simulation are shown in fig. 16. for different leak positions (0.1L, 0.3L, 0.5L, 0.7L and 0.9L) and the pressure transient is recorded at the same location 0.2L downstream of the valve with flow rate reduction about 20%. Using the same relation [1] eq. (14); it can be proved that the leak position can be detected with a reasonable degree of accuracy.

Experimental results are compared to numerical prediction to investigate the capability of the model in simulating pressure transient due to partial upstream valve closure.

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

$$\frac{t_r - t_c}{T} = \frac{XL - XT}{L}. \qquad (14)$$

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).

Table 2 represents the results of precision on the location of various leaks. The results show that leaks may be located with average error 0.034 L, which is larger than in case of full closure of downstream valve [1] because of the small pressure wave (about few meters) and the noise in the pressure wave.

It is important to monitor the pressure transient at different locations to detect the position of leak. This is since pressure transient profile clearly depends on the position of leak and the location of pressure measurement.

The experimental and numerical results of upstream partially closed valve in case of leak at the middle of the pipe with flow rate reduction about 20% are shown in figs. 17a-e. Contrary to the full valve closure, fig. 17-a. shows the monitored transient pressure profile directly downstream of the partially closed valve (XT =0). It is clear from the figure that there is no significant difference between the monitored transient pressure profile for the case with leak and that for the case without leak. This is a result of the existence of the upstream tank just upstream of the valve. The water level in the large upstream tank is kept constant at 11m. The large upstream tank is acting as a surge tank. Therefore, that pressure profile, recorded just downstream of the valve cannot recognize the pressure wave propagation and hence the reflected pressure wave from the leak. Therefore, the leak cannot be detected nor located from that pressure reading.

Fig. 17-b shows the pressure profiles monitored at XT= 0.2L. The positive wave reflection from the leak is detected after $t_r/T \approx 0.4$. Hence, applying eq. (14) and substituting for $t_c/T \approx 0.1$ predicts the leak location at distance of 0.3L upstream of transducer location. Meanwhile, the positive wave reflected from the leak position and recorded at XT= 0.4L is detected at $t_r/T \approx 0.3$ as shown in fig. 19-c. The location of leak can therefore, be predicted by substituting for $t_c/T \approx 0.2$.

Figs. 17d-e show the results monitored at 0.6L and 0.8L after the leak location indicating only the presence of leak indicated by the extent of pressure variation due to partial valve closure.

Table 2
Comparison between actual and predicted leak locations

Actual leak location (m)	Predicted location (m)	Error (m)	Error %
18 m (0.3 L)	19.38 m (0.323 L)	1.38 m	2.3%
30 m (0.5 L)	30.84 m 0.514 L	0.84 m	1.4%
42 m (0.7 L)	45.66 m (0.761 L)	3.66 m	6.1%
54 m (0.9 L)	56.28 m (0.938 L)	2.28 m	3.8%

4. Conclusions

The reliability of using pressure transients, generated by full or partial closure of an upstream 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 partial reflection of pressure wave takes to travel from the measurement section to the leak location and vice versa.

A numerical model is developed for modeling pressure transients in the presence of leak. The model is capable of dealing with column separation, unsteady friction and the viscoelastic behavior of the pipe wall. 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 in viscoelastic pipes. Application in which the cavity formation occurred, the numerical model shows a slight discrepancy, which may be attributed to the Discrete Vapor Cavity Model (DVCM) itself and the inlet air flow through the leak location due to negative pressure in the pipeline.

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 drawbacks of using the full closure of upstream valve is the cavity formation, which results in dramatic pressure rise due to the collapse of cavity. In addition, full valve closure will results in complete disruption of the pipe flow.

A realistic technique of using pressure transient in pipeline leak detection and localization is presented and investigated experimentally and numerically. Instead of initiating pressure transients using full valve closure of upstream valve, a partial valve closure is implemented. Closing a valve partially generates a reasonably small pressure rise, which causes no risk of damaging the pipeline. Also, it does not cause full interruption of pipeline operation. The effect of leak quantity is studied to give an impression of the minimum value of leak that would result in a detectable signal due to partial valve closure. The effect of pressure transducer position is also investigated by measuring pressure signal at five different locations along the pipeline. The reflected wave from the leak could be detected only if the pressure transducer upstream the leak location in pressure wave direction and hence the leak could be detected and located. On other hand only the downstream transducer, recorded the extent of pressure variation, indicating the presence of leak.

