ARTICLE TEMPLATE

Hydraulic modeling during filling and emptying processes in pressurized pipelines: A literature review

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ABSTRACT
Filling and emptying processes are common maneuvers while operating, controlling and managing water pipelines systems. Currently, these operations are executed following recommendations from technical manuals and pipe manufacturers; however, these recommendations have a lack of understanding about the behavior of these processes. The application of mathematical models considering transient flows with entrapped air pockets is necessary because a rapid filling operation can cause pressure surges due to air pocket compressions, while an uncontrolled emptying operation can generate troughs of sub-atmospheric pressure caused by air pocket expansion. Depending on pipe and installation conditions, either situation can produce a rupture of pipe systems. Recently, reliable mathematical models have been developed by different researchers. This paper reviews and compares various mathematical models to simulate these processes. Water columns can be analyzed using a rigid water column model, an elastic water model, or 2D/3D CFD models; air–water interfaces using a piston flow model or more complex models; air pockets through a polytropic model; and air valves using an isentropic nozzle flow or similar approaches. This work can be used as a starting point for planning filling and emptying operations in pressurized pipelines. Uncertainties of mathematical models of two-phases flow concerning to a non-variable friction factor, a polytropic coefficient, an air pocket sizes, and an air valve behavior are identified.

KEYWORDS
Air-water; emptying; filling; transient flow; water distribution system

1. Introduction

The analysis of transient phenomena of a single phase (only water) is complex considering the intricacy of calculations and configurations of water pipelines systems. Filling and emptying processes are too complex to be captured by single-phase models because there are two fluids (water and air) in two phases (liquid and gas)(Fuertes-Miquel 2001; Coronado-Hernández 2019). These operations must be performed periodically in pipelines for maintenance, cleaning or repairs by technical personnel (Fuertes-Miquel et al. 2019). Planning water distribution systems requires considering the effects of en-

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trapped air pockets to guarantee successful maintenance and repair procedures. During filling processes, air pockets can be rapidly compressed, producing pressure surges; during emptying processes, air pockets expand, causing sub-atmospheric conditions. As a consequence, the modeling of the air phase is crucial to determine extreme values of absolute pressure. The correct identification of a type of model (adiabatic, polytropic or isothermal) and an air valve characterization have to be considered.

The effects of trapped air in water pipelines are generated basically with regards to two features: (i) air density is much lower than water density by a ratio approximately $1 : 800$ times considering atmospheric conditions and a temperature of $20°C$; and (ii) the elasticity of air is much higher than the elasticity of water. The elasticity depends on the type of process (isothermal, polytropic or adiabatic) and the absolute pressure of the air pocket. For instance, the bulk modulus in an isothermal process, at atmospheric condition, presents a ratio of 20000 times, and for an absolute pressure of 10 bar, the ratio is of 2000 times. Some of the problems cause by entrapped air pockets are: (i) additional head losses by increasing the water velocity as a consequence of the reduction of the cross section (Stephenson 1997), (ii) pressure surges for starting or stopping the system because of the compression of the air pocket, (iii) reduction of the efficiency of the pumps, (iv) vibrations in pipelines, which generate rapid changes in the water velocity pattern, (iv) pipe corrosion owing to temperature and absolute pressure changes, and (v) troughs of sub-atmospheric pressure by the expansion of the air pocket (Fuertes-Miquel et al. 2019; Coronado-Hernández, Fuertes-Miquel, and Angulo-Hernández 2018).

Entrapped air pockets are a problem for pipeline operations. It is important to perform a filling process correctly to eliminate air pockets from hydraulic systems. However, entrapped air could also enter through air valves, joints and valves, during the stopping and failure of hydraulic systems, during the release of dissolved air, and by vortex generation at pump inlets. High points along pipelines are likely locations for the accumulation of air pockets (AWWA 2001; Ramezani and Karney 2017), which can experience pressure surges during a filling process (Zhou, Liu, and Karney 2013b; Fontana, Galdiero, and Giugni 2016; Martins et al. 2016; Covas et al. 2010) or drops of sub-atmospheric pressure during an emptying process (Fuertes-Miquel et al. 2019; Tijsseling et al. 2016; Coronado-Hernández et al. 2018c). Air valves are used as protective devices to avoid these situations (AWWA 2001).

