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ANALYSIS OF FRICTION MODELS DURING SIMULATIONS OF FILLING PROCESSES IN SINGLE PIPELINES

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Abstract

The analysis of filling processes in pressurized pipelines has been conducted using a steady friction model in the implementation of governing equations. This research is focused on the case of a filling process of a single pipeline without an air valve. Three equations were used to represent the phenomenon: (i) a rigid water column approach, which describes the water movement along the water system; (ii) a piston flow model, which assumes a perpendicular air-water interface to the main direction of the pipe; and (iii) a polytropic model for representing the thermodynamic behaviour of an entrapped air pocket. This research studies the filling processes occurrence using equations of steady and unsteady friction models, where Moody, Wood, Hazen-Williams, and Swamee-Jain equations are analysed. The analysis is applied to a case study of a single pipe of a total length of 1000 m with an internal diameter of 595 mm variation of pressure surges in the implementation of these formulations. Results confirm that there is a minimum discrepancy between steady and unsteady friction models since values of pressure surges pattern are similar.

Keywords
Filling process, unsteady, friction models, transient flow.

1 INTRODUCTION

Hydraulic installations should be designed to guarantee reliable infrastructures due to their high costs. Therefore, engineers should select pipe resistance and stiffness class to protect water pipelines of extreme absolute pressure [1].

In the last century, water hammer effects have been investigated due to pipe collapses occurrence. At the beginning, the analysis focused only on the water phase involving the operation of valve closure manoeuvring and pump's stoppages. These hydraulic events have been extensively studied both numerically and experimentally using commercial packages.

Regulations transient flow in pressurized hydraulic systems are considered in many countries around the world. In this sense, engineers and designers are implementing the developed knowledge in the field to have reliable designs [2].

In the last decades, the transient flow with entrapped air is being analysed since air pockets can produce higher extreme absolute pressure patterns compared to transient flow only for the water phase [1, 3]. This phenomenon is generated because air elasticity is higher than water and pipe elasticity. When an air pocket volume is reduced for the compression of the water phase, then the air pocket pressure is increased and vice versa [1]. Transient flow with entrapped air involves complex formulations that should be modelled to represent both hydraulic and thermodynamic behaviour of the water and air phase, respectively. Several formulations have been implemented to simulate filling processes in water pipelines. Zhou et al. (2002) [4] used an elastic water column model to simulate the behaviour of water over time considering a steady friction factor considering for filling process. Fuertes et al. (2019) [5] and Coronado-Hernández et al. (2018) [6] developed a mathematical model to predict filling and emptying operations in pressurized pipelines considering a steady friction factor. Also, filling and emptying processes have been analyzed using Computational Fluids Dynamics (CFD). The implementation of this kind of models have been used to determine the effect of backflow air in emptying operation [7], and secondary pressure peaks for uncontrolled filling operation [8].

Recently, Zhou et al. (2020) [9] introduced an unsteady friction factor (UFM) using an elastic water column model for filling operations. Coronado-Hernández et al. (2021) [10] implemented an UFM for analysing the emptying operation using a rigid water column model in the water phase.

This research focuses on the implementation of unsteady friction model for predicting filling operations using a rigid water column model. The current analysis is presented for a water pipeline without admitted air. The Brunone model [11] was included to simulate the friction factor [11]. The Moody [12], Wood [13], Hazen-Williams [14], and Swamee-Jain [15] were used to analyse a steady friction factor. The mathematical model was validated using an experimental facility with a pipe length of 3.867 m. The mathematical model using an unsteady friction factor was applied to a practical application to observe air pocket pressure, water velocity, and length of a water column variations.

2 MATHEMATICAL MODEL

2.1 Equations

- Mass oscillation equation: equation (1) represents the behaviour of a water column along of an entire pipe system.

$$\frac{dv_f}{dt} = \frac{p_0^* - p_1^*}{\rho_w L_f} + g\frac{\Delta z_1}{L_f} - gJ - \frac{R_v g A^2 v_f |v_f|}{L_f} \tag{1}$$

Where v_f = water filling velocity (m/s); p_0^* = initial pressure supplied by a tank or a pump (Pa); p_1^* = air pocket pressure (Pa); ρ_w = water density for a specific environmental temperature; Δz_1= difference elevation of ends of a pipe installation; g = gravitational acceleration (m/s^2); L_f= length of a water filling column; J = unsteady friction losses per unit length (m/m); R_v = resistance coefficient of a valve (s^2/m^5); and A= cross-sectional area of a single pipe.

The unsteady friction losses term is expressed as:

$$J = f\frac{v_f|v_f|}{2gD} + \frac{k_\delta}{g}\frac{dv_f}{dt} \tag{2}$$

Where f = friction factor; D = internal pipe diameter; and k_δ = Brunnone friction coefficient.

