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ARTICLE TEMPLATE

Subatmospheric pressure in a water draining pipeline with an air pocket

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ABSTRACT
An air pocket behaviour inside of a pipeline during transient conditions is of great importance due to its effect on the safety of the hydraulic system and the complexity of modeling its behaviour. The emptying process from water pipelines needs more assessment because the generation of troughs of subatmospheric pressure may lead to serious damages. This research studies the air pocket parameters during an emptying process from a water pipeline. A well-equipped experimental facility was used to measure the pressure and the velocity change throughout the water emptying for different air pocket sizes and valve opening times. The phenomenon was simulated using a one-dimensional (1D) developed model based on the rigid formulation with a non-variable friction factor and a constant pipe diameter. The mathematical model shows good ability in predicting the trough of subatmospheric pressure value as the most important parameter which can affect the safety of hydraulic systems.

KEYWORDS
Air-water; air pocket; pipelines emptying; subatmospheric pressure; transient flow; water distribution systems

1. Introduction

The simulation of transient phenomenon of a flow with two phases (air and water) is a complex procedure to analyze considering the air effect and the intricacy of calculations (Vasconcelos, Klaver, and Lautenbach 2014; Fuertes 2001; Wylie and Streeter 1993).

Air pockets can be injected in hydraulic systems by air valves, through joints and water intakes, during pumps' stoppages or failure of the hydraulic installation, by releasing of dissolved air, by vortex formation at pump inlets, and during a surge occurrence in open-channel flow (Ramezani, Karney, and Malekpour 2016). Hydraulic systems can be damaged due to blowback phenomenon of large air pockets under certain circumstances (Pozos et al. 2010; Falvey 1980). High points along the hydraulic profile are vulnerable to accumulate air pockets (Ramezani and Karney 2017; AWWA

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2001). Entrapped air is presented during filling/draining maneuvers in hydraulic systems, where is required expelled/admitted air to relieve systems and to avoid dangerous problems.

Understanding the actions of air pockets in hydraulic systems is of utmost importance in order to be possible to develop prediction analyses of two phase flow effects on the system behaviour and on the reliability level (Martins, Ramos, and Almeida 2015; Bousso, Daynou, and Fuamba 2013; Abreu et al. 1999) since: (i) a compression of air pockets can generate extreme pressure surges (Bashiri-Atrabi and Hosoda 2015; Pozos-Estrada et al. 2015; Covas et al. 2010); and (ii) an expansion can generate drops of absolute pressure (Coronado-Hernández et al. 2018; Tijsseling et al. 2016) causing the collapse of the hydraulic system depending on the installation conditions (Coronado-Hernández, Fuertes-Miquel, and Angulo-Hernández 2018).

Compression effects of air pockets have been analyzed in some experimental facilities both storm water systems (Vasconcelos, Klaver, and Lautenbach 2014; Bousso, Daynou, and Fuamba 2013; Vasconcelos and Wright 2008) and water supply networks (Fuertes-Miquel et al. 2018; Zhou, Liu, and Karney 2013a; Hou et al. 2012) knowing the behaviour of the filling procedure, transient effects and head losses associated with hydraulic devices and the consequences of the propagation of entrapped air. However, expansion effects of air pockets have been studied only by few authors available in the literature which may occur during the draining water process in water supply networks. It is a normal procedure that engineers have to face in the system operation, control, and management (AWWA 2001). The draining process does not cause problems in storm water drainage systems since the atmospheric conditions are reached in the free surface flow region (Laanearu and Van't Westende 2010; Koppel et al. 2010).