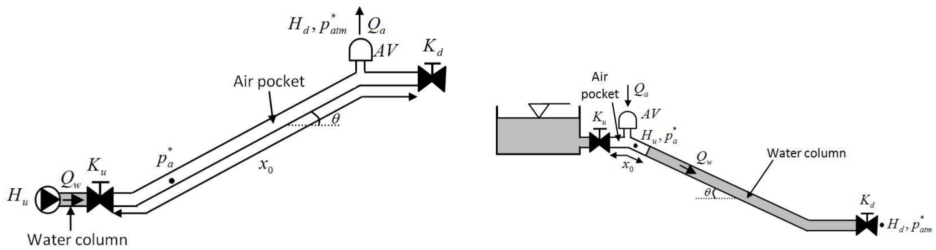
Entrapped air can be expelled by permanent joints of hydraulic systems to the atmosphere (downstream conditions, fire hydrants, among others). The most common method is via air valves located along the system (Martino, Fontana, and Giugni 2001), in high points or others places where entrapped air can accumulate.

The emptying and filling of a pipeline cannot be simulated with the commonly used 1D transient commercial packages like Bentley Hammer, H2O Surge, Allievi, among others; since they are not capable of predicting a two-phase flow (water and air).

This paper aims to accomplish the following: (1) review available knowledge regarding filling and emptying processes in pressurized hydraulic systems, which is missing in the current literature; (2) describe mathematical models for water and air phase; (3) describe methods of resolutions of transient flow during pipeline operations; (4) mention the sources of uncertainty in current models; and (5) comment regarding some considerations to protect pipelines during these operations.

2. Understanding of filling and emptying processes

A basic hydraulic scheme is presented to show the performance of filling and emptying processes (Figure 1).



(a) Filling process (b) Emptying process

Figure 1. Basic hydraulic scheme

The filling process begins when a discharge valve is opened (K_u). Consequently, the water column driven by an energy source (tank or pump) starts to fill the hydraulic system (see Figure 1a) by compressing the entrapped air pocket (Zhou, Liu, and Karney 2013a; Hou et al. 2014; Martins, Delgado, and Ramos 2017; Malekpour, Karney, and Nault 2016) producing peaks of absolute pressure (pressure surges). It is important to note that air valve slamming should not occur; otherwise very large spikes could have occurred at the end of the filling process. Valve K_d is closed to produce the rapid compression of an air pocket. The process is adequately completed when the entrapped air is replaced by the water column (Apollonio et al. 2016; Balacco, Apollonio, and Piccinni 2015). Two situations can occur: (i) when the air valve (AV) has been installed, the process finishes successfully with a well-sized device; and (ii) when there is no air valve, it results in an unfinished process and the highest pressure surges.

To note the order of magnitude of a filling process, a numerical analysis has been conducted in a single pipeline where the authors used an own code in Matlab (Fuertes-Miquel et al. 2016, 2019; Coronado-Hernández et al. 2017, 2018c). Figure 2 shows the peaks of the absolute pressure for the two aforementioned situations using the following data: $L_t = 600$ m, $D = 0.3$ m, $f = 0.018$, $n = 1.2$, $D_{av} = 50$ mm, $C_{exp} = 0.6$, $H_u = 20.38$ m, $x_0 = 500$ m, and $K_u = 0.45$ m/(m^{3}s^{-1})^2. A comparison is conducted with a relative value of air pocket pressure (p_a^*/p_{atm}^*) and the time. According to the results, when an air valve has not been installed, the maximum peak of the absolute pressure head is rapidly reached at 112.1 s with a value of 2.97 p_a^*/p_{atm}^*. After that, oscillations of the absolute pressure continue. However, when an air valve is working, the maximum value is $1.29 p_a^*/p_{atm}^*$ (at 53.4 s). A reduction of an absolute pressure of $1.68 p_a^*/p_{atm}^*$ upon the peak value is reached by using a protection device (air valve) and the pipeline is completely filled at 113.4 s when the water column has occupied the entire pipeline ($L/L_t = 1$). A pipeline with no air valve implies an incomplete filling and an air pocket trapped inside the installation. Maximum values of absolute pressure for different scenarios (such as filling operation, pump failure, among others) should be compared them to select an appropriate pipe resistance.