The left term in equation (2) represents the steady friction losses per unit length; in constant, the right term simulates the variation over time of friction losses.

The Brunnone coefficient can be computed using the formula as follows:

$$k_\delta = \frac{\sqrt{C^*}}{2} \tag{3}$$

The Vardy's shear decay coefficient (C^*) is calculated depending on the flow regime: for a laminar flow (Re < 2000) its value is 0.00476; and calculation for a turbulent flow (Re > 4000) is computed using equation (4).

$$C^* = \frac{7.41}{\mathrm{Re}^{\log(14.3/\mathrm{Re}^{0.05})}} \tag{4}$$

Where Re = Reynolds number.

By plugging equations (2), (3), and (4) into equation (1):

$$\frac{dv_f}{dt} = \frac{\frac{p_0^* - p_1^*}{\rho_w L_f} + g\frac{\Delta z_1}{L_f} - \frac{f v_f |v_f|}{2D} - \frac{R_v g A^2 v_f |v_f|}{L_f}}{1 + \omega \frac{\sqrt{\frac{7.41}{\mathrm{Re}^{\log(14.3/\mathrm{Re}^{0.05})}}}}{2}} \tag{5}$$

The coefficient (ω) is introduced to represent either SFM or UFM. A value ω = 0 implies a SFM, while a value ω = 1 represents simulation using an UFM.

- Piston-flow model: a perpendicular air-water interface was considered for simulating a filling operation, which is modelled using Equation (6).

$$\frac{dL_f}{dt} = v_f \tag{6}$$

- Polytropic model: this formulation describes how the air pocket size changes with air pocket pressure pulses. These changes are described by the polytropic law (see Equation (7)) which is applied without injected air into hydraulic installations.

$$p_1^* x^k = p_{1,0}^* x_0^k = \text{constant} \tag{7}$$

Where $\boldsymbol{x}$ = air pocket size (m) and $\boldsymbol{k}$= polytropic coefficient.

The polytropic coefficient describes a type of thermodynamic evolution. A value of 1.0 indicates an isothermal process, while a value of 1.4 simulates an adiabatic evolution. Intermediate values consider a polytropic behaviour.

2.2 Friction factor formulations

The friction factor is a dimensionless parameter, which is used in fluid dynamics to compute head loss (or pressure loss) due to friction in pipeline installations. Table 1 shows different formulations that have been used to compute the friction factor considering various boundaries of Reynolds number, relative roughness, water filling velocity, regime flow, and internal pipe diameter [16, 17]. Equations from (4) to (10) are used to evaluate the sensitivity of the filling model described in section 2.1.

Table 1. Friction factor formulations

Author	Equation	Equation number	Application range
Laminar flow (Re < 2000)			
Hagen-Poiseuille	$f=\frac{64}{\mathrm{Re}}$	(8)	-
Turbulent flow (Re > 4000)			
Swamee-Jain	$f=\frac{0.25}{\left[\log\left(\frac{k_s}{3.7D}+\frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2}$	(9)	Transition zone ($10^{-6}<k_s/D<2\text{x}10^{-2}$; $3\text{x}10^{3}<\mathrm{Re}<3\text{x}10^{8}$)
Moody	$f=0.0055\left[1+\left(20000\frac{k_s}{D}+\frac{10^6}{\mathrm{Re}}\right)^{1/3}\right]$	(10)	$k_s/D>0.01$
Wood	$f=0.094\left(\frac{k_s}{D}\right)^{0.225}+0.53\left(\frac{k_s}{D}\right)+88\left(\frac{k_s}{D}\right)^{0.44}\mathrm{Re}^{-1.62\left(\frac{k_s}{D}\right)^{0.134}}$	(11)	$Re>10000$; $10^{-5}<k_s/D<0.04$
Hazen-Williams	$f=\frac{133.89}{C_{HW}^{1.851}D^{0.017}v_f^{0.15}\mathrm{Re}^{0.15}}$	(12)	D>75 mm; $v_f<3$ m/s

Where k_s is the absolute roughness, and C_{HW} is the Hazen-Williams coefficient.

