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Intrusion problematic during water supply systems' operation

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Abstract
Intrusion through leaks occurrence is a phenomenon when external fluid comes into water pipe systems. This phenomenon can cause contamination problems in drinking pipe systems. Hence, this paper focuses on the entry of external fluids across small leaks during normal operation conditions. This situation is especially important in elevated points of the pipe profile. Pressure variations can origin water volume losses and intrusion of contaminants into the drinking water pipes. This work focuses in obtaining up the physical representation on a specific case intrusion in a pipe water system. The combination of two factors is required to generate this kind of intrusion in a water supply system: on one hand the existence of at least a leak in the system; on the other hand, a pressure variation could occur during the operation of the system due to consumption variation, pump start-up or shutdown. The potential of intrusion during a dynamic or transient event is here analyzed. To obtain this objective an experimental case study of pressure transient scenario is analyzed with a small leak located nearby the transient source.

Keywords: Transient pressure, Experimental model, CFD model, Leaks, Water pollution.

1. Introduction
1.1 Pressure transients vs intrusion
The pressure transient occurs during water supply system operations. Sudden changes in the demand and pump start-up and shut down are the more frequent sources of transients [1]. These quick changes are originated by: flushing operations, opening and closing fire hydrants, pump startup and shut down, valve operation (open and close), air venting, among others. With all these factors, the intrusion is favoured and it can have a significant implication in the quality of the drinking water and the public health [2].
Pressure transients depend on some characteristics of pipe system [1], as the system size, the kind of pumping water source and the configuration of the distribution network. Fleming made a study of several water pipe systems and the main characteristics related to pressure transients [1]. According to the size of the distribution networks were classified the on smaller and larger. The smaller ones increase the susceptibility to transients; five from six networks (83%) with less than 0.44 m^3/s of delivered flow presents negative pressures. On the other hand, the 35% of larger networks were susceptible to negative pressure with a pump shutdown. Depending on the physical water source, the water supply system with groundwater source have an increased susceptibility to low or negative pressure transients. Depending on the system topography; systems with less than 45 m of level difference in its topography were less

susceptible. Water pipe systems with more storage facilities were less susceptible to negative pressure. And if the locations of tanks are at or near dead ends were more susceptible to negative pressure.
In this paper is analyzed a case where the negative pressure is induced by hydraulic transient condition from a valve closure at upstream which is equivalent to a pump shutdown. Whenever pressure goes down in buried pipes, where most of times the pipe is enveloped by terrain with saturated water, the intrusion can easily occurred.

2.1 Leakage and hydraulic performance

The presence of an initial failure increases the possibility of additional failures in a pipe, in near zones and on relatively short periods of time. This happens due to imbalances forces appearing around the first failure and its possible repair [3]. The presence of leaks is unavoidable and generates secondary economic losses (in addition to primary economic losses, i.e. cost of raw water, besides its treatment and transport) due to damages in the distribution network [4]. This can cause erosion in the bed of the pipe settlement and possibly more leaks, affecting streets and constructions.
According to the performance of the water pipe systems, it is possible to obtain the potential problems associated to possible sources of pollutants. The statistics of performance of water pipe systems is normally expressed in terms of burst frequency/kilometre/year (bursts are events that commonly cause water service interruption). A frequency greater to 5 burst/100km/year is highly unfavourable [5].
A leak can vary depending on type of soil, water quality, specifications and construction quality, materials, infrastructure age, operation practices and maintenance [6, 7, 8]. Leaks, as mentioned, can appear as a result of cross-section crack, crushing and longitudinal crack. The first case is due to efforts and vibrations produced by surface loadings, the second is caused by defective construction, and the third comes from fatigue materials, manufacture defects or water hammer. Phenomena as corrosion can increase this problem or others, like imperfections in joints or failures in valves. In domiciliary services, leaks can take place by split, perforation, cuts or loose pieces. Splits and loose pieces are associated to bad quality of used materials or deficient installation, while perforations and cuts are due to external factors. In domiciliary connections, almost 75% of leaks appear in pipes, whereas 25% rest is in accessories.
Although the statistic of types of failures varies in every installation, in average 70% of burst in pipes are circumferential and other 30% are longitudinal, holes and leaks through service connections and hydrants [5]. Consequently, as the most failures are circumferential and that type of burst happens mainly during winter season, in which an axial interaction between pipe-soil is suggested as the main mechanism.
This work considers the source of exterior pollution merge with the fluid leakage in a trunk main. This consideration is because around the failure could have a saturated land, and based on this it is established the conceptual conditions to model this type of event. The Table 1 presents a kind of classification for the leakages, which is stated according to its flow and the capability to detect and report it.