During an emptying operation, water flow will be replaced by air flow (Tijsseling et al. 2016; Fuertes-Miquel et al. 2019; Coronado-Hernández et al. 2018b). Figure 1b presents a scheme of the operation. The operation starts when drain valves located at

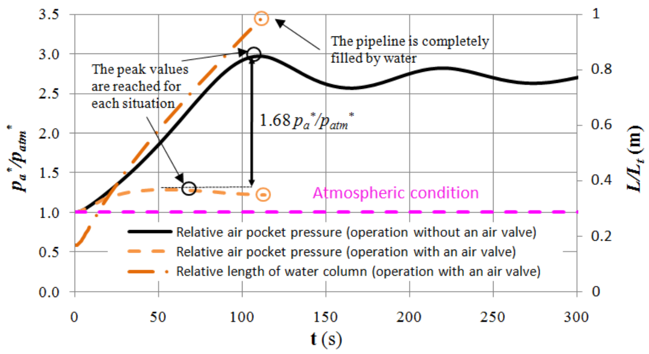


Figure 2. Evolution of the absolute pressure head during the filling process for different conditions

the low points of the pipeline are opened (K_d). Then, the entrapped air pockets start to expand, generating troughs of the sub-atmospheric pressure, which can cause the system to collapse (Coronado-Hernández et al. 2017). A single pipeline was considered with data similar to that of the filling process, but using $K_d = K_u$, $C_{adm} = C_{exp}$, $\Delta z = 12$ m, and $x_0 = 100$ m. An entrapped air pocket is assumed to be at atmospheric conditions. Figure 3 shows the results regarding the relative absolute pressure. According to the results, when there is no air valve, the trough of the absolute pressure head is $0.3 p_a^*/p_{atm}^*$ (at 145.8 s), which continues until the end of the hydraulic event, and part of the water column remains inside the single pipeline. By contrast, when an air valve is installed, the relative absolute pressure is $0.91 p_a^*/p_{atm}^*$ (at 77.2 s), reducing the trough of relative absolute pressure by $0.61 p_a^*/p_{atm}^*$ compared to the condition without an air valve. Under this situation, the hydraulic event finishes around 281.0 s, and the water column is completely drained.

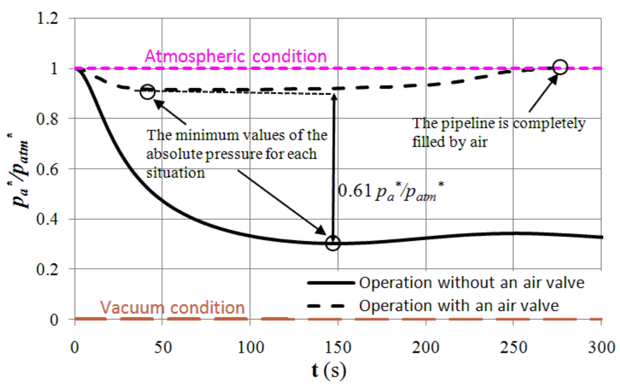


Figure 3. Evolution of the absolute pressure head during he emptying process for different conditions

3. Review of mathematical models

Mathematical models are complex to develop when there is water column separation (Bergant, Simpson, and Tijsseling 2006). Water column separation can occur for different reasons such as (i) cavitation (Yang 2001), (ii) when the water column movement finds an entrapped air pocket, as occurs during filling and emptying processes (Martins, Delgado, and Ramos 2017), (iii) for releasing of the dissolved air in saturated water (Ramezani, Karney, and Malekpour 2016), or (iv) when an inflow front in a filling pipeline fails to expel air in a given location (e.g. a high point), and an air pocket becomes entrapped (Hamam and McCorquodale 1982; Li and McCorquodale 1999). Pipelines always carry an air-water mixture during filling and emptying operations. Depending on the flow characteristics and conditions of pipelines, these operations can be modeled using a piston-flow model (Cabrera et al. 1992) or two-phase flow model (Bousso, Daynou, and Fuamba 2013). Assumptions to apply these models depend on water velocity, internal diameter, and hydraulic slope.

The piston-flow model can be used when a hydraulic event is fast. In this case, the air-water interface is perpendicular to the pipe direction (see Figure 4) (Fuertes-Miquel 2001; Lee 2005). As a consequence, along the pipeline, there are pipe branches completely filled with water and the remaining by air. The smaller the internal diameter is, the higher the water velocity and pipe slope. The piston-flow model is used by the majority of mathematical models for simulating filling and emptying processes in pipelines (Liou and Hunt 1996; Zhou, Liu, and Karney 2013b; Coronado-Hernández et al. 2017; Fuertes-Miquel et al. 2016). The length of a water column (L) and its water velocity (v_w) are related by the following formulation: $dL/dt = \pm v_w$ (Izquierdo et al. 1999; Zhou, Liu, and Karney 2013a).

