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ScienceDirect
Procedia Engineering 119 (2015) 243 – 252
Procedia Engineering
www.elsevier.com/locate/procedia

13th Computer Control for Water Industry Conference, CCWI 2015

Leak-induced pressure decay during transients in viscoelastic pipes. Preliminary results.

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Abstract

In this paper, the dynamics of pressure peaks in a single viscoelastic pipe with a leak (*leaky pipe*) is examined by means of laboratory and numerical experiments. Experimental tests are the necessary premise to a reliable calibration of a 1-D numerical model which allows to investigate in detail a wide range of both geometrical and flow conditions by taking into account not only the leak but also energy dissipation due to viscoelasticity and unsteady friction. In the analysis, the decay of the maximum values of the pressure is assumed as a representative characteristic of the dynamics of the examined transients in the long term. The numerical campaign has pointed out the characteristic quantities affecting the investigated phenomenon as well as the structure of the pressure decay law.

Peer-review under responsibility of the Scientific Committee of CCWI 2015

Keywords: leak; pipe systems; transients; viscoelasticity

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1. Introduction

Properties of pressure waves — traveling along the pipe and giving rise to a reflected pressure wave at any singularity (e.g., leaks, partial blockages, and internal wall damages) — are the key principle on which transient test-based techniques (TTBTs) for pressurized pipe fault diagnosis are based. A leak, as an example, characterizes remarkably the dynamics of transients with respect to other system configurations, such as the *single* integer *pipe* — i.e., a pipe with constant discharge and internal diameter, D — and the *in-line valve pipe* — i.e., a single pipe with a partially closed in-line valve. With regard to transients due to the fast closure of a valve placed at the downstream end section — considered in this paper for the sake of simplicity — clear differences emerge both in the short and long term. In fact, during the first characteristic time of the pipe — $\tau = 2L/a_{\mathrm{el}}$, with L = pipe length, and a_{el} = elastic pressure wave speed — at the downstream end section of the *leaky pipe* (i.e., a pipe with a leak) at $t = 2(L - s_E)/a_{\mathrm{el}}$ a pressure decrease (Fig. 1a) happens in the pressure signal (i.e., the time-history of the piezometric head, H) with respect to the single pipe, with s = spatial co-ordinate, and the subscript E indicating the leak. On the contrary, at $t = 2(L - s_V)/a_{\mathrm{el}}$ in an in-line valve pipe a pressure rise (Fig. 1b) occurs in the pressure signal, with the subscript V indicating the in-line valve. In the phases following the end of the maneuver, a much more severe pressure damping takes place in

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1877-7058
Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.882