Laanearu et al. (2015, 2012) studied the behaviour of the draining process in a pipeline using pressurized air in an experimental facility, Karadžić et al. (2015) conducted similar develeopments about drainage maneuvers in a pipeline aparatus, and Coronado-Hernández et al. (2018) developed a mathematical model for predicting it. Recently, Fuertes-Miquel et al. (2018) also developed a mathematical model for simulating the draining process to compute the main hydraulic variables in a single pipe considering two possible situations: (i) where an air valve has been installed in the highest point of the pipe profile to give reliability by admitting air into the pipe, preventing troughs of subatmospheric pressure; and (ii) where none air valve was installed or when it failed due to operational and maintenance problems (Tran 2017; Ramezani, Karney, and Malekpour 2015) which represents the worse case due to the lowest troughs of subatmospheric pressure attained. Coronado-Hernández et al. (2017) implemented and validated the resolution of the aforementioned mathematical model applied to a pipeline of irregular profile with an air valve. However, there is a lack of information regarding the behaviour of a pipeline with an irregular profile and without air valves. To face this problem, it is important to consider that drain valves are located at low points along a pipeline and when they are opened, the atmospheric pressure is at the exit. Not admitting atmospheric air into the pipeline, the pipeline cannot be completely emptied, and troughs of the subatmospheric pressure occurrence can affect the pipe and all existent hydromechanical devices such as valves, joints, pumps, and turbines. The development of a reliability model for simulating this transient event, can be used for detecting problems related to the subatmospheric pressure occurrence in real pipelines.

This research presents a $1D$ mathematical model for simulating the draining process in a pipeline of irregular profile without air valves, not studied before, and can be used for detecting real problems. The mathematical model includes the equation for the water phase described by the rigid water column model, the equation for the moving air-water interface, and the equation for the air phase, described by the polytropic model. The numerical resolution gives information about the air pocket pressure variation, the water velocity and the movement of the water column. Finally, the mathematical model is validated in an experimental facility which consists of a pipeline with irregular profile and without air valves installed.

2. Mathematical Model

The draining procedure in a pipeline, where air valves have not been installed along on it or where they failed due to the lack of maintenance and operational problems is shown in Figure 1. This is one of the most critical situations in this procedure because it generates the lowest troughs of subatmospheric pressure, which can produce the collapse of the system. Initially, the air in pockets are at atmospheric pressure (101325 Pa). Valves CV_1 and CV_2 are closed to drain the system between them. When drain valves DV_s are opened, the air pressure decreases rapidly in the air pockets until they reach the lowest troughs of subatmospheric pressure. The main trough occurs in the first oscillation of the transient event. Then, some oscillations in the absolute pressure pattern are observed. Hence, a setback occurs while emptying the water column. Finally can occur two situations: (i) the draining is stopped, and part of the water can remain inside the pipeline when backflow air does not occur; and (ii) the draining of the system will be completed when the backflow phenomenon occurs.

A common configuration of a pipeline (Figure 1) presents n air pockets located at the high points, drain valves located at the low points of the system, and k pipes in this set-up. This problem is described by three main hydraulic variables: the water velocity v_j $(j = 1, 2, ..., k)$, the length of the water column $L_{w,j}$ $(j = 1, 2, ..., k)$, and the absolute pressure of the air pocket p_i^* $(i = 1, 2, ..., n)$. The length of the pipe L_j $(j = 1, 2, ..., k)$ can be estimated as $L_j = \sum L_{j,r}$ where r is the total numbers of branches of the pipe j. During this process the friction factor f, and the polytropic coefficient m can be considered constant (Coronado-Hernández, Fuertes-Miquel, and Angulo-Hernández 2018; Zhou, Liu, and Karney 2013b; Izquierdo et al. 1999).

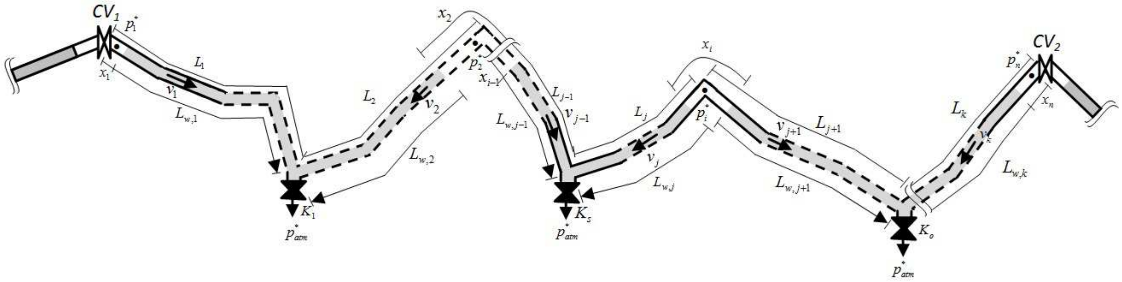


Figure 1. Scheme of entrapped air into a pipeline during the draining procedure.