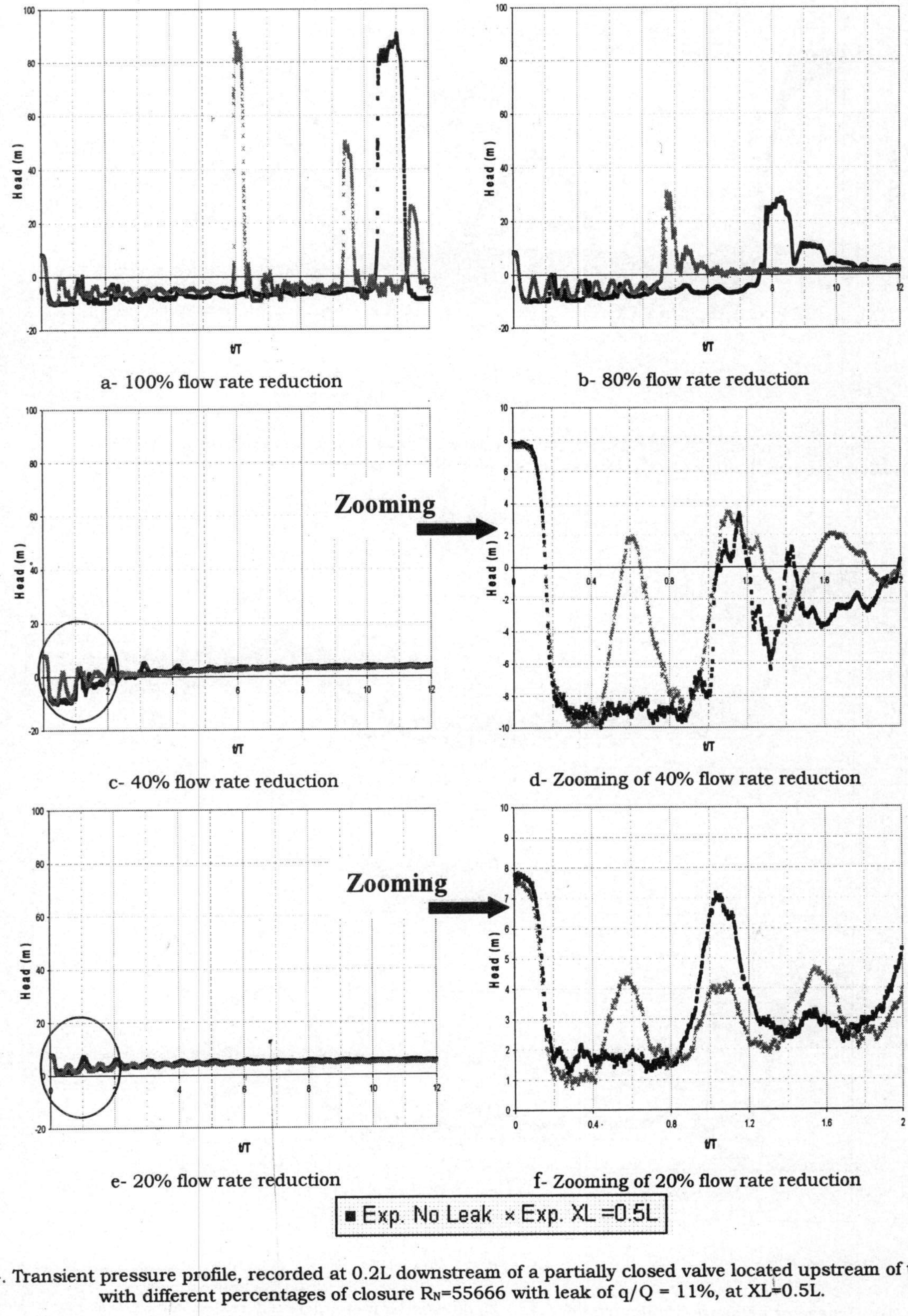


Fig. 14. Transient pressure profile, recorded at 0.2L downstream of a partially closed valve located upstream of the pipe, with different percentages of closure R_N=55666 with leak of q/Q = 11%, at XL=0.5L.