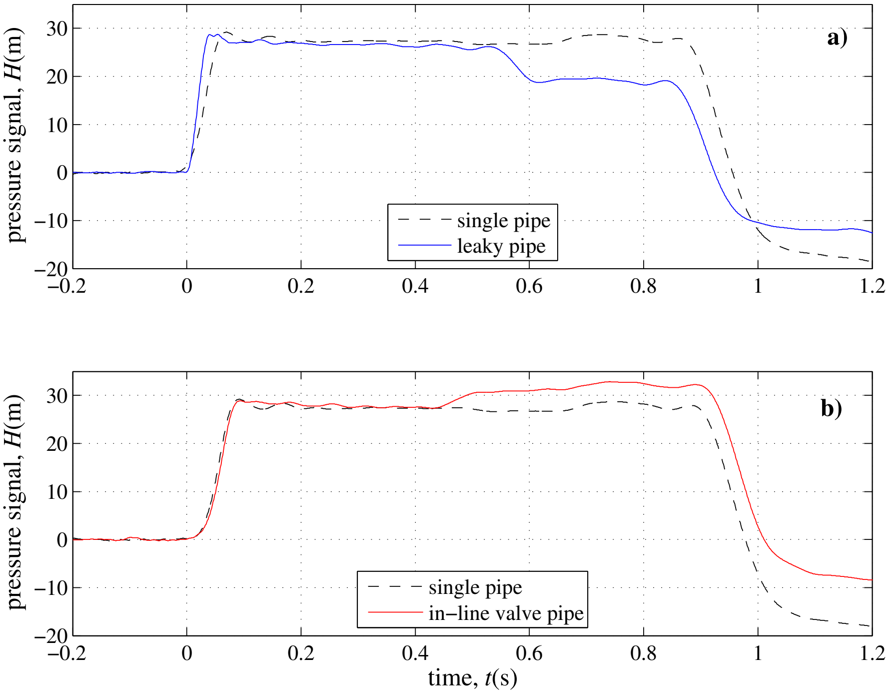

Fig. 1: Experimental pressure signals during the first characteristic time of transients due to the fast closure of the end valve: comparison between the case of the single pipe and a) the leaky pipe, and b) the in-line valve pipe.

the leaky pipe with respect to both the single and in-line valve pipe (Fig. 2).This is the reason why in the last couple of decades a more and more intense research activity concerned the analysis of transient pressure signals as a powerful tool for pipe diagnosis and, particularly, leak detection (Colombo et al.,2009).
In this paper attention is focused on leak-induced damping of pressure peaks within TTBTs. Such a feature is analyzed as an important characteristic of leaky pipes with respect to integer pipes for the diagnosis of pressurised pipes (Wang et al.,2002,Nixon et al.,2006). By means of both laboratory and numerical experiments — the latter executed through a calibrated 1-D model — quantities affecting the damping of pressure peaks are examined with regard to both pipe system geometrical characteristics and flow conditions.

2. Materials and methods

As in Ramos et al.(2004) — for the single pipe — and Meniconi et al.(2014) — for the in-line valve pipe — the time-history of dimensionless pressure maxima, $h^*_{\max}$, at the downstream end section is assumed as a representative character of the examined transients:

$$h^*_{\max} = f(t^*), \tag{1}$$

where the dimensionless pressure, h^*, and time, t^*, are defined as

$$h^* = \frac{H - H_F}{\Delta H_{AJ}}, \tag{2}$$

$$t^* = \frac{t}{\tau} \tag{3}$$

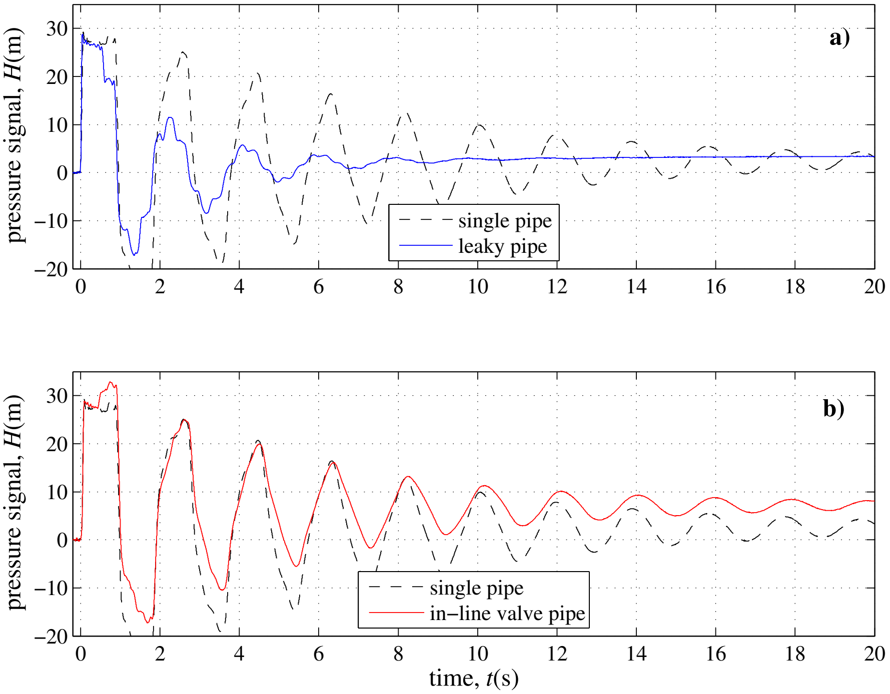

Fig. 2: Experimental pressure signals during transients due to the fast closure of the end valve: comparison in the long term between the case of the single pipe and a) the leaky pipe, and b) the in-line valve pipe.