3 VALIDATION MODEL

An experimental facility was configured (see Figure 1) at the Hydraulic Lab at the University of Lisbon (Lisbon, Portugal) to check the governing equations presented in Section 2.1. The installation is composed of a hydro-pneumatic tank to supply various initial pressure, a 7.6-m-long PVC pipe, a pressure transducer located at the highest point of the installation, a manual valve (MV_1) to isolate the pipeline from the hydro-pneumatic tank, and four electro-pneumatic valves (BV_1 to BV_4). BV_1 and BV_2 remain opened during the filling phenomenon occurrence. Air pockets are injected in the highest point of system, where the pressure transducer is located. An initial air pocket size (x_0) of 0.517 m is configured for all experimental tests. The right water column remains constant during experiments (named as blocking water column). A 3.867-m-long total left branch pipe is used to produce a filling operation, which includes lengths of the inclined and vertical branch pipes (see Figure 1). The filling process begins with the opening of the BV_4. A synthetic manoeuvring of BV_4 was introduced considering an opening time of 0.2 s (given by the manufacturer) with a resistance coefficient (R_v) for a full opening of $1.7\text{x}10^5$ ms^2/m^6. Immediately, the filling water column (left water column) starts to fill the hydraulic system while a compression of the injected air pocket is provoked. Valve BV_3 is closed to produce a rapid compression of the entrapped air. The blocking water column acts as a boundary condition, producing a behaviour like a single pipeline. In this sense, the filling process of this installation is simulated using equations (1), (2), and (3). The hydro-pneumatic tank was configured using an initial gauge pressure (H_t) of 1.25 bar. Values of p_0^* were computed as the sum of H_t and atmospheric pressure.

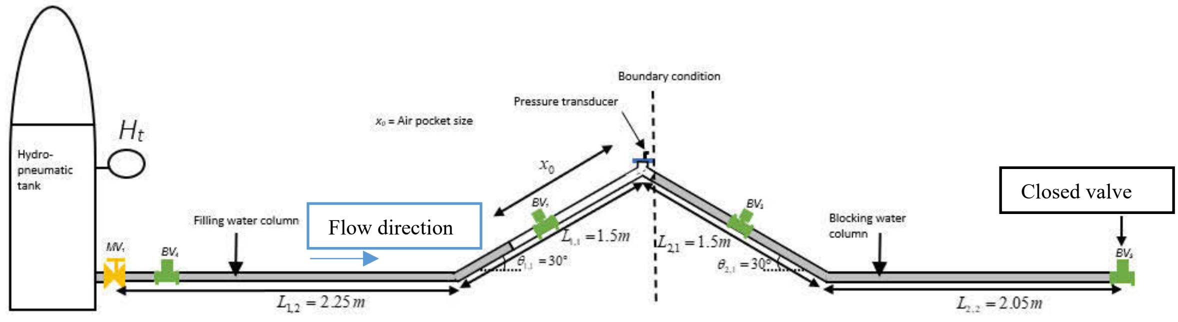


Figure 1. Experimental facility

Unsteady friction models are more adequate than steady friction models to represent filling operations with entrapped air since involves a variable friction factor during transient event. The Brunnone friction coefficient was used to evaluate this evolution. In addition, the Swamee-Jain equation (see equation (9)) was used to calculate the variation of the friction factor in steady flow. This equation was utilized considering that results are similar compared to the Colebrook-White formula (based on a physical formulation). Reynold numbers ranging from 0 to 2000 (laminar flow) were modelled using equation (8), while the remaining conditions of Reynold numbers were simulated using the Swamee-Jain formulation, since is suitable for values located at critical and turbulent zone flow.

The polytropic coefficient (k) was calibrated for three kinds of evolution: (i) an isothermal process (k = 1.0), (ii) an intermediate process (k = 1.2), and (iii) an adiabatic process (k = 1.4). Figure 2 presents a comparison of the mentioned polytropic coefficients the analysed run, where the best result is obtained using an isothermal evolution since the mathematical model can follow fluctuations of the average experimental. Using a polytropic coefficient of k = 1.0 (isothermal process), the peak of air pocket pressure head is 50.00 m; while for intermediate and adiabatic processes, values of 48.14 and 47.19 mm are reached, respectively. Therefore, a polytropic coefficient of k = 1.0 was selected for the analysis, which the pressure head peak is compared with the measured value of 50.42 m. Also, the mathematical model for UFM can represent oscillations of measured air pocket pressure patterns. Figure 2 shows how the mathematical model is suitable to represent air pocket pulses.