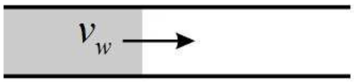


Figure 4. Piston-flow model

Two-phase flow models (see Figure 5) can be used to analyze filling and emptying processes when pipeline installations have been reached a free surface condition, as well as the behavior of air bubbles inside of a water column. The cavitation occurrence is an application of these models in pressurized systems. These models are classified as bubble flow, bubble and air pocket flow, plug flow, stratified wave flow, and stratified smooth flow (Bousso, Daynou, and Fuamba 2013). Several researchers used two-phase flow models to understand the behavior of transient flow with trapped air in free-surface flow (Vasconcelos and Wright 2008; Vasconcelos, Klaver, and Lautenbach 2015; Beecham and Lucke 2015; Guinot 2001).

3.1. *Water phase*

Inertial models can be used to simulate transient phenomena (Abreu et al. 1999) such as filling and emptying processes in pressurized pipelines. Inertial models consider system inertia.

There are two types of inertial models (Zhou, Liu, and Ou 2011): (i) water hammer or elastic models, which consider the elasticity of the pipe and the water; and (ii) mass oscillation or rigid models, which neglect these factors.

The elastic model can be written in the simplified form as follows (Chaudhry 2014; Wylie and Streeter 1993):

- Mass conservation equation

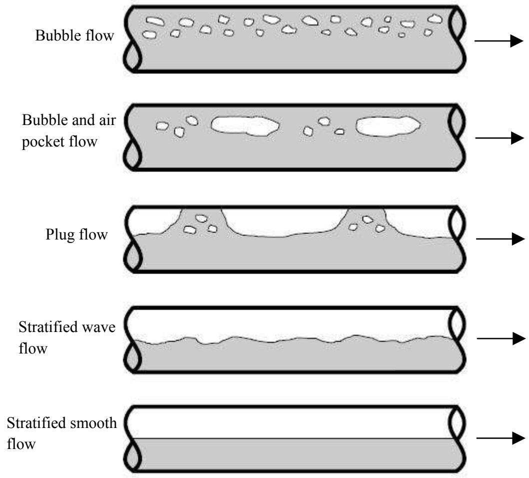


Figure 5. Two-phases flow models

$$\frac{gA}{a^2}\frac{\partial H}{\partial t} + \frac{\partial Q_w}{\partial X} = 0 \tag{1}$$

- Momentum equation

$$\frac{\partial Q_w}{\partial t} + gA\frac{\partial H}{\partial X} + f\frac{Q_w|Q_w|}{2DA} = 0 \tag{2}$$

where g = gravity acceleration, A = the cross-sectional area of the pipe, t = time, a = wave speed, X = the distance along a pipe, H = the piezometric head, Q_w = water discharge, f = the friction factor, and D = the internal diameter.

Elastic models have been used for analyzing the filling processes in water pipelines and analyzing the influence of entrapped air pockets (Zhou et al. 2011; Ghidaoui 2004), the effects of two entrapped air pockets (Zhou, Liu, and Karney 2013a), the phenomenon of white mist with entrapped air pockets (Zhou, Liu, and Karney 2013b), and the consequences of using a bypass (Wang et al. 2017). However, the elasticity of an entrapped air pocket into a pipeline is much higher than the elasticity of the water and pipe. As a consequence, $a \longrightarrow \propto$ or $\partial H/\partial t \longrightarrow 0$, which implies that the water phase can be modeled by the rigid water model (RWM). The mass conservation equation reduces to:

$$\frac{\partial Q_w}{\partial X} = 0 \longrightarrow Q_w = Q_w(t) \tag{3}$$

Then, the momentum equation can be expressed as:

$$H_u = H_d + \frac{fL}{2gDA^2}Q_w|Q_w| + R_v Q_w|Q_w| + \frac{L}{gA}\frac{dQ_w}{dt} \tag{4}$$

where H_u = the upstream piezometric head, H_d = the downstream piezometric head, L = the length of the pipe, and R_v = the resistance coefficient of the valve.

Several investigations have been conducted using rigid models for filling processes. Izquierdo et al. (1999) and Liou and Hunt (1996) applied the rigid model for analyzing a water pipeline with different air pockets, Zhou, Hicks, and Steffler (2002) presented the analysis of the transient flow in a rapidly filling horizontal pipe with an entrapped air pocket, and Hou et al. (2014) investigated a large-scale pipeline. Regarding the emptying process, Laanearu et al. (2012) experimentally analyzed this operation in a large-scale pipeline by pressurized air, Tijsseling et al. (2016) proposed a semiempirical model to predict the emptying process by pressurized air, Fuertes-Miquel et al. (2019) proposed and validated a mathematical model of a single pipe, and Coronado-Hernández et al. (2017) studied emptying processes using various air valves in a water pipeline. According to Coronado-Hernández et al. (2018b) the backflow air occurrence cannot be detected with a 1D model.