respectively; in Eq. (2), $\Delta H_{AJ} = a_{\mathrm{el}} V_{0,d}/g$ is the Allievi-Joukowski overpressure, with V = mean flow velocity, g = gravitational acceleration, and the subscripts d and F indicating the branch of pipe downstream of the leak, and the final steady-state conditions, respectively.

In the light of Eq. (1), the aim of this paper can be reformulated in terms of defining function f. Since a general solution in a closed form to the partial differential equations governing the investigated phenomena (see §2.2) is not available, function f is obtained by means of laboratory and numerical experiments. The former are finalized to calibrate and check the 1-D numerical model, the latter allow to explore a large range of system configurations in terms of geometrical and flow conditions.

2.1. Laboratory tests

Laboratory tests have been executed on a high density polyethylene (HDPE) pipe (L = 164.93 m, D = 93.3 mm, and wall thickness e = 8.1 mm) at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy. In such an experimental setup (Fig. 3), a device simulating a leak is placed at s_E = 60.84 m. The rectangular hole with rounded edges which gives rise to the leak is machined on a steel plate. During transient tests, caused by the fast closure of the maneuver valve, two different holes have been used (A_E = 52.52 mm^2 for the hole #1 and A_E = 116.64 mm^2 for the hole #2, with A_E being the area of the hole) as well as a quite large range of pre-transient flow conditions with no water column separation is explored. In Tab. 1 the main characteristics of representative tests are reported (dimensionless quantities are defined in §4). During tests, the pressure signal has been measured at the end section of the pipe (section M in Fig. 3) by means of a piezoresistive transducer with a frequency acquisition of 1024 Hz. The steady-state discharge in the d-branch and water temperature have been measured by means of a magnetic flow meter and a digital thermometer, respectively. In Fig. 4, as an example, the pressure signal for test no. 4 is reported ($V_{0,d}$ = 0.16 m/s and hole #2).

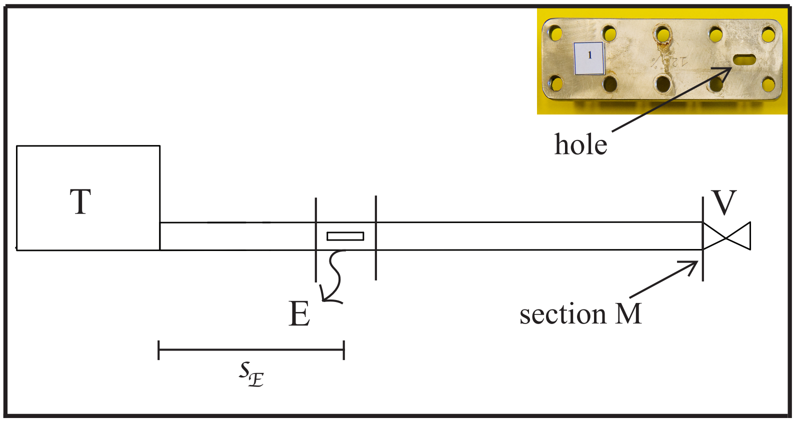

Fig. 3: Experimental set-up (T = supply tank, E = leak, V = maneuver valve, and M = measurement section); in the inset one of the steel plates (hole #1) used to cause the leak is shown.