2.1. *Assumptions*

The one-dimensional proposed model can be applied for analyzing the emptying procedure in a pipeline with irregular profile. The assumptions of the mathematical model are:

- The rigid water column model is used to simulate the water phase where the fiction factor is considered constant along the hydraulic event.
- A polytropic model is used to represent the behaviour of the air phase.
- The moving air-water interface is considered perpendicular to the pipe direction.
- The backflow air phenomenon does not occur during the hydraulic event, which implies that there is not admitted air by the drain valves.

2.2. *Equations*

2.2.1. *Water phase equation*

The water phase can be modeled by using an inertial model. The water hammer (or elastic model) considers the elastic effects of the water and the pipe. However, since the elasticity of the entrapped air pocket into the pipeline is much higher than the elasticity of the water, this means that the water phase can be modeled by the rigid water column model (Coronado-Hernández et al. 2017; Hou et al. 2014; Liu et al. 2011). Then the momentum equation can be expressed as:

$$\frac{dv_j}{dt} = \frac{p_i^* - p_{atm}^*}{\rho_w L_{w,j}} + g\frac{\Delta z_j}{L_{w,j}} - f_j\frac{v_j|v_j|}{2D} - \frac{gA^2 Q_T|Q_T|}{L_{w,j}K_s^2} \tag{1}$$

where p_i^* = absolute pressure of the air pocket i, ρ_w = water density, p_{atm}^* = atmospheric pressure (101325 Pa), Δz_j = elevation difference, A = cross-sectional area, Q_T = total discharge in the drain valve, and K_s = flow factor of the drain valve s.

2.2.2. *Air phase equation*

The compression and the expansion of the air pocket i obey to the polytropic law, which relates the absolute pressure and the total volume of the air pocket by

$$p_i^* V_{a,i}^m = p_{i,0}^* V_{a,i,0}^m \tag{2}$$

where $V_{a,i}$ = volume of the air pocket i, $p_{i,0}^*$ = initial condition of the p_i^*, and $V_{a,i,0}$ = initial condition of the $V_{a,i}$.

However, along of the pipeline the cross-sectional area (A) is constant, then:

$$p_i^* x_i^m = p_{i,0}^* x_{i,0}^m \tag{3}$$

where x_i = length along of the pipe of the air pocket i, and $x_{i,0}$ = initial value of the x_i.

The air pocket size can be computed as $x_i = L_j - L_{w,j} + L_{j+1} - L_{w,j+1}$, thus:

$$p_i^*(L_j - L_{w,j} + L_{j+1} - L_{w,j+1})^m = p_{i,0}^*(L_j - L_{w,j,0} + L_{j+1} - L_{w,j+1,0})^m \tag{4}$$

2.2.3. Equation for the air-water interface

To compute the air-water interface, a piston flow was assumed which means that the hydraulic event occurs very fast. It is perpendicular to the pipe direction where there are some reaches of the pipe completely filled by air and others by water.

$$\frac{dL_{w,j}}{dt} = -v_j \rightarrow L_{w,j} = L_{w,j,0} - \int_0^t v_j \mathrm{d}t \tag{5}$$

2.2.4. Numerical resolution

To calculate the hydraulic variables during the emptying process v_j $(j = 1, 2, ..., k)$, $L_{w,j}$ $(j = 1, 2, ..., k)$, and p_i^* $(i = 1, 2, ..., n)$ a differential-algebraic equations system integrated by equations (1), (4) and (5) have to be solved which are compound by $2k + i$ equations. The initial conditions for the system are described by: $v_j(0) = 0$, $L_{w,j}(0) = L_{w,j,0}$, and $p_i^*(0) = p_{atm}^* = 101325$ Pa.