On the other hand, Zhou, Liu, and Ou (2011) and Martins, Delgado, and Ramos (2017) have studied rapid filling operations using 2D and 3D CFD simulations, respectively. Besharat et al. (2018) analyzed emptying maneuvers using 2D CFD simulation in a pipeline of undulating profile. The phenomenon of backflow air is detected with a 2D CFD simulation, which is important to know the behavior of air flow from downstream to upstream. A CFD model uses the mass conservation and the momentum formulations to represent a two-phases flow (Wang et al. 2016).

Table 1 presents the main advantages and disadvantages of various mathematical models for the water phase during filling and emptying processes.

3.2. *Air phase*

During the filling and the emptying operations, alterations occur on the thermodynamic proprieties of the entrapped air pockets (Martins, Ramos, and Almeida 2015), which can produce important changes in their absolute pressure and volume. These alterations are generated for two reasons: (i) the compression or the expansion of the air pockets, and (ii) the expelled or the admitted air flow by air valves.

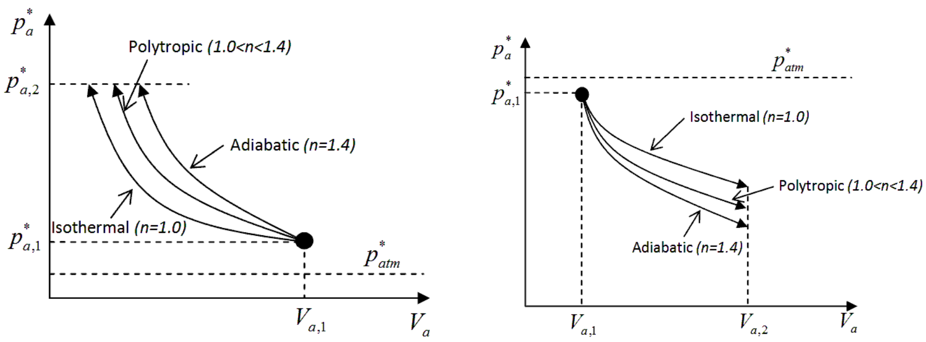
3.2.1. Compression and expansion of the entrapped air pocket

The compression of the entrapped air pocket occurs during the filling process. It starts with a value of absolute pressure $p^*_{a,1}$, and then the initial air volume $V_{a,1}$ begins to compress, generating a higher absolute pressure value $p^*_{a,2}$. For an adiabatic process ($n = 1.4$) the air volume size is higher than for an isotherm process ($n = 1.0$), which implies that an isotherm process is more risky for this operation because higher absolute pressure values can be reached (see Figure 6a). In contrast, during the emptying process, the expansion of the entrapped air pocket occurs. The entrapped air pocket starts with an initial air volume $V_{a,1}$ at sub-atmospheric pressure value $p^*_{a,1}$ and finishes with a higher air volume size $V_{a,2}$ (see Figure 6b). An adiabatic process produces higher troughs of the sub-atmospheric pressure than an isotherm process. If the hydraulic event occurs slowly enough then the process can be considered isothermal, whereas if the hydraulic event occurs fast enough, then the process is adiabatic because there is not enough time to produce the heat transfer in adiabatic processes. Intermediate processes are reached in actual installations.

An entrapped air pocket can be modeled considering its energetic behavior. According to the first law of thermodynamics, the change in internal energy (E) is the sum of

Table 1. Mathematical models for the water phase.