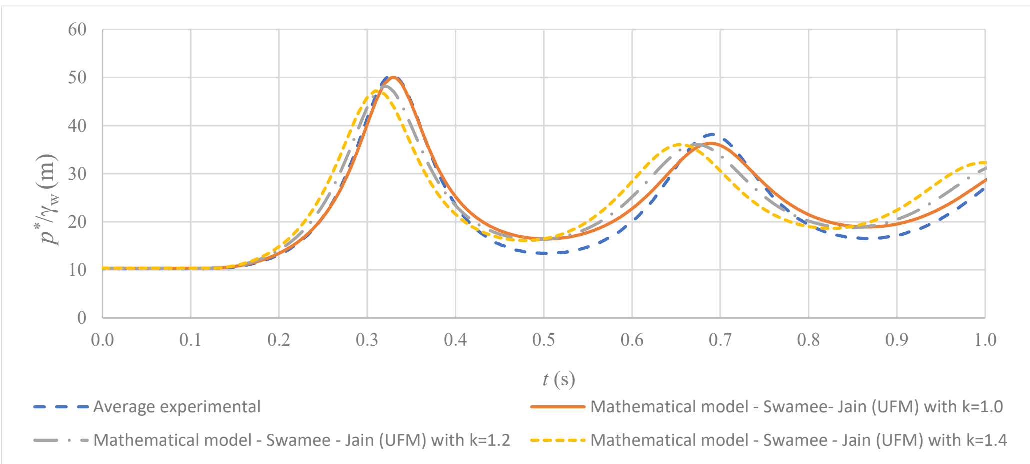
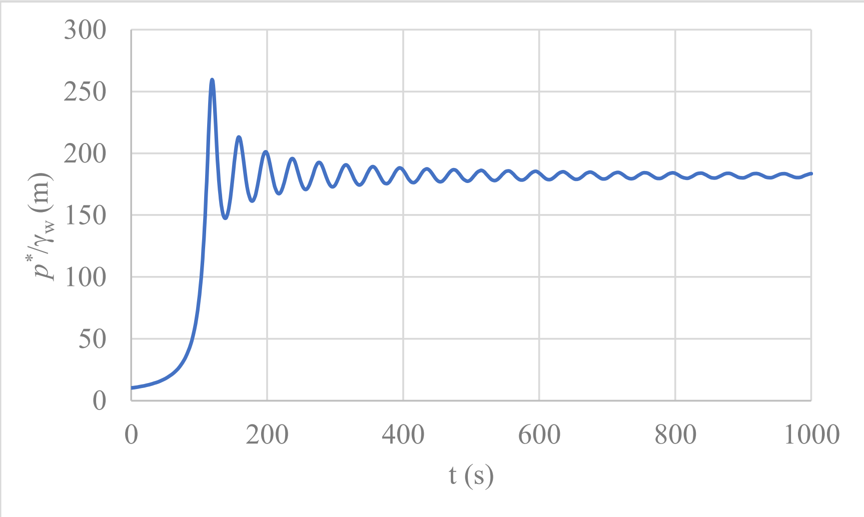


Figure 2. Comparison of values of polytropic coefficients with regards to average experimental of air pocket pressure pulses using the UFM

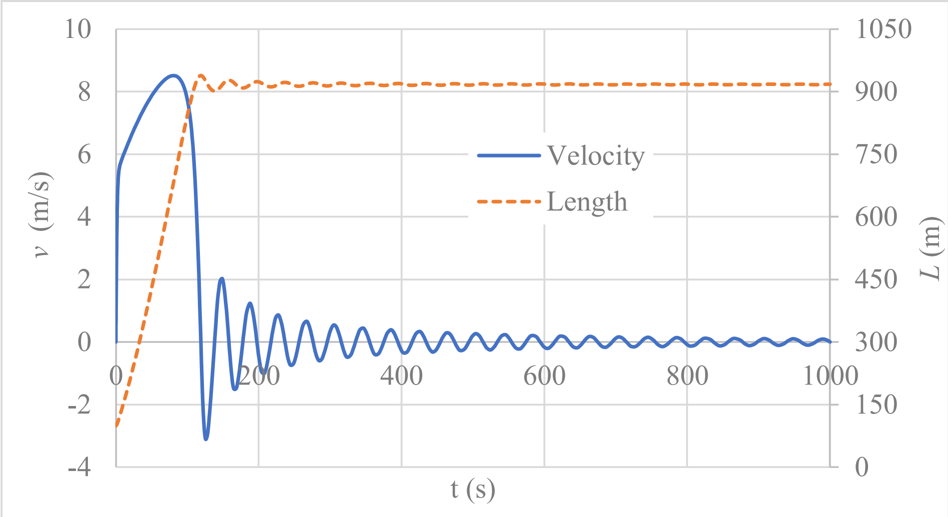
4 PRACTICAL APPLICATION

The mathematical model was performed to study the behavior of the filling operation in a single pipeline with the characteristics as follows: a total length (L_T) of 1000 m, an internal diameter (D) of 595 mm, a longitudinal slope of 10°, an absolute roughness (k_S) of 0.0015 mm, a polytropic coefficient of 1.2, an initial hydro-pneumatic absolute pressure (p_0^*) of 226387 Pa, an initial air pocket (x_0) of 900 m, and a resistance coefficient (R_v) of 12 ms^2/m^6 for a total opening condition. The numerical resolution of algebraic-differential equations (5) to (7) was carried out using the method ODE 23s in Matlab. For all simulations, the air pocket is at atmospheric conditions (p_1^*).