Table 1. Leakage classification

Type of Leakage	**q_L (m^3/s)**
Undetected leakage	$q_L < 3\times10^{-6}$
Leakage reported but difficultly detectable	$3\times10^{-6} < q_L < 5\times10^{-5}$
Leakage reported, easily detectable	$5\times10^{-5} < q_L < 1.5\times10^{-4}$
Reported Leakage	$1.5\times10^{-4} < q_L < 1.5\times10^{-2}$

The water companies must take actions in order to have knowledge of the system status, to estimate the problem magnitude and to determine an adequate level of leakage allowed. This paper focuses on obtaining real (physically) volumes of intrusion that could enter on the worst conditions during a hydraulic transient event. The flow fluctuation during the transient event is produced by a suddenly variation of the velocity and consequently of the pressure, that generates a negative pressure inside the pipe and with this the intrusion happens. This is evaluated experimentally and by a numerical representation using a CFD modelling. The objective of this contribution is to identify the potential relation among the intrusion flow and the pressure in the failure zone, to represent the event in a numerical way by using different scenarios and to show the achievements of this modelling.

2. Experimental model

2.1 Experimental set-up

The experimental set up used to model the intrusion phenomenon is made by a closed circuit, depicted in Figure 1. Firstly, at upstream, there is an air vessel, being possible to control and maintained a constant pressure. The tank is followed by 200 m of high density polyethylene pipe of 0.05 m diameter. On the first two meters of the main pipe a spherical valve is used. At downstream of the valve an orifice of 2 mm simulates a leak. The pipe has a free discharge at downstream directly to a tank. From this discharge the water is pumped to the air vessel tank in a continuous loop operation.

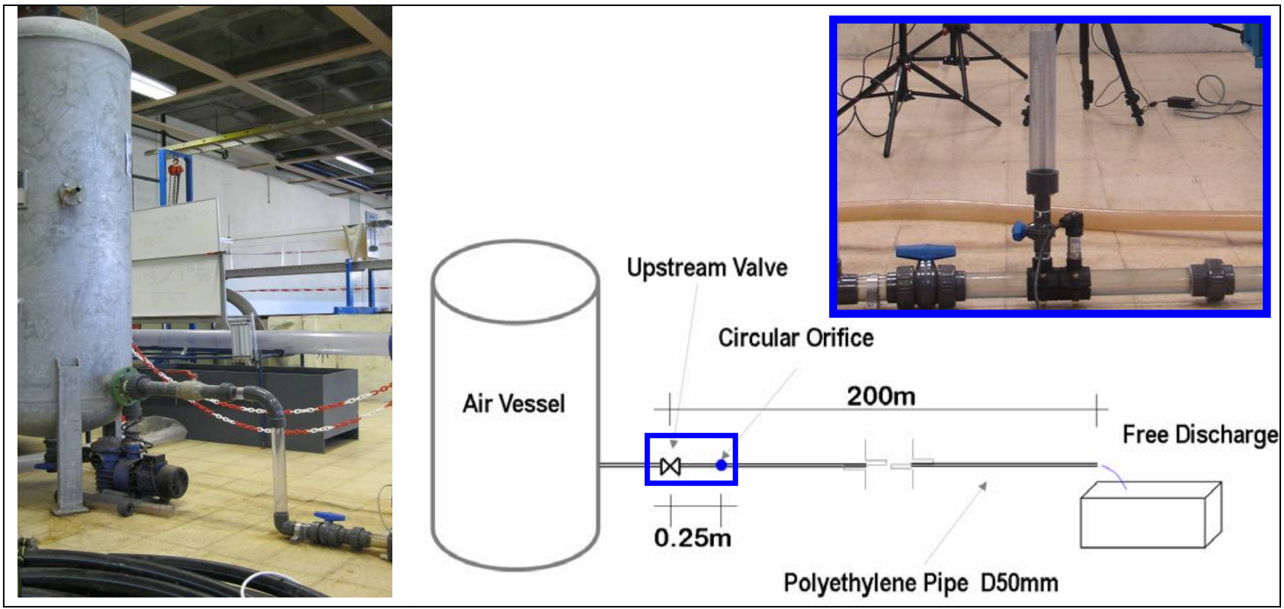

Figure 1. Scheme of the physically installation

The data that are collected from the physical model is registered by a transducer pressure close to the orifice. The initial or steady flow is measure by a V-Notch (triangular) weir. The transducer pressure presents a range from -1 to 24 bar (relative pressures), and it is calibrated to measure every 0.005 s. The data is collected by an acquisition system, pico-scope™, and then processed to be used in the numerical model.