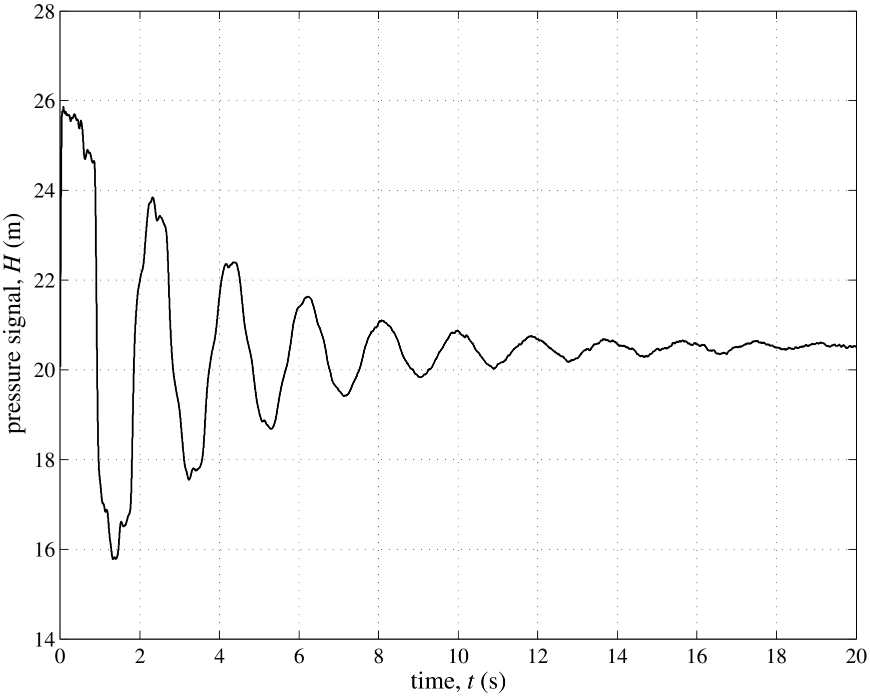

Fig. 4: Pressure signal in a leaky pipe for test no. 4 ($V_{0,d}$ = 0.16 m/s and hole #2).

Test no.	$V_{0,d}$ (m/s)	$H_{0,E}$ (m)	A_E (mm^2)	$N_{0,d}$	$h^*_{0,E}$	Σ^*
1	0.69	18.62	52.52	$6.45\ 10^4$	$5.07\ 10^{-2}$	203.48
2	0.16	20.50	52.52	$1.47\ 10^4$	$5.32\ 10^{-2}$	203.48
3	0.44	19.04	52.52	$4.07\ 10^4$	$5.12\ 10^{-2}$	203.48
4	0.16	20.10	116.64	$1.46\ 10^4$	$5.26\ 10^{-2}$	82.77
5	0.73	17.78	116.64	$6.76\ 10^4$	$4.95\ 10^{-2}$	82.77
6	0.20	20.25	116.64	$1.90\ 10^4$	$5.28\ 10^{-2}$	82.77

Table 1: Main characteristics of representative laboratory tests in a leaky pipe; left section: dimensional quantities, right section: corresponding dimensionless quantities (see §4).

2.2. 1-D model

Key points in 1-D numerical modelling of transients in viscoelastic leaky pipes concern: i) simulation of pipe material behavior, ii) friction term evaluation, and iii) leak law (Meniconi et al.,2014,Covas et al.,2005,Franke and Seyler,1983,Ghilardi and Paoletti,1986,Keramat et al.,2012,Keramat and Kolahi,2013,Meniconi et al.,2012a,b,Soares et al.,2008).

With regard to the first aspect, when a circumferential stress, σ, is applied to a viscoelastic material, the total strain, ϵ, is given by the sum of the instantaneous elastic, ϵ_{el}, and retarded component, ϵ_r:

$$\epsilon = \epsilon_{\mathrm{el}} + \epsilon_r. \tag{4}$$

In this paper, a single element Kelvin-Voigt model — i.e., a viscous damper and an elastic spring connected in parallel jointed to a simple elastic spring in series — is used to simulate such a behavior. As a consequence, the following relationship links σ and ϵ_r:

$$\sigma = E_r\epsilon_r + \frac{E_r}{T_r}\frac{d\epsilon_r}{dt}, \tag{5}$$

where E_r = dynamic modulus of elasticity, and T_r = retardation time of the viscous damper element. According to Hooke's law, the elastic strain, ϵ_{el}, of the spring is given by:

$$\epsilon_{\mathrm{el}} = \frac{\sigma}{E_{\mathrm{el}}}, \tag{6}$$

where the elastic Young's modulus of elasticity, E_{el}, is linked to a_{el} (Hachem and Schleiss,2011) by:

$$a_{\mathrm{el}} = \sqrt{\frac{\frac{k}{\rho}}{1+\psi\frac{kD}{eE_{\mathrm{el}}}}}, \tag{7}$$

with ρ = density, k = bulk modulus of elasticity, and ψ = dimensionless parameter accounting for longitudinal support situation (Parmakian,1963,Montuori,1966). By means of Eqs. (5) and (7), the second and the third term in the continuity equation:

$$\frac{\partial H}{\partial t} + \frac{(a_{\mathrm{el}})^2}{g}\frac{\partial V}{\partial s} + \frac{2(a_{\mathrm{el}})^2}{g}\frac{d\epsilon_r}{dt} = 0, \tag{8}$$

can be calculated.

To evaluate the total friction term, J, in the momentum equation:

$$\frac{\partial H}{\partial s} + \frac{V}{g}\frac{\partial V}{\partial s} + \frac{1}{g}\frac{\partial V}{\partial t} + J = 0, \tag{9}$$

both the steady-state, J_s, and unsteady-state, J_u, component are taken into account. In this paper, J_u is evaluated by means of an Instantaneous Acceleration Based (IAB) model (Bergant et al.,2001,Brunone et al.,1995,2004,Brunone and Golia,2008,Ghidaoui et al.,2005):

$$J_u = \frac{k_{uf}}{2g}\left(\frac{\partial V}{\partial t} + \mathrm{sign}\left(\mathrm{V}\frac{\partial \mathrm{V}}{\partial \mathrm{s}}\right)\mathrm{a_{el}}\frac{\partial \mathrm{V}}{\partial \mathrm{s}}\right), \tag{10}$$

Test no.	E_f
1	0.9862
2	0.9864
3	0.9770
4	0.9750
5	0.9852
6	0.9792

Table 2: Nash-Sutcliffe efficiency coefficient, E_f, for numerical simulation of tests of Tab. 1.

where k_{uf} = unsteady friction coefficient, and sign($V\partial V/\partial s$) = (+1 for $V\partial V/\partial s \geq 0$ or -1 for $V\partial V/\partial s < 0$).
As a boundary condition at the leak ($s = s_E$), since A_E does not depend on the internal pressure and no hysteresis takes place (Ferrante et al.,2011), the Torricelli's equation can be assumed as leak law:

$$q_E = C_E A_E \sqrt{2g(H_E - z_E)} \tag{11}$$

where q_E = flow through the leak, C = discharge coefficient, and z = elevation. With regard to the boundary conditions at the supply tank and the maneuver valve, a distinction has to be made between the calibration phase (§3) and successive numerical experiments (§4). Within the numerical model calibration: *i*) the measured values of the supply head, H_T, are assumed as data, since during laboratory tests H_T increases slightly with time after the end of the maneuver (Meniconi et al.,2012b); and *ii*) the actual flow rate curve of the maneuver valve and the duration of the maneuver, Θ, are determined within an inverse transient analysis (Meniconi et al.,2012b). On the contrary, for the sake of simplicity, in the numerical experiments: *i*) H_T is assumed as a constant; and *ii*) transients are generated by an instantaneous closure of the maneuver valve.