3. Experimental facility

3.1. *Description of the experimental facility*

The experimental facility was developed at Instituto Superior Técnico, CERIS, University of Lisbon (Portugal), where measurements were conducted to study the behaviour of the draining process in a pipeline with irregular profile (Figure 2). The system is composed by two PVC pipes with a total length of 7.3 m and a nominal diameter of 63 mm. There are two water columns represented by $L_{w,1}$ and $L_{w,2}$ which will empty by drain valves DV_1 and DV_2. The water velocity of the water columns was measured with an Ultrasonic Doppler Velocimetry (UDV) located at the horizontal PVC pipe with a transducer of 4 MHz frequency. The length of the water columns was measured by using a Sony Camera DSC-HX200V. The drain valves have a nominal diameter of 25 mm. The maneuvering time and the opening percentage of the valves were similar during the draining process, with the same resistance coefficients ($K_1 = K_2 = K_s$). The drain valves have a free discharge. There is only an air pocket inside the system which is distributed in the two PVC pipes (see detail of Figure 2). The air pocket size can be computed as $x_1 = 0.04 + x_{1,1} + x_{1,2}$. A transducer PT_1 was installed in the high point of the pipe profile to measure the absolute pressure pattern. A pico-scope device was used to record these values.

The gravity term, suggested by Coronado-Hernández et al. (2017), was included in the mathematical model in order to consider the slope change in the water column 1:

$$\frac{\Delta z_1}{L_{w,1}} = \left(1 - \frac{L_{1,2}}{L_{w,1}}\right) \sin(30°) \tag{6}$$

The gravity term for the water column 2 can be computed in similar way used for the water column 1.

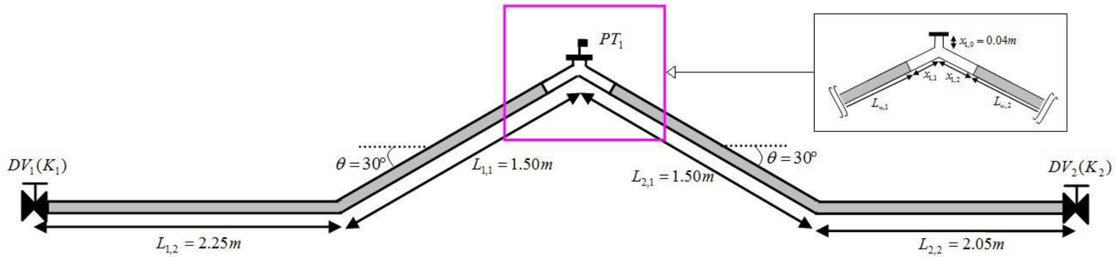


Figure 2. Experimental facility.

3.2. *Proposed model definition*

The system presented in Figure 2 is solved with the following data: $L_1 = 3.77$ m, $L_2 = 3.57$ m, $f = 0.018$, $D = 51.4$ mm, $m = 1.1$ (based on experiments), and $p^*_{1,0} = 101325$ Pa.

The differential-algebraic equations system is given by:

1. Rigid water column model applied to the water column 1

$$\frac{dv_1}{dt} = \frac{p^*_1 - p^*_{atm}}{\rho_w L_{w,1}} + g\frac{\Delta z_1}{L_{w,1}} - f\frac{v_1|v_1|}{2D} - \frac{gA^2 v_1|v_1|}{K_1^2 L_{w,1}} \tag{7}$$

2. Air-water interface for the water column 1

$$\frac{dL_{w,1}}{dt} = -v_1 \rightarrow L_{w,1} = L_{w,1,0} - \int_0^t v_1 \mathrm{d}t \tag{8}$$

3. Rigid water column model applied to the water column 2

$$\frac{dv_2}{dt} = \frac{p^*_1 - p^*_{atm}}{\rho_w L_{w,2}} + g\frac{\Delta z_2}{L_{w,2}} - f\frac{v_2|v_2|}{2D} - \frac{gA^2 v_2|v_2|}{K_2^2 L_{w,2}} \tag{9}$$

4. Air-water interface for the water column 2

$$\frac{dL_{w,2}}{dt} = -v_2 \rightarrow L_{w,2} = L_{w,2,0} - \int_0^t v_2 \mathrm{d}t \tag{10}$$

5. Polytropic model for the air pocket 1

$$p^*_1(L_1 - L_{w,1} + L_2 - L_{w,2})^m = p^*_{1,0}(L_1 - L_{w,1,0} + L_2 - L_{w,2,0})^m \tag{11}$$

4. Results and discussion

There are 3 types of physical behaviour according to the experiments. Type A corresponds to a partial opening of the drain valves by considering the air pocket volume is distributed equally inside water columns 1 and 2; Type B is similar to the aforementioned but considering a completely opening of the drain valves; and Type C considers that the air pocket volume is not distributed uniformly inside the water columns. Table 1 shows the runs considered during the experiments. The valve maneuvering time (T_m) for all runs was 0.7 s. For partial opening the flow factor (K_s) was 0.9x10^{-4} m^3/s m$^{1/2}$, whereas for the total opening it was 1.4x10^{-3} m^3/s m$^{1/2}$.