The water height obtained over the triangular weir is used by the standardized equations (1) in order to estimate the flow from the simulations. It was used the LMNO engineering adjust™, through the equation Kindsvater-Shen by ISO-1980, ASTM-1993, and USBR-1997, [9].

$$Q = 4.28C\tan\left(\frac{\theta}{2}\right)(h+k)^{5/2} \quad (1)$$

where: Q is the discharge (m^3/s); C is the discharge coefficient; θ is the notch angle; h is the head (m); k is the head correction factor (m).

2.2 Experimental test

The transient was generated closing the upstream valve. The procedure was made for several scenarios, with different initial pressures, maintaining the air vessel and the pumping conditions.

Table 2 shows the stationary data for a scenario, being H_0 the hydraulic pressure on the pipe before the transient simulation, h the water height over the triangular weir, and Q the flow discharge in the system under steady state condition.

Table 2. Initial data of the transient simulations

Test	H_0 (N/m^2)	h weir (m)	Q (m^3/s)
Experiment	1.32×10^5	0.078	0.0023

After a steady state condition, the transient pressure is generated. Figure 2 presents transient scenario and the exterior fluid (colored) entering by the orifice. The transient and the intrusion around the failure were filmed during the scenario simulation.

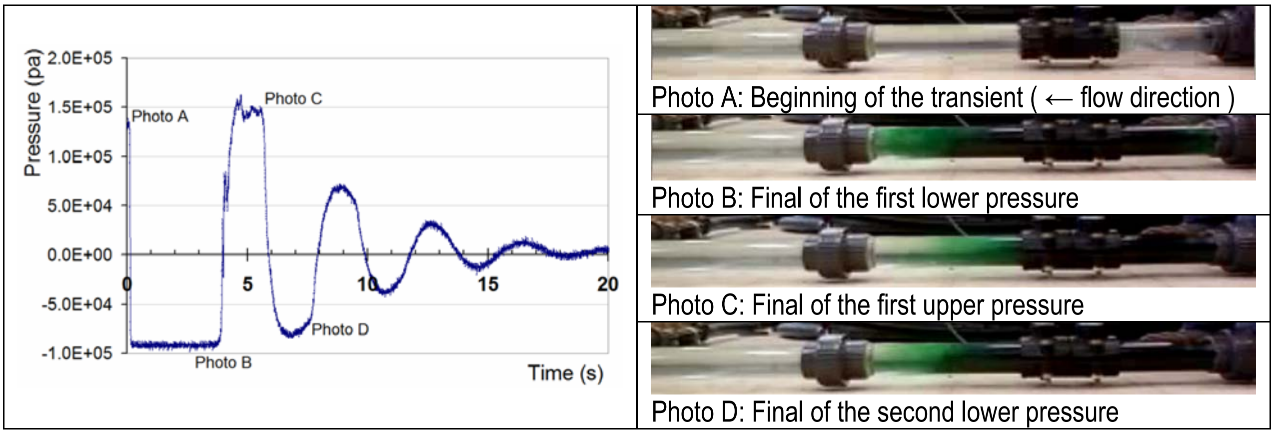

Figure 2. Experimental results of the tested transient scenario and images of the occurrence of intrusion

3. Numerical transient simulation

3.1 MOC model

The pressure transients in pipes are modeled by the well-known water hammer equations, through the simplified continuity and momentum equations, that constitute a set of two hyperbolic partial differential equations [10, 11, 12]. The basic differential equations of unsteady pressurized flows, neglecting the convective acceleration terms ($Q\,\partial Q/\partial x$ and $Q\,\partial H/\partial x$), can be written in the matrix form as follows,

$$\frac{\partial U}{\partial t}+\frac{\partial F(U)}{\partial x}=D(U) \tag{2}$$

yielding the following vectors:

$$U=\begin{bmatrix} H \\ Q \end{bmatrix} \qquad F(U)=\begin{bmatrix} \frac{c^2}{g\ S}Q \\ g\ S\ H \end{bmatrix} \qquad D(U)=\begin{bmatrix} 0 \\ -\frac{J\ g\ S}{Q^2}Q|Q| \end{bmatrix} \tag{3}$$

where x = distance along the canal bottom or the pipe axis; t = time; S = cross-section flow area; Q = discharge; H = piezometric head; J = slope of the energy grade line; g = gravity acceleration; c = wave speed.