Model	Advantages	Disadvantages
Rigid column models	Models are simpler to implement.	Generally, mathematical models use a piston flow model to define an air-water interface; but more complex shapes can be used with additional efforts (Tijsseling et al. 2016; Laanearu et al. 2012).
	Models give similar results compared to the EWM because the elasticity of air pockets is much higher than pipe and water elasticity (Coronado-Hernández et al. 2017, 2018c)	Models neglect pipe and water elasticity (Zhou, Hicks, and Steffler 2002; Izquierdo et al. 1999).
	Numerical solutions and others methods are used.	The evolution of the backflow air phenomenon has not been implemented.
	Filling and emptying processes with air valves have been developed by Fuertes-Miquel et al. (2016) and Coronado-Hernández et al. (2017), respectively.	
	Models require a low computing time.	
Elastic models	Models are more complex to implement than the RCM.	A piston flow model is used to simulate an air-water interface; however, more complex shapes of air-water interfaces have not been defined.
	EWMs consider pipe and water elasticity (Zhou, Liu, and Ou 2011), and formulations include water hammer effects.	Mathematical models of filling and emptying processes with air valves have not been defined in the literature.
	Numerical resolution is conducted using the MOC in combination with others methods (Zhou, Liu, and Karney 2013a,b; Zhou and Liu 2013).	The evolution of the backflow air phenomenon has not been implemented.
	Computing times are higher compared to the RCM.	
2D/3D models	Complex shapes of air-water interface can be considered (Martins, Delgado, and Ramos 2017), and the position of air-water interfaces can be modeled adequately.	Length and time scales are not defined in pipelines using air valves during filling and emptying processes.
	Backflow air phenomenon can be simulated.	Models require a low time step which implies a high computing time (Martins, Delgado, and Ramos 2017; Zhou, Liu, and Ou 2011).



(a) Compression of the entrapped air pocket (b) Expansion of the entrapped air pocket

Figure 6. Diagram p_a^* vs. V_a

the net quantity of heat (Q_e) supplied to the system plus the work done by the system (W) (Graze, Megler, and Hartmann 1996). A simplification of these relationships for an entrapped air pocket can be represented by a polytropic model (Martin 1976; Leon et al. 2010) where a constant polytropic coefficient (n) considers the effects of the heat transfers in the variables p_a^* and V_a. As a consequence, two formulations can be used for representing the behavior of an entrapped air pocket, which depends on whether the air mass is changing with time:

- If $dm_a/dt \neq 0$, then:

$$\frac{dp_a^*}{dt} = -n\frac{p_a^*}{V_a}\frac{dV_a}{dt} + \frac{p_a^*}{V_a}\frac{n}{\rho_a}\frac{dm_a}{dt} \tag{5}$$

- If $dm_a/dt = 0$, then:

$$p_a^* V_a^n = p_{a,0}^* V_{a,0}^n \tag{6}$$

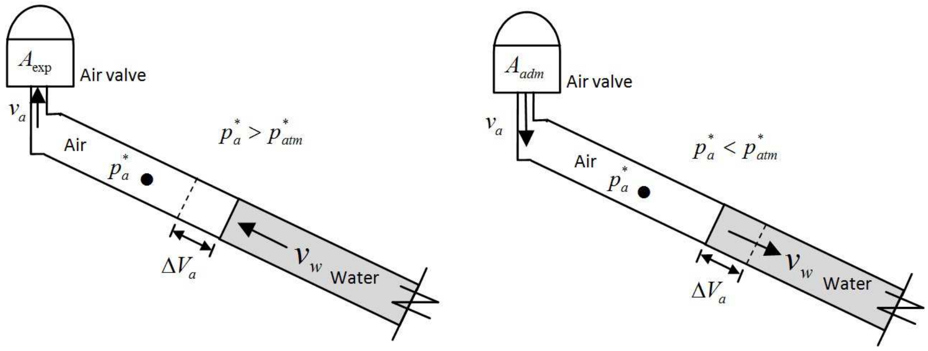
where ρ_a is the air density, m_a is the air mass, and subscript 0 refers to initial conditions of absolute pressure of air pocket and air volume.

There are mathematical models that performed discretized representation of gas phase, which can be used to simulate a backward moving bore when a water column is filling a pressurized pipeline with air valves (Trindade and Vasconcelos 2006; Arai and Yamamoto 2003). Also, this phenomenon can be analyzed in the context of multi-phase flow (Issa and Kempf 2003).

3.2.2. Air valves characterization

Air valves can be used to avoid the peaks and troughs of the absolute pressure (AWWA 2001) for filling and emptying operations, respectively. For air valves the admitted and expelled flow air for each differential pressure should be known (Carlos et al. 2011) in order to mitigate the extreme absolute pressures. When the filling process starts ($p_a^* > p_{atm}^*$), the air valve begins to expel air out of the system and the water column starts to compress ($\Delta Q_e > 0$) the entrapped air pocket, which implies $\Delta W < 0$. In contrast, during the emptying process ($p_a^* < p_{atm}^*$), the work done by the system is

$\Delta W > 0$ considering the expansion of the entrapped air pocket. Figure 7 shows the air valves' behavior during these operations.