Table 1. Types of physical behaviour.

	Characteristics				
Type (-)	Run No.	Opening drain valves (%)	$x_{1,1}$ (m)	$x_{1,2}$ (m)	x_1[a] (m)
A	1	Partial	0.28	0.28	0.60
	2	Partial	0.61	0.61	1.26
B	3	Completely	0.28	0.28	0.60
	4	Completely	0.61	0.61	1.26
C	5	Completely	0.26	0.60	0.90
	6	Completely	0.28	0.98	1.30

[a] x_1 refers to the total length of the air pocket. It can be computed as $x_1 = 0.04 + x_{1,1} + x_{1,2}$ (see Fig 2).

The proposed model presents a good agreement between the computed and measured water flow oscillations and gauge pressures, which indicates that viscosity and surface tension effects are not significant along of the hydraulic system (Pothof and Clemens 2010).

4.1. *Type A: Partial opening of the drain valves with air pocket volume distributed uniformly*

Figure 3 shows the results which corresponds to the less critical case for the pipeline because the subatmospheric pressure pattern reaches values close to the atmospheric pressure head. The hydraulic event starts with the atmosphetic pressure head (10.33 m), and after decreases rapidly until reaches the trough of the subatmospheric pressure head of 9.74 m for run No. 1. Practically there are not oscillations on the evolution of the absolute pressure pattern during the first two seconds, as a consequence of the partial opening of the ball valves. After this time, the subatmospheric pressure pattern remains constant. The mathematical model fits quite well regarding the two experiments in each run. Results are similar for run No. 2. For Type A was not possible to measure the water velocities because during the hydraulic event they reached values lower than 0.015 m/s, which could not be detected by the UDV.

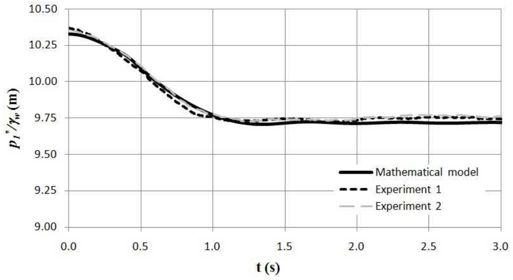


Figure 3. Comparison between computed and experiments of the absolute pressure pattern of Type A and Run No. 1.

4.2. *Type B: Total opening of the drain valves with air pocket volume distributed uniformly*

The initial conditions of the Type B are similar to the Type A, but now the two ball valves are completely opened. As a consequence, the troughs of the subatmospheric pressure reached in the Type B are lower than in the Type A which indicates that the risk of collapse for the Type B is higher than for the Type A.

Again, the subatmospheric pressure pattern in the hydraulic event starts in atmospheric conditions, and after it decreases quickly until reaches the minimum value of 9.28 m (at 0.4 s) for run No. 3 (see Figure 4). Then, some oscillations are presented along of the hydraulic event which indicates the subatmospheric pressure pattern is able to move from upstream to downstream and reciprocally the two water columns behave as a piston flow. The mathematical model predicted adequately runs No. 3 and No. 4.

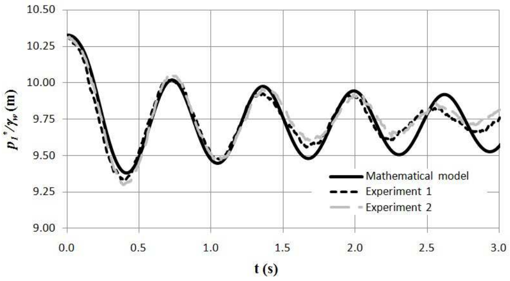


Figure 4. Comparison between computed and experiments of the absolute pressure pattern for Type B and Run No. 3.