For the solution of one-dimensional hydraulic transients, MOC has become extensively used, having proven to be better than other methods due to easiness programming and efficiency of results. The partial derivatives are replaced by finite differences approximations. However, the stability conditions restrict the time and the space step to Courant-Friedrich-Lewy condition.

$$\frac{\Delta x}{\Delta t}\geq V\pm c \tag{4}$$

By transforming the set of partial differential equations into a set of ordinary differential equations valid along the characteristic lines, and integrating in the x-t plane, the finite difference schemes can be written as follows:

$$\begin{aligned} C^+ &: H_P-H_A+\frac{c}{gS}(Q_P-Q_A)+I^+=0 \\ C^- &: H_P-H_B-\frac{c}{gS}(Q_P-Q_B)+I^-=0 \end{aligned} \tag{5}$$

Several numerical techniques can be used to integrate the term I, which represents the friction losses, but in the paper, this term was evaluated by a first and second order approximation.

3.2 Dissipative effects
Ramos et al. (2004) has presented an approach of the damping effect considering the damping of the pressure peaks throughout time. This dynamic effect can be influenced, on the one hand, by the non elastic behavior of the pipes, and on the other hand, by the friction effect. The objective of the proposed technique is to allow the characterization of the energy dissipation, through the variation of the maximum and minimum piezometric head observed in a transient regime.
Having in mind to obtain a generic formulation applicable to any system characteristics, the use of dimensionless parameters of relative head, h, relative head losses, Δh_0, and relative discharge, q, is considered [13]:

$$h = \frac{H}{\left(\frac{c \cdot Q_0}{g \cdot S}\right)} = \frac{H}{\Delta H_J}; \Delta h_0 = \frac{\Delta H_0}{\Delta H_J}; q = \frac{Q}{Q_0} \quad (6)$$

in which H is the piezometric head, c is the wave speed propagation, Q is the discharge, g is the gravity acceleration, S is the cross section flow area and ΔH_J is the overhead of Joukowsky.
In an elastic behavior and assuming $\tau = \frac{t}{(2L/c)}$, the head variation is given by:

$$h = \frac{h_0}{1 + h_0 \cdot K \cdot \Delta h_0 \cdot (\tau - \tau_o)} \quad (7)$$

in which h_0 is the dimensionless head at time τ_0.
According to the same type of analysis, whenever there is a non-elastic behavior of the system (e.g. presence of gas pockets or plastic pipes), this is the main effect in damping occurrences, and the energy dissipation can be evaluated by:

$$h = h_0 \cdot e^{-K \cdot \Delta h_0 \cdot (\tau - \tau_0)} \quad (8)$$

For systems with combined effects (i.e. elastic and plastic), the damping surge can be evaluated by the following formulation:

$$h = \frac{1}{\left(\frac{K_{elas}}{K_{visc}} + \frac{1}{h_0}\right) \cdot e^{K_{visc} \cdot \Delta h_0 \cdot (\tau - \tau_0)} - \frac{K_{elas}}{K_{visc}}} \quad (9)$$

where K_{visc} and K_{elas} are decay coefficients for the plastic and elastic effects, respectively.
For the description of fluid and pipe material non-elastic behavior simpler decay coefficients (*KH* and *KQ*) were estimated, based on energy dissipation equations (6) and (7), and included in the MOC equations as simpler dissipative parameters:

$$\Delta H = KH \frac{c}{gS} \Delta Q - J \quad (10)$$

$$\Delta Q = KQ \frac{\Delta H - J}{c/(gS)} \quad (11)$$

where J = the headloss term; g = the gravitational acceleration; S = the pipe cross-section; ΔH and ΔQ = head and discharge variation, respectively.