(a) Air flow out: $\Delta W < 0$; $\Delta Q_e > 0$ (b) Air flow in: $\Delta W > 0$; $\Delta Q_e < 0$

Figure 7. Effects of air valves behavior during the filling and emptying processes

An appropriate modeling of air valves is crucial to understand the behavior during the filling and emptying operations in pipelines. Some theoretical expressions for modeling air valves are presented by Wylie and Streeter (1993) and Chaudhry (2014). Air valves can be simulated considering an isentropic nozzle flow that is practically adiabatic given that the time required for the air flow through this device is very small. Consequently, heat transfer cannot occur (Wylie and Streeter 1993). The air can be modeled by applying the ideal gas law ($p_a^* = \rho_a RT$), and an adiabatic coefficient value (n) of 1.4. The air flow can be classified considering the relationships between air velocity (v_a) and the speed of sound (c). In this sense, a subsonic flow occurs if $v_a < c$, and a critical flow occurs when $v_a = c$. The speed of sound is computed as $c = \sqrt{KRT}$, where K is the polytropic coefficient in adiabatic conditions ($K = 1.4$ for air). Considering an isentropic flow, the air valves formulations for expelling and admitting air are presented as follows:

For expelling air

- Subsonic air flow out ($p_{atm}^* < p_a^* < 1.893 p_{atm}^*$):

$$Q_a = C_{exp} A_{exp} p_a^* \sqrt{\frac{7}{RT}\left[\left(\frac{p_{atm}^*}{p_a^*}\right)^{1.4286} - \left(\frac{p_{atm}^*}{p_a^*}\right)^{1.714}\right]} \tag{7}$$

- Critical air flow out ($p_a^* \geq 1.893 p_{atm}^*$):

$$Q_a = C_{exp} A_{exp} \frac{0.686}{\sqrt{RT}} p_a^* \tag{8}$$

where C_{exp} is the outflow discharge coefficient, and A_{exp} is the cross-sectional area of the air valve when air is expelled.

For admitting air

- Subsonic air flow in ($p^*_{atm} > p^*_a > 0.528p^*_{atm}$):

$$Q_a = C_{adm}A_{adm}\sqrt{7p^*_{atm}\rho_{a,nc}\left[\left(\frac{p^*_a}{p^*_{atm}}\right)^{1.4286} - \left(\frac{p^*_a}{p^*_{atm}}\right)^{1.714}\right]} \tag{9}$$

- Critical air flow in ($p^*_a \leq 0.528p^*_{atm}$):

$$Q_a = C_{adm}A_{adm}\frac{0.686}{\sqrt{RT}}p^*_{atm} \tag{10}$$

where A_{adm} is the cross-sectional area of the air valve when air is admitted, and C_{adm} is the inflow discharge coefficient.

Figure 8 presents the air valve characterization of the examples shown in Section No. 2, using an inflow and outflow coefficient of 0.6. Manufacturers should obtain this curve experimentally. The horizontal axis represents the air flow rate in normal conditions (at atmospheric pressure and ambient air temperature). The vertical axis is the differential pressure (Δp), which is computed as $\Delta p = p^*_a - p^*_{atm}$ for expelling air (filling operation) and $\Delta p = p^*_{atm} - p^*_a$ for admitting air (emptying operation).

To apply the formulations (7) - (10), the inflow discharge coefficient (C_{exp}) and the outflow discharge coefficient (C_{adm}) should be obtained based on manufacturer data. In this sense, discharge coefficients (C_{exp} and C_{adm}) depend on the type of selected air valve with mean values ranging from 0.3 to 0.7 (Iglesias-Rey et al. 2014).