3. 1-D model calibration and performance

To simulate properly transients by means of the 1-D model described in §2.2, a calibration procedure has been followed to evaluate parameters describing the viscoelastic behavior of pipe material — E_{el}, ψ, a_{el}, E_r, and T_r — transient energy dissipation — k_{uf} — and leak behavior, $C_E A_E$. Methodology used to obtain the values of E_{el}, ψ, a_{el}, E_r, T_r, and k_{uf} is based on the comparison between numerical and experimental data for transients in a single pipe (Meniconi et al.,2014,2012a). Then such values — $E_{\text{el}} = 2.20 \cdot 10^9$ N/m^2, $\psi = 1.2535$, $E_r = 8.10 \cdot 10^9$ N/m^2, $T_r = 0.15$, and $k_{uf} = 1.5 \cdot 10^{-3}$ — have been checked by considering the same type of transients in more complex systems such as the in-line valve pipe (Meniconi et al.,2014), the leaky pipe (Meniconi et al.,2013), and the pipe with an extended partial blockage (Meniconi et al.,2012a). The values of $C_E A_E$ have been obtained by means of steady-state tests ($C_E A_E$ is equal to 3.36 10^{-5} and 8.26 10^{-5} for hole # 1 and # 2, respectively). As an example of the performance of the model, numerical and experimental pressure signals are reported in Fig. 5 for two tests of Tab. 1. Reliability of the model is confirmed by the values of the Nash-Sutcliffe efficiency coefficient, E_f:

$$E_f = 1 - \sum_{i=1, t>\Theta}^{M} \frac{(H - H_n)^2}{(H - \bar{H})^2} \tag{12}$$

reported in Tab. 2 where M = number of samples, $\bar{H}$ = experimental mean value, and subscript n indicates numerical model values. E_f ranges from -∞ to 1: an efficiency of 1 ($E_f = 1$) indicates a perfect match of numerical data to the experimental ones. An efficiency of 0 ($E_f = 0$) indicates that the model test is as accurate as the mean of the experimental, whereas $E_f < 0$ occurs when the residual variance is larger than the data variance.

4. Formulation of the pressure peak decay law. Numerical experiments

The available 1-D model allows to identify quantities affecting the response of a leaky pipe to a given type of transient. Accordingly, a wide numerical experiment campaign has been executed. By considering $V_{0,d}$, H_E, $C_E A_E$,

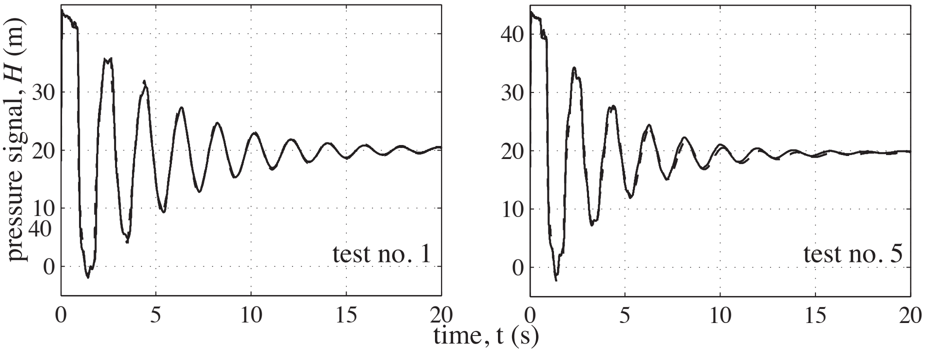

Fig. 5: Leaky pipe: transients due to the fast closure of the end valve. Comparison between experimental (continous line) and numerical (dashed line) pressure signals.

and s_E as possible characteristic quantities for given pipe material and size, in dimensionless terms Eq. (1) can be rewritten as:

$$h^*_{\max} = f\,[N_{0,d}, h^*_E, \Sigma^*, s^*_E]\,(t^*), \tag{13}$$

where:

$$N_{0,d} = V_{0,d}D/\nu \tag{14}$$

$$s^*_E = 1 - s_E/L \tag{15}$$

$$\Sigma^* = A/(C_E A_E) \tag{16}$$

$$h^*_E = \sqrt{2gH_E}/a_{\mathrm{el}} \tag{17}$$

with ν = kinematic viscosity, and A = pipe cross-sectional area. Then, the aims of this section are: i) to exclude possible redundant variables (Yalin,1970), and ii) to define the characteristics of function f. The below analysis concerns the period of time starting from the fifth characteristic time of the pipe when a clear periodicity — at least in terms of the shape of the pressure oscillations — can be observed in the pressure signal since the effect of the first pressure wave produced by the maneuver vanishes.