The UFM was performed considering the Swamee-Jain equation. Results are shown in Figure 3. According to these values, a sudden increased trend is presented at the beginning of the hydraulic event (see Figure 3a). A maximum value of air pocket absolute pressure head of 259.67 m is reached at 118.7 s, which is 11 times higher compared to the initial pressure supplied by the hydro-pneumatic pressure tank of 226387 Pa (or 23.08 m). After that, some oscillations are presented, and at the end the air pocket pressure pattern trends to be a constant around of 182 m (from 400 to 1000 s). Regarding the water velocity (see Figure 3b), it increases rapidly reaching a maximum value of 8.50 m/s at 79.7 s. When the air pocket pressure pattern attains its maximum value (at 118.7 s), then the water velocity is null. Then, some pulses are presented along of a value of 0 m/s, which indicates that the water column is reaching a rest condition. The length of the water column beings with an initial value of 100 m. After the instant opening of the discharge valve, the pipe is quickly filled by the water replacing the air column (see Figure 3b). The maximum value is obtained at the same time for the condition of the maximum value of air pocket pressure (at 118.7 s).



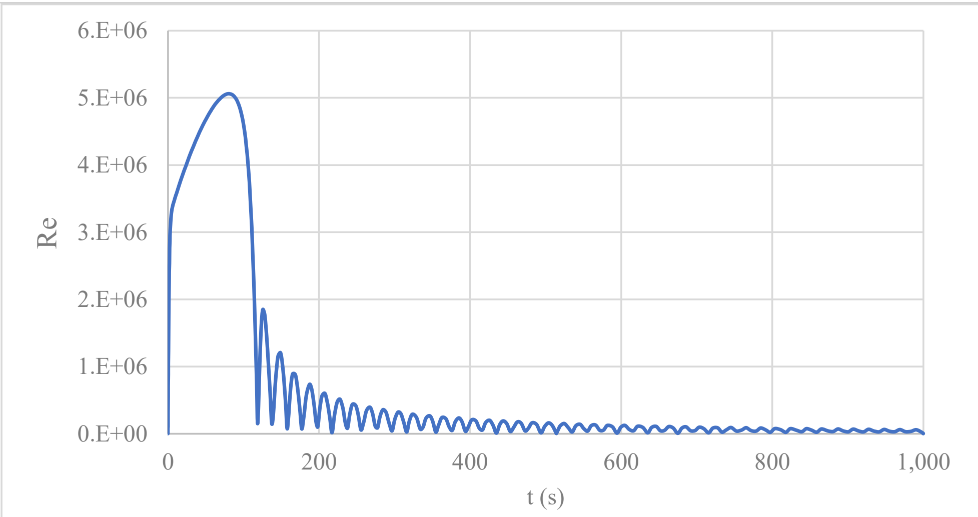
(a) Air pocket pressure



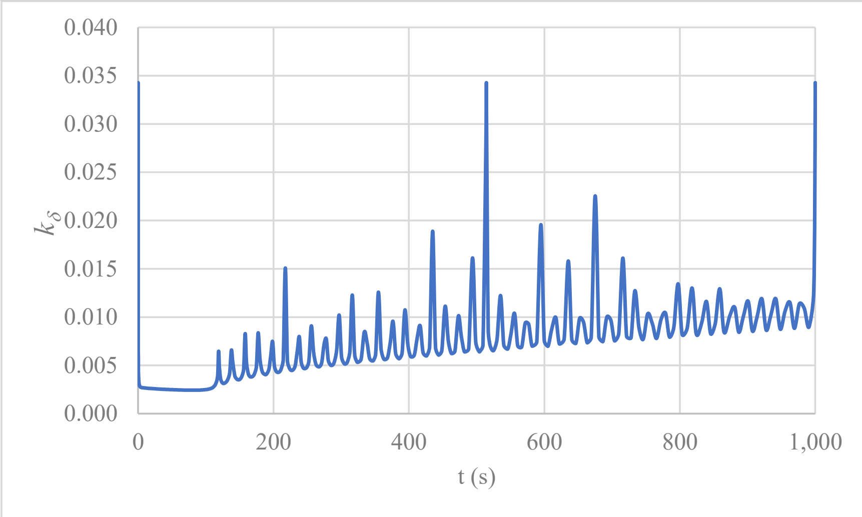
(b) Water velocity and length of the filling water column

Figure 3. Evolution of air pocket pressure, water velocity, and length of the filling water column pulses for the practical application