3.3 Model application and comparisons
In the developed MOC it was considering the variation proposed by equations (10) and (11). Table 3 shows the physical characteristics coming from the experimental simulations. The head and the flow were measured from the experiments. The wave speed is obtained from the physical pressure configuration. The valve time closure was obtained from the real time conditions related by a movie and the total simulation time is experimentally recorded.
The model works with a fixed grid. The pipe sections presenting vaporization pressure are considered as internal boundary. The numerical solution is based on the traditional vapor-liquid model, with a second order approximation for the calculation of quasi-steady friction losses. The incorporations influence on

the observed dissipation and dispersion of transient pressure due to mechanical frictional and inertial dynamic effects [14].

Table 3. Description of the physical characteristics of the laboratory facility considered

Parameter	Variables	Experiments	units
Upstream head	H_0	13.5	m
Flow discharge	Q_0	0.0023	m^3/s
Wave speed	c_0	240	m/s
Time closure of the valve	TF	0.11	s
Total simulation time	TT	28	s

Finally the coefficients adjusted for the tested scenario is quantified on Table 4.

Table 4. Model coefficients for the simulations

Physical behaviour	Parameter	Value
Reduction in the head variation when induced by a discharge variation by non-elastic fluid and pipe deformation	KH	0.60
Reduction in the discharge value caused by a head variation, due to a non-elastic response in the recuperation phase of the occurred deformation	KQ	1.15

Graphically the MOC dissipative model obtains the representation of the transient in the tested scenario that was simulated experimentally (Figure 3).
The numerical model generates a pressure transient, in which the positive and negative oscillation along the time of simulation is adjusted to the experimental data. Along the time, the MOC dissipative model presents a slightly displaced when compared to the experiments. However the experience shows a good fitness between results.