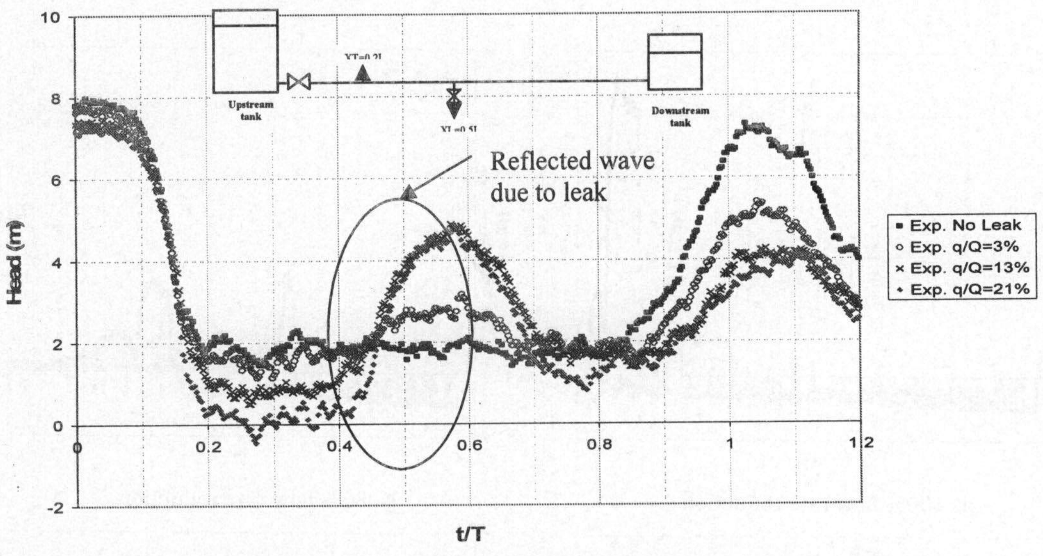
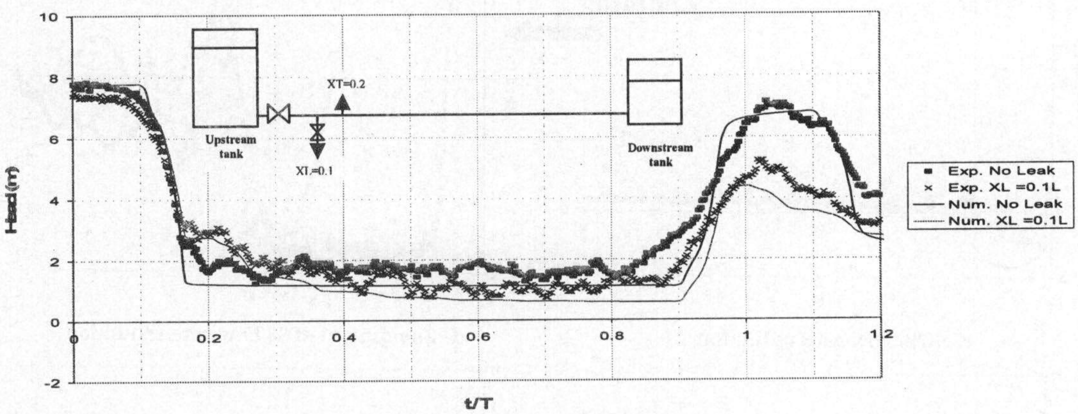
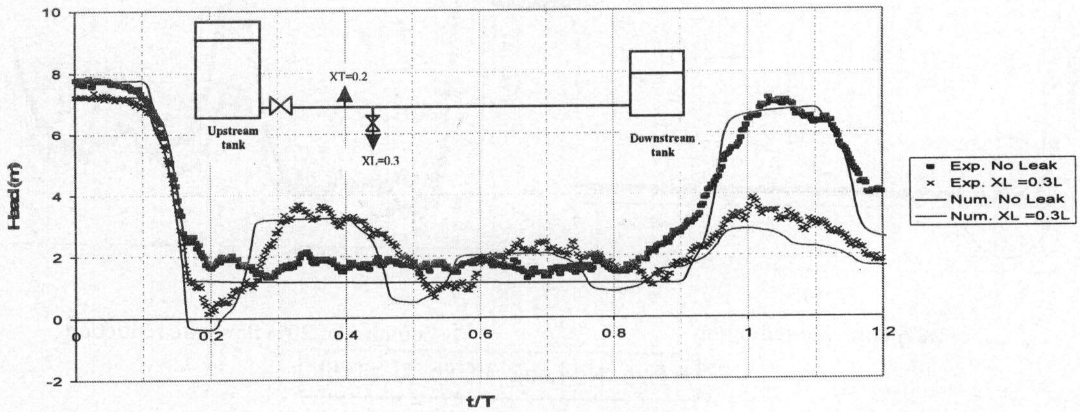