In such a context, the crucial role played by Σ^* and s^*_E proceeds clearly from the mentioned pressure wave mechanism of interaction with the external flow and the importance of h^*_E — demonstrated in (Ferrante et al.,2014) according to (Liou,1998) — is confirmed by numerical pressure signals reported in Fig. 6a. On the contrary, numerical experiments show that the importance of $N_{0,d}$ is negligible. In fact, the dimensionless pressure signals of Fig. 6b are almost indistinguishable for different values of $N_{0,d}$.

According to Ramos et al.(2004) — who examined the case of the single pipe — and Wang et al.(2005) and Meniconi et al.(2014) — for the case of the in-line valve pipe — a possible formulation of function f of Eq. (13) is in terms of an exponential law:

$$h^*_{\max} = ae^{-bt^*}, \tag{18}$$

where a = initial value coefficient, and b = decay coefficient.

In Fig. 7, as an example, the simulation of pressure peak decay by means of Eq. (18) is reported with its reliability supported by the small values of relative residuals.

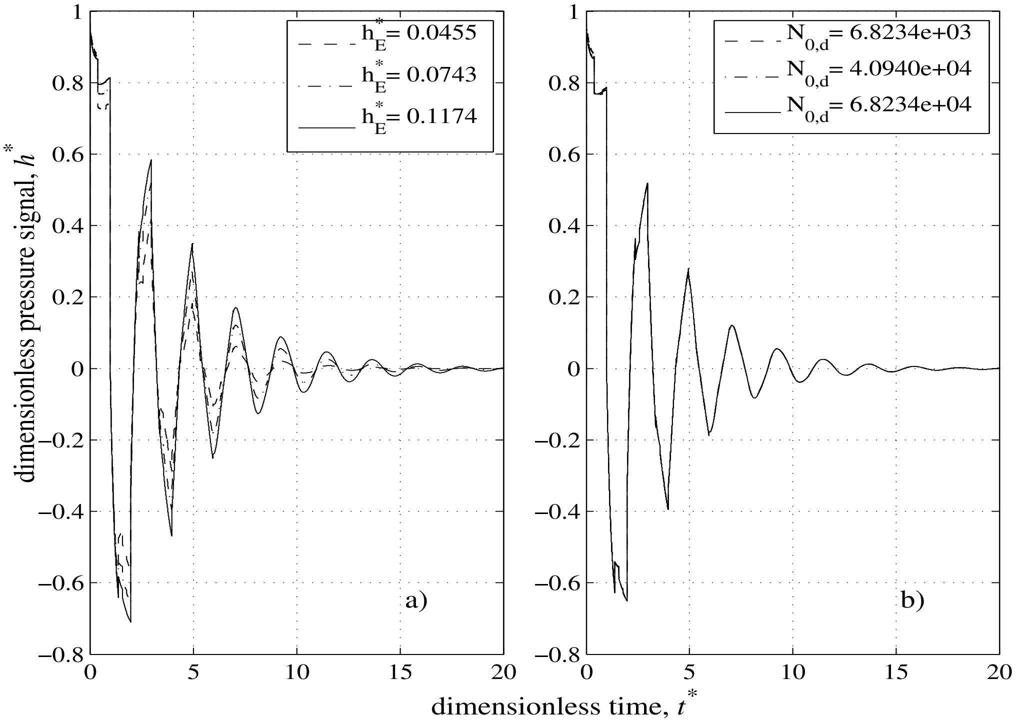

Fig. 6: Dimensionless pressure signals for given s^*_E (= 0.400), Σ^* (= 85.46), and a) given $N_{0,d}$ (= 4.094 10^4) with different values of h^*_E, and b) given h^*_E (= 0.074) with different values of $N_{0,d}$.