Figure 5 shows water columns velocities. For runs No. 3 and No. 4 the values of the water velocities in the two water columns are similar due to the air pocket size was distributed uniformly. For run No. 3, the water velocity increases rapidly until reaching a maximum value. Subsequently, the water velocity decreases until it reaches a value of 0 m/s at 0.4 s. Then it continues to decrease until reaching a minimum value of the −0.11 m/s, indicating negative velocities occurrence. After some oscillations, with a similar amplitude, a setback of the water columns occur. The mathematical model can follow the behaviour of the water velocity experiments.

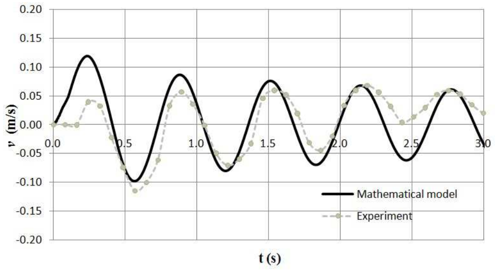
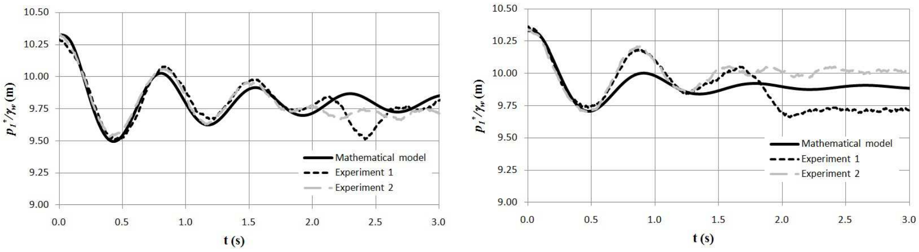


Figure 5. Comparison between computed and experiments of the water velocity for Type B and Run No. 3.

4.3. *Type C: Total opening of the drain valves with air pocket volume distributed non-uniformly*

Type C is the most complex to be analyzed because the behaviour of the two water columns are different. Figure 6(a) shows the results of the subatmospheric pressure pattern for run No. 5 where according to the experiments the trough of the subatmospheric pressure presented is 9.50 m at 0.4 s. The two water columns have different movements, then the amplitude of the oscillations of the air pocket along the transient is lower compared with the Type B. The mathematical model predicts accurately the subatmospheric pressure pattern along of the hydraulic event. However, Figure 6(b) presents the results for run No. 6 where the mathematical model can predict only the first oscillation during the transient. This case occurs because the mathematical model considers an air-water interface perpendicular to the pipe direction at downstream of the water columns, which does not really happen for an air pocket distributed asymmetrically.



(a) Run No. 5 (b) Run No. 6

Figure 6. Comparison between computed and experiments of the absolute pressure pattern for Type C

Figure 7 presents the results of the water velocities for the two water columns in run No. 5, with different subatmospheric pressure pattern. The water column 1 is characterized because velocity values always are positive generating in this column the emptying process occurs. According to the experiments, the maximum velocity is presented at 1.05 s with a value of 0.175 m/s, which is very close to the value predicted by the mathematical model (0.19 m/s). In contrast, the water column 2 presents negative velocities according to the experiments. As a consequence, the water column 2 moves from downstream to upstream during the hydraulic event. The mathematical model predicts the tendency regarding water velocities for both water columns.

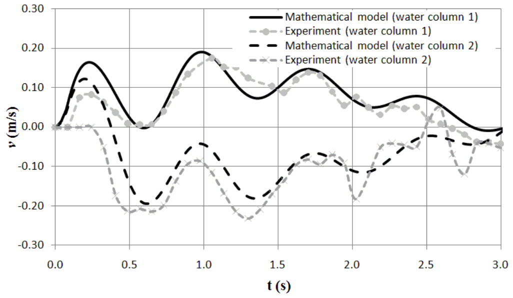


Figure 7. Comparison between computed and experiments of the water velocities for Type C and run No. 5.

Type C represents the case where the evolution of the lengths of the water columns 1 and 2 are different during the transient. Figure 8 shows that the water column 1 has at the beginning of the transient an initial value of 3.5 m and at the end of the hydraulic event a value of 3.2 m, indicating that 0.3 m could be drained during the process. In contrast, the water column 2 starts with 3.0 m (at $t = 0$ s) and finishes with 3.2 m (at $t = 3$ s), indicating the entire water column 2 was displaced 0.2 m from downstream to upstream and practically this water column could not be drained. The mathematical model predicts accurately the length of the water columns.