Fig. 15. Transient pressure profile, recorded at 0.2L downstream of a partially closed valve (20% flow rate reduction) located upstream of the pipe, R_N=55666 with different leak flow ratios at 0.5L.

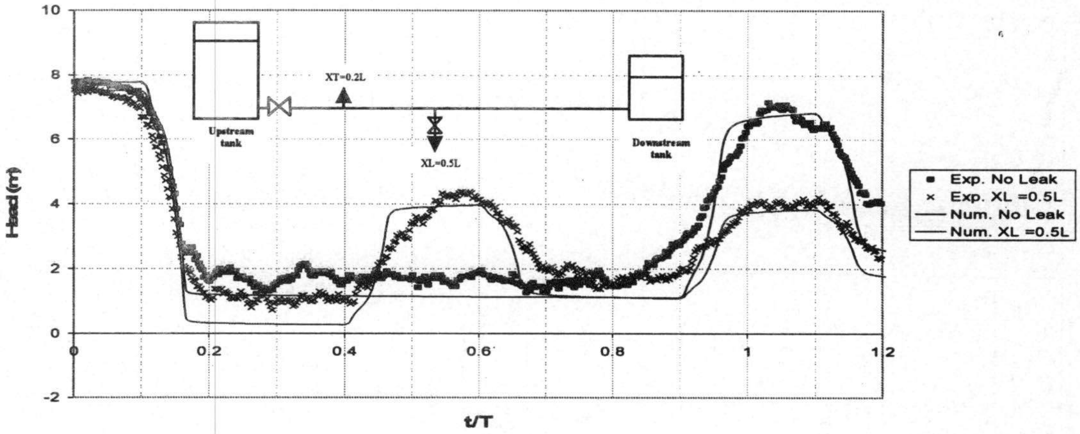


a- Leak at 0.1L ,q/Q =13%

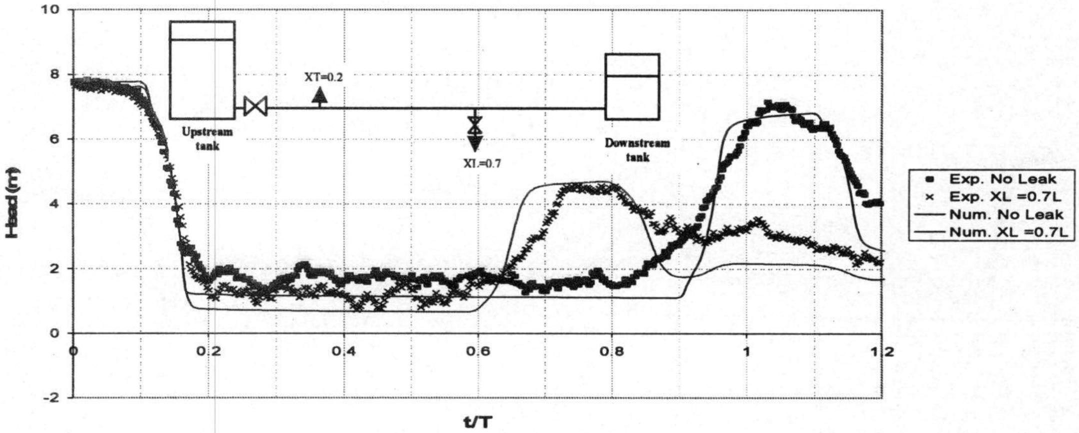


b- Leak at 0.3L ,q/Q =12%

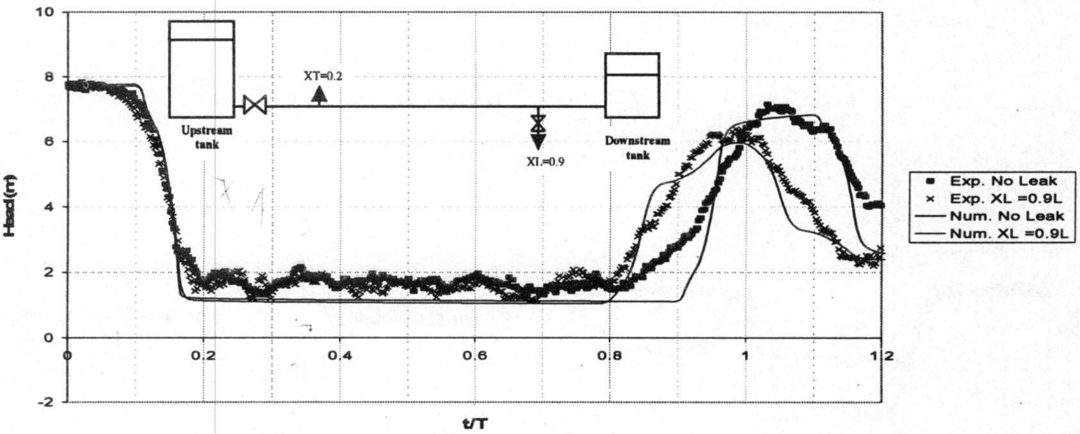
Fig. 16. Transient pressure profile, recorded at 0.2L downstream of a partially closed valve (20% flow rate