5. Conclusions

This paper analyses the transient response of a single pipe with a leak (*leaky pipe*) in terms of the decay of the pressure peaks. For the sake of simplicity, transients due to the fast and complete closure of a valve placed at the downstream end section of the pipe are considered.

In the first part of the paper, the results of laboratory tests are offered as an essential premise to a reliable calibration of the 1-D model used in the following numerical experiments. In the range of the examined leaky pipes, calibration procedure has confirmed the values of the model parameters previously obtained for transients executed in quite different system layouts (i.e., *single pipe*, and *in-line valve pipe*).

In the second part of the paper, numerical tests have been carried out to define the structure of the decay law of pressure peaks as well as the most important quantities that dominate the transient response of the leaky pipe. These experiments confirm adequacy of an exponential law to capture the decay of peaks of pressure peaks pointing out the important role played by leak entity and location as well as pre-transient pressure at the leak.

Acknowledgements

This research has been supported by the Italian Ministry of Education, University and Research (MIUR) — under the Projects of Relevant National Interest “Advanced analysis tools for the management of water losses in urban aqueducts” and “Tools and procedures for an advanced and sustainable management of water distribution systems” — and Fondazione Cassa Risparmio Perugia, under the project “Hydraulic and microbiological combined approach towards water quality control (no. 2015.0383.021)”.

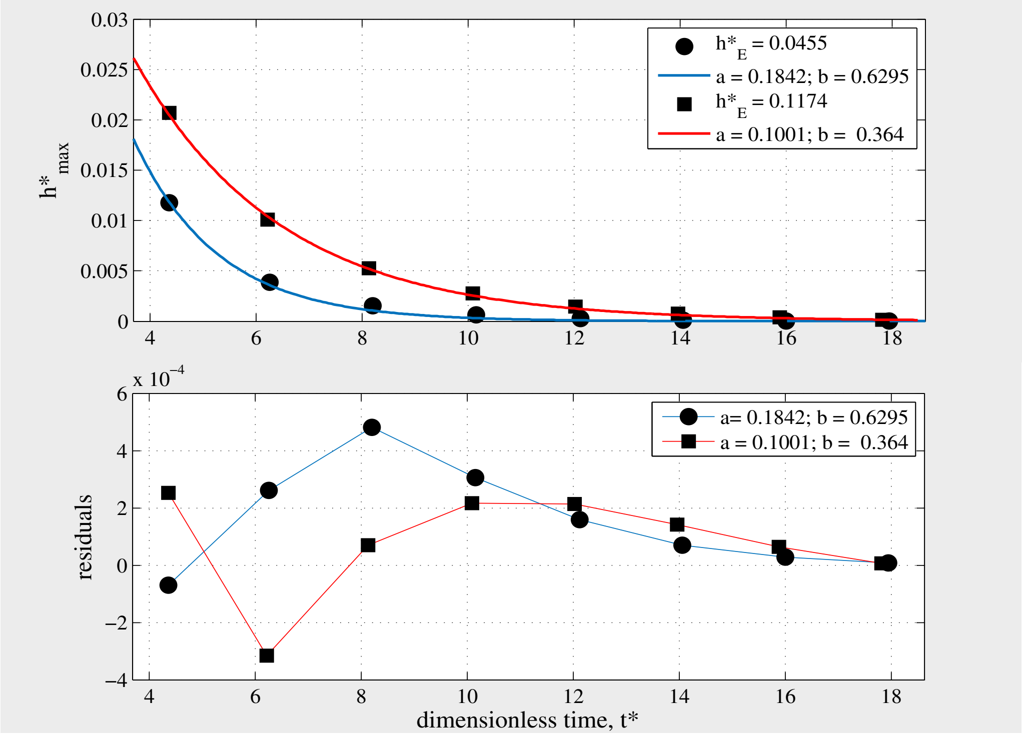

Fig. 7: Transients in a leaky pipe: fitting of the exponential law to the envelopes of numerical pressure maxima and relative residuals.

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