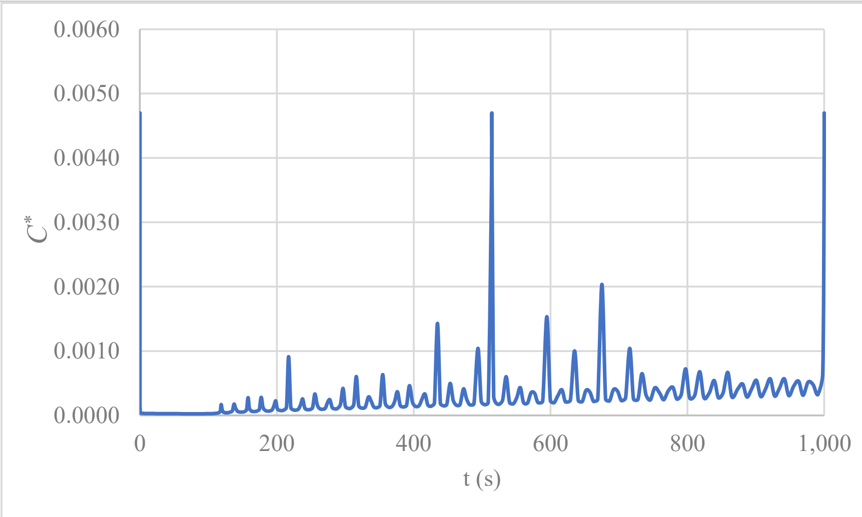
The UFMs also show the variation of the Brunnone friction and Vardy's shear decay coefficient, which depend on Reynolds number. Figure 4 shows the evolution of the Reynolds number and these coefficients. For the analysed scenario, Reynolds number varies from 0 to 5,061,794, following the same trend of the water velocity (see Figure 3b). The maximum value of Reynold number is found at 0.25 s and 0.24 s for Runs No.1 and No. 2, respectively. Brunnone friction and Vardy's shear decay coefficients have a similar trend. The higher Reynolds number, the lower Brunnone friction and Vardy's shear decay coefficients are obtained. The hydraulic transient starts with values of C^* and k_δ of 0.0047 and 0.034, respectively, which corresponds to the conditions of the laminar flow. After that, from 0 to 118.7 s, the values of these coefficients decrease since the water velocity pattern (see Figure 3b) reaches its maximum values. At the end of the transient event, an increasing trend of these coefficients are presented from 118.7 s.



(a) Reynolds Number



(b) Brunnone friction coefficient (k_δ)



(c) Vardy's shear decay coefficient (C^*)

Figure 4. Analysis of patterns of variables: (a) Reynolds number, (b) Brunnone friction coefficient, and (c) Vardy's shear decay coefficient

The SFM and UFM were compared to note the discrepancy in the determination of air pocket pressure pattern. Figure 5 shows how both models can follow the same trend during the entire transient event. In this sense, peak values of air pocket pressure head of 259.55 and 259.67 m are obtained for the SFM and UFM, respectively. Also, the peak values occurrence is obtained closely with time of 119.2 and 118.7 s for the SFM and UFM, respectively.