reduction) located upstream of the pipe, R_N=55666 with different leak positions.



c- Leak at 0.5L ,q/Q =11%

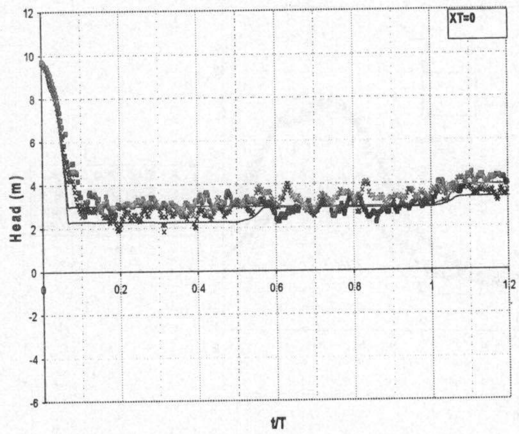


d- Leak at 0.7L ,q/Q = 9%

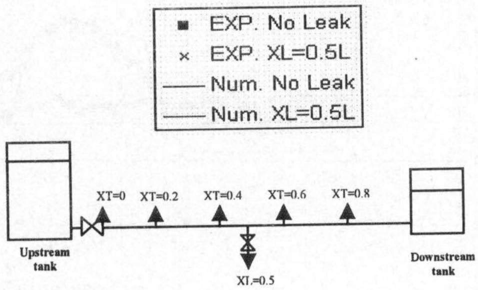


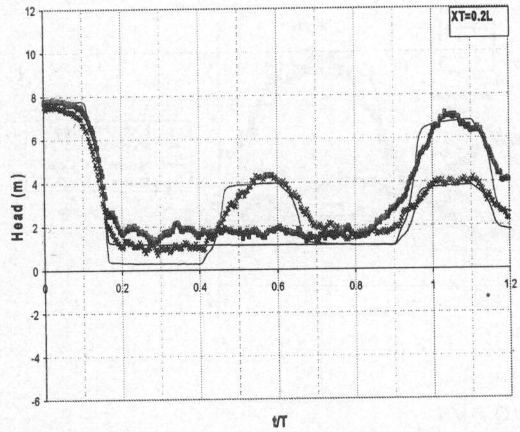
e- Leak at 0.9L ,q/Q = 6%

Fig. 16. Cont. Transient pressure profile, recorded at 0.2L downstream of a partially closed valve (20% flow rate reduction) located upstream of the pipe, RN=55666 with different leak positions.