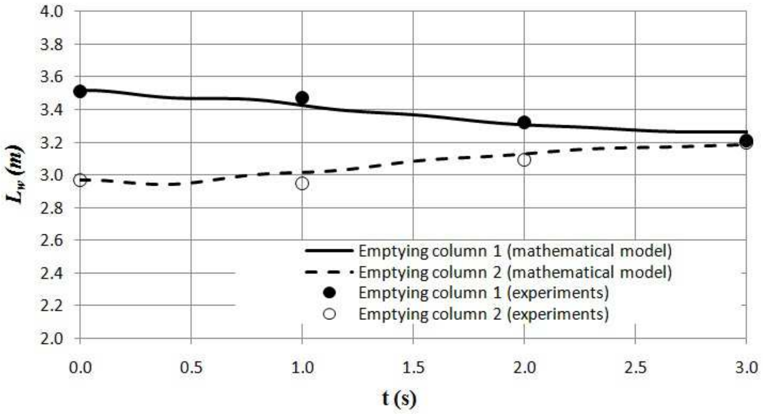


Figure 8. Comparison between computed and experiments for the length of water columns of Type C (run No. 5)

5. Conclusions

The authors developed a mathematical model to predict water draining pipelines based upon four (4) assumptions: rigid water column model, 1D modelling, constant pipe diameter, and constant friction factor.

After the validation of the mathematical model with several experiments carried out in an experimental facility where the comparison between the computed and the measured of the main hydraulic variables (absolute pressure of the air pocket, water velocity and the length of the water column) confirmed the goodness of the mathematical model. The mathematical model developed by the authors predicted adequately the behaviour of the draining process of the hydraulic event.

Regarding the results, the following conclusions can be drawn:

- Three types of behaviour have been analyzed. They depend on the opening percentage of the drain valves, and the distribution of the air pocket volume inside the water columns.
- The backflow air phenomenon depends on the opening percentage of the drain valves: (i) for a partial opening, it did not occur during the experiments (Type A), and (ii) for the total opening, the air moved from downstream to upstream (Types B and C).
- The Type C was the most complex case to predict by the mathematical model. When the initial interface air-water difference elevation (Δz_j) is very close for the water columns (run No. 5), then the mathematical model can predict the evolution of the hydraulic variables. However, when the difference elevation is

higher (run No. 6), the mathematical model can only predict the first oscillation during the hydraulic event.

To simulate a water draining operation without admitted air in real pipelines is necessary to know the location and the technical maneuver of drain valves, pipe characteristics (material, internal diameter, and pipe slope), and applying the proposed model in this research to compute both absolute pressure pattern and the trough of subatmospheric pressure.

The proposed model cannot predict the backflow air phenomenon. However, it reduces the risk of collapse the system by inserting air at atmospheric pressure into the pipeline. As a consequence, the backflow relieves the troughs of the subatmospheric pressure, and the system can reach the atmospheric conditions.

Acknowledgements

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Nomenclature/Notation

A = cross sectional area of pipe (m^2)
CV_h = Used valves to establish the boundary conditions
D = internal pipe diameter (m)
DV_s = Drain valve s
f = Darcy-Weisbach friction factor (–)
g = gravity acceleration (m/s^2)
K_s = flow factor of the drain valve s (m^3/s m$^{1/2}$)
$L_{w,j}$ = length of the water column j (m)
L_j = total length of the pipe j (m)
m = polytrophic coefficient (–)
p_i^* = absolute pressure of the air pocket i (Pa)
p_{atm}^* = atmospheric pressure (Pa)
Q_T = total discharge (m^3/s)
t = time (s)
T_m = valve maneuvering time (s)
r = number of reaches of the pipe j (–)
$V_{a,i}$ = volume of the air pocket i (m^3)
v_j = water velocity of the water column j (m/s)
x_i = length of the air pocket i (m)
Δz_j = elevation difference of the water column j (m)
ρ = density (kg/m^3)
0 = refers to initial condition (e.g., initial length of the water column)

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