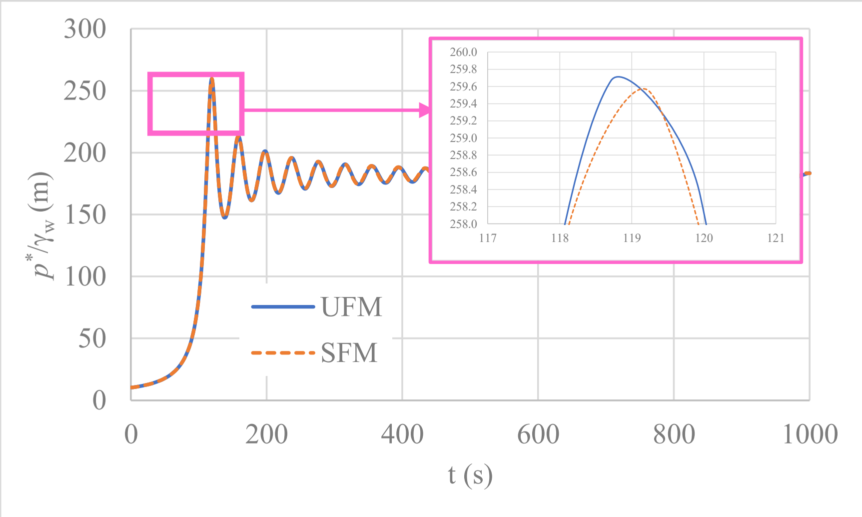
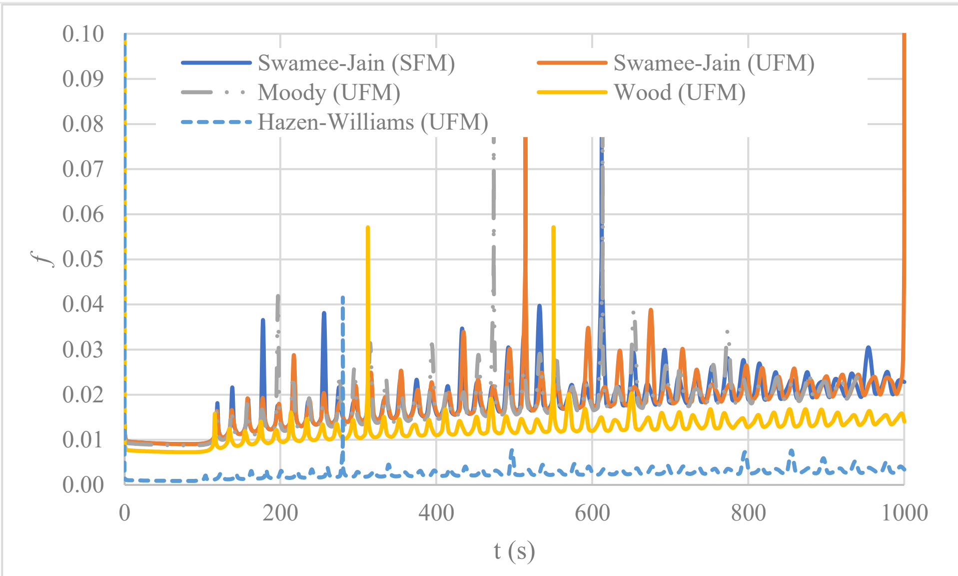
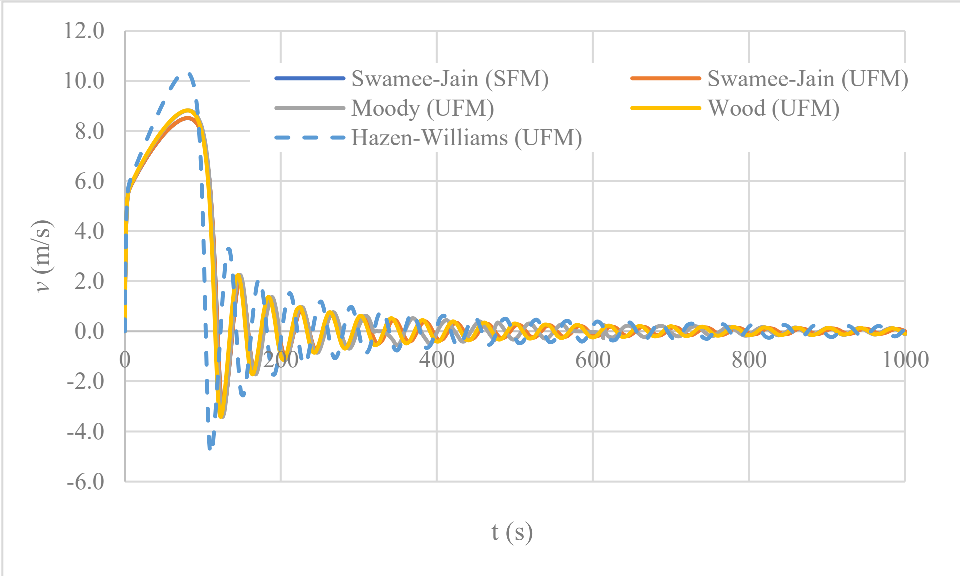


Figure 5. Comparison of air pocket pressure pulses between UFM and SFM

The analysis of the friction factor was performed considering Moody, Wood, and Hazen-Williams equations, as shown in Figure 6a. Swamee-Jain equation provided similar results using SFM and UFM. The friction factor has an increasing trend, and at the end of the hydraulic event it converges to an asymptotic value of 0.022. In addition, Moody equation also provides a good accuracy since its trend is similar compared to the results of Swamee-Jain equation. Wood equation gave lower values of friction factor than Swamee-Jain equation. The worst results were obtained using Hazen-Williams equation due to the hydraulic system exhibits water velocities higher than 3 m/s from 1.28 to 114.97 s (see Figure 6b), where the analysed empirical equation is not applicable.



(a) Friction factor



(b) Water velocity

Figure 6. Analysis of friction factor formulations with UFM and SFM

5 CONCLUSIONS

A mathematical model to simulate filling processes without admitted air (or air valves) is developed considering an unsteady friction model, which is based on a rigid water column model, a piston flow model, and a polytropic model. The mathematical model was validated in an experimental facility of 7.6-m-long PVC pipe, where the analysed filling operation was performed slowly obtaining an isothermal evolution. Results confirm that the mathematical model is suitable to simulate experimental measurements of air pocket pressure. UFM provided a better calibration compared to SFM.