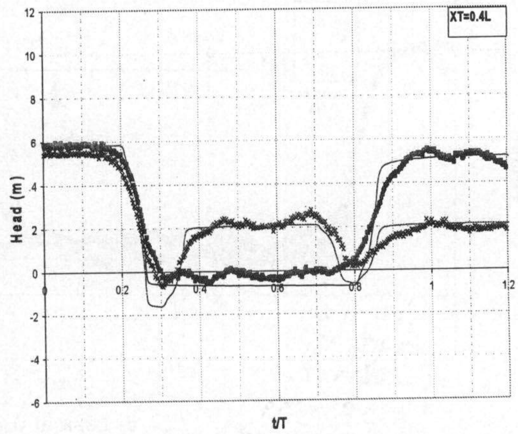


a- Transducer at 0

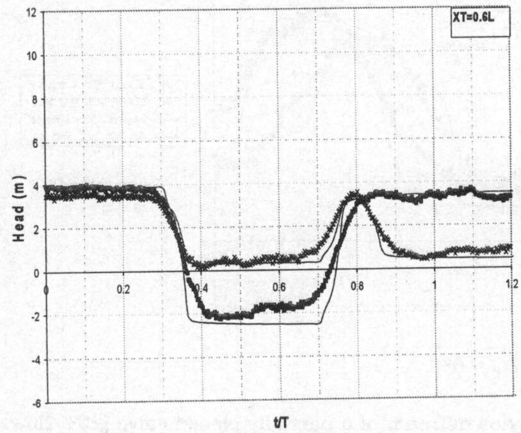




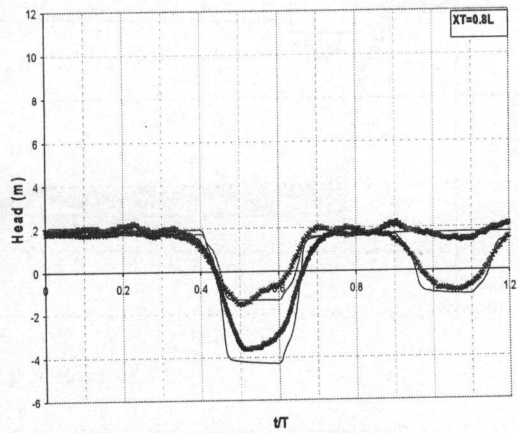
b- Transducer at 0.2L



c- Transducer at 0.4L



d- Transducer at 0.6L



e- Transducer at 0.8L

Fig. 17. Transient pressure profile, recorded at different stations downstream of a partially closed valve (20% flow rate reduction) located upstream 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,
C^+	is the characteristic curve, transmitting information downstream,
C^-	is the characteristic curve transmitting information upstream,
D	is the pipe diameter,
E_j	is the modulus of Elasticity of the jth Kelvin-Voigt element,
e	is the pipe wall thickness,
f	is the Darcy-Weisbach friction factor,
g	is the acceleration due to gravity,
H	is the local flow head,
H_{Res}	is the head of the upstream reservoir (m),
H_{Leak}	is the head at the leak location,
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,
Q	is the steady-state pipe flow rate,
q	is the leak flow rate,
R	is the pipe radius,
R_N	is the Reynolds Number,
s	is the distance along the pipe,
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 (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,
$W(\,)$	is the weighting function for the unsteady friction models,
XL	is the leak location,
XT	is the transducer position,
ΔH	is the head drop across the valve,
Δt	is the time step in method of characteristics solution,
ε_j	is the strain of the jth Kelvin-Voigt element,
λ	is used as the multiplier in the solution by the method of characteristics,
ρ	is the fluid density,
τ	is the dimensionless time in the unsteady friction models, and
τ_j	is the retardation time of the jth Kelvin-Voigt element.

Subscripts

d	is the refers to the downstream point,
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,
L	is the known condition downstream at time (t-Δt) to be used in the C^- characteristic equation, and
u	is the refers to the upstream point.

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