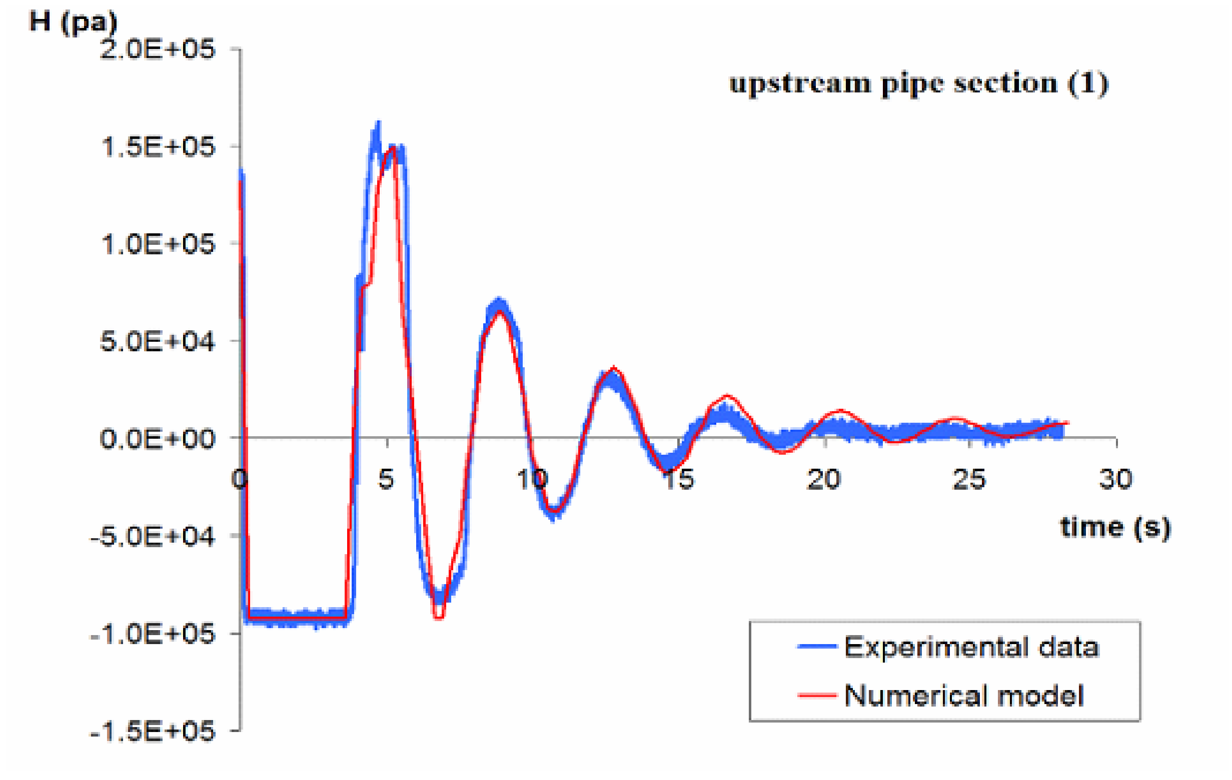

Figure 3. Comparison between MOC dissipative model results and experimental data

Based on the transient behavior induced by the valve maneuver, the accumulate intrusion has been calculated, in different way was calculated like in López et al. [15]. In the experimental test, the intrusion volume has been obtained from images captured from a video (high definition slow motion) performed during the test development. Figure 4 shows the difference water level in the pipe-intrusion ruler. The difference between the two levels is quantified as the maximum and minimum pressure values during the transient event. Based on the water level difference and the area of the intrusion pipe, the intrusion volume estimated from the video-images is then quantified as 0.23 l on the first 11.7 s of the transient of 28s.

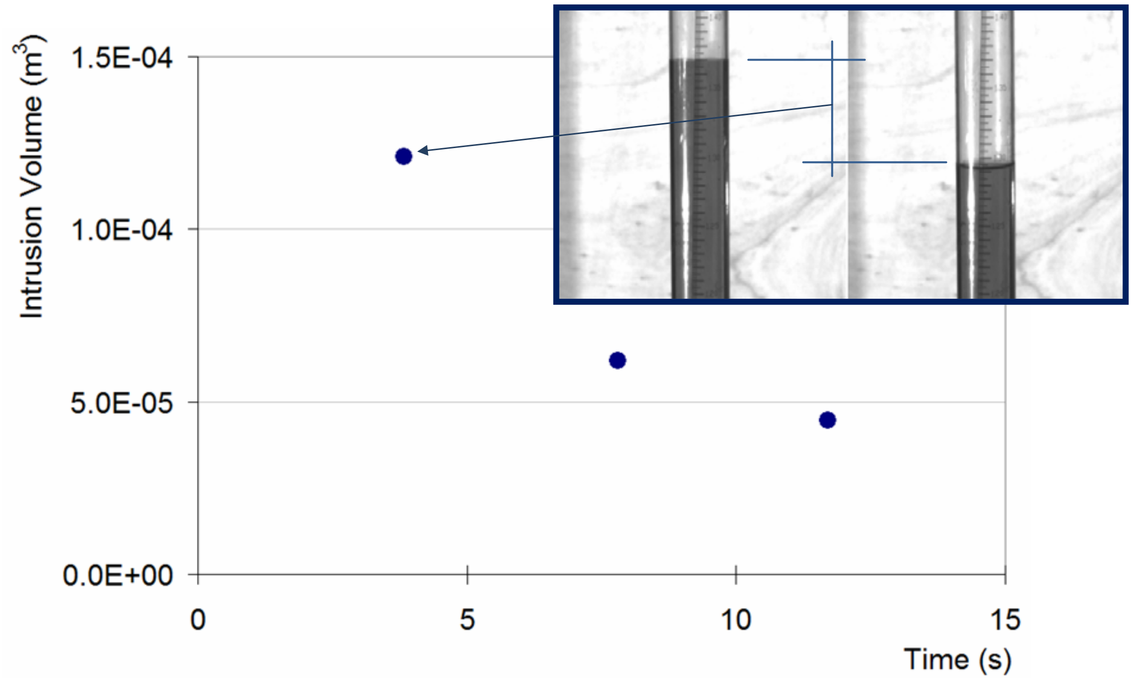

Figure 4. Experimental intrusion volume estimation by using the video of the transient

4. Conclusions

This paper shows the problematic associated to the intrusion into a water drinking system under dynamic operation induced by a valve maneuver or a pump shutdown.

The analysis is based on experimental research and Computational-1D modeling simulation for the pressure variation and intrusion volume estimation. A novel formulation based on the MOC including special dissipative effects due to rheological pipe behavior and cavitation incident has been used to generate a transient event. This novel numerical Computational-1D model is validated by comparisons with experiments.

The estimation of the volume of a possible contamination in a water drinking system has been described in a point of view that has not been previously presented in specialized scientific literature. This methodology is of utmost importance for assessing the intrusion problematic and the contamination in buried pipe transporting potable water. Even though a very small leak (of a 2 mm diameter) tested under lab conditions, the volume of contaminant is not negligible if we are analyzing drinking pipe systems.

The main contribution of this work shows an interesting methodology to quantify the volume of intrusion that occurs during a pressure transient event.

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