A practical application of a water installation is presented to note the responses of variables of Brunone model (Brunnone friction and Vardy's shear decay coefficient). Swamee-Jain equation was calibrated with measured data and used as a reference model for the friction factor. Moody, Wood and Hazen-Williams equations where evaluated for computing the friction factor. Results show that Moody equation provides a good accuracy compared to the results obtained from Swamee-Jain equation. Wood equation gave lower values of friction factor than Swamee-Jain equation. Hazen-Williams equations is not recommended for filling operations since water velocities reach values higher to 3 m/s.

Authors suggest that futures works can focus on the assessment of filling operation with air valves considering unsteady friction models.

6 REFERENCES

[1] V.S. Fuertes-Miquel, Ó.E. Coronado-Hernández, D. Mora-Meliá, and P.L. Iglesias-Rey, "Hydraulic Modeling during Filling and Emptying Processes in Pressurized Pipelines: A Literature Review", Urban Water Journal, 2019, 16(4), pp. 299-311.

[2] J. Abreu, E. Cabrera, J. Izquierdo, and J. García-Serra, "Flow Modeling in Pressurized Systems Revisited", Journal of Hydraulic Engineering, 1999, 125(11), pp. 1154-1169.

[3] L. Zhou, D. Liu, and C. Ou, "Simulation of Flow Transients in a Water Filling Pipe Containing Entrapped Air Pocket with VOF Model", Engineering Applications of Computational Fluid Mechanics, 2011, 5(1), pp. 127-140.

[4] F. Zhou, M. Hicks, and P.M. Steffler, "Transient Flow in a Rapidly Filling Horizontal Pipe Containing Trapped Air", Journal of Hydraulic Engineering, 2002, 128(6), pp. 625-634.

[5] V.S. Fuertes-Miquel, Ó.E. Coronado-Hernández, P.L. Iglesias-Rey, and D. Mora-Meliá, "Transient Phenomena during the Emptying Process of a Single Pipe with Water-Air Interaction", Journal of Hydraulic Research, 2019, 57(3), pp. 318-326.

[6] O.E. Coronado-Hernández, V.S. Fuertes-Miquel, M. Besharat, and H.M. Ramos, "Subatmospheric Pressure in a Water Draining Pipeline with an Air Pocket", Urban Water Journal, 2018, 15(4), pp. 346-352.

[7] M. Besharat, O.E. Coronado-Hernández, V.S. Fuertes-Miquel, M.T. Viseu, and H.M. Ramos, "Backflow Air and Pressure Analysis in Emptying Pipeline Containing Entrapped Air Pocket", Urban Water Journal, 2018, 15(8), pp. 769-779.

[8] A.M. Aguirre-Mendoza, D.A. Paternina-Verona, S. Oyuela, O.E. Coronado-Hernández, M. Besharat, V.S. Fuertes-Miquel, P.L. Iglesias-Rey, and H.M. Ramos, "Effects of Orifice Sizes for Uncontrolled Filling Processes in Water Pipelines", Water, 2022, 14(6), 888.

[9] L. Zhou, Y. Cao, B. Karney, J.G. Vasconcelos, D. Liu, and P. Wang, "Unsteady friction in transient vertical-pipe flow with trapped air", Journal of Hydraulic Research, 2020, 59(5), pp. 820-834.

[10] Ó.E. Coronado-Hernández, I. Derpich, V.S. Fuertes-Miquel, J.R. Coronado-Hernández, and G. Gatica, "Assessment of Steady and Unsteady Friction Models in the Draining Processes of Hydraulic Installations", Water, 2021, 13(14), 1888.

[11] B. Brunone, B.W. Karney, M. Mecarelli, and M. Ferrante, "Velocity profiles and unsteady pipe friction in transient flow", Journal of Water Resources Planning and Management, 2000, 126(4), pp. 236-244.

[12] L.F. Moody, "Friction Factors for Pipe Flow", Transactions of the American Society of Mechanical Engineers, 1994, 66, pp. 671-684.

[13] D.J. Wood, "An Explicit Friction Factor Relationship", American Society of Civil Engineers, 1972, pp. 383-390.

[14] Q. Travis, and L.W. Mays, "Relationship between Hazen-William and Colebrook-White Roughness Values", Journal of Hydraulic Engineering, 2007, 133(1), pp. 1270-1273.

[15] D.K. Swamee, and A. K. Jain, "Explicit Equations for Pipe Flow Problems", Journal of the Hydraulics Division, 1976, 102(5), pp. 657-664.

[16] J. Saldarriaga, Hidráulica de Tuberías, Alfaomega Bogotá, 2007.

[17] V. Streeter, and E. Wylie, Fluid Mechanics, Ed. McGraw-Hill, NY, 1979.