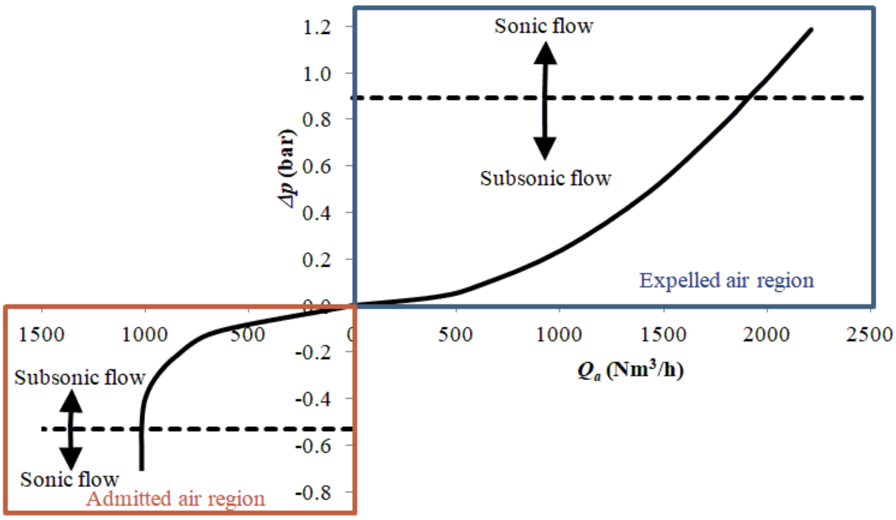


Figure 8. Example of an air valve characterization

3.3. *Summary of mathematical models and methods of resolution*

Table 2 contains a summary of mathematical models used for water, as well as the air phase, during filling and emptying processes.

Table 2. Summary of mathematical models for water and air phase.

Author	RCM	EWC	CFD	PF	CS	AP	AV
Coronado-Hernández et al. (2017, 2018c)	✓			✓		✓	✓
Liu, Zhang, and Yu (2018)		✓		✓		✓	
Wang et al. (2017)		✓		✓		✓	
Martins, Delgado, and Ramos (2017); Zhou et al. (2018b)			✓		✓	✓	
Fuertes-Miquel et al. (2016)	✓			✓		✓	✓
Tijsseling et al. (2016); Laanearu et al. (2012)	✓				✓	✓	
Hou et al. (2014)	✓			✓		✓	
Zhou, Liu, and Karney (2013a,b); Liu et al. (2011); Zhou et al. (2018a)		✓		✓		✓	✓
Hou et al. (2012)	✓			✓		✓	
Zhou, Liu, and Ou (2011)			✓		✓	✓	
Chaudhry and Reddy (2011)	✓			✓		✓	
Malekpour and Karney (2011)		✓		✓		✓	
Lee (2005)	✓					✓	
Zhou, Hicks, and Steffler (2002)	✓			✓		✓	
Fuertes-Miquel (2001); Izquierdo et al. (1999)	✓			✓		✓	✓
Liou and Hunt (1996)	✓						
Martin (1976)	✓			✓		✓	

Notes: RCM = rigid column model, EWC = elastic water column (1D), CFD = corresponds to 2D/3D CFD models, PF = air-water interface as piston flow, CS = complex shapes to represent an air-water interface with a two-phase model, AP = entrapped air pocket, and AV = air valve or orifice size.

It is important to mention how is the resolution of mathematical models for these operations. Currently, there is no single mathematical expression to directly solve the differential-algebraic equations (DAE) system for simulating the transient phenomena. Many techniques have been applied to solve a DAE system. Some of them are (i) the method of characteristics (Chaudhry 2014; Wylie and Streeter 1993), (ii) finite-difference methods (Cunge and Wegner 1964), (iii) finite-element methods (Watt 1975; Baker 1983), (iv) finite volume method (Guinot 2003), (v) volume of fluids (Zhou, Liu, and Ou 2011; Martins, Delgado, and Ramos 2017), and (vi) smoothed particle hydrodynamics (Hou et al. 2012).

Since the 60s, the method of characteristics was used to solve the characteristic equations of a transient flow. At present, many researchers use it to model filling and emptying processes (Shimada, Brown, and Vardy 2008; McInnis, Karney, and Axworthy 1997; Ghidaou and Karney 1994; Wang et al. 2017; Zhou, Liu, and Karney 2013a) because of its computationally efficient and explicit resolution scheme.

Finite-difference methods (explicit and implicit) (Chaudhry 2014) are useful in combination with the method of characteristics to solve complex situations in transient flow (Wang et al. 2017; Zhou and Liu 2013). Zhou, Liu, and Karney (2013a,b) used this method to simulate an air-water interface and the method of characteristics to model the water phase.

Finite-element methods cannot efficiently solve problems related to the evolution of the hydraulic variables because temporal and spatial scaling are complex to model, resulting in inadequate wave propagation (Chaudhry 2014).

Finite volume methods numerically solve the partial differential equations in the form of algebraic equations similar to finite-difference methods or finite-element methods. They are used to solve the conservation laws of hydraulic systems.

In this regard, Hou et al. (2012) presented a method based on Smoothed Particle Hydrodynamics (SPH), Zhou, Liu, and Ou (2011) solved the transient flow problem using a method of Volume of Fluid (VOF), Coronado-Hernández et al. (2017) and Izquierdo et al. (1999) used numerical solutions based on Runge-Kutta or Rosenbrock formula.

Air valves can be modeled using the method of characteristics (Ramezani, Karney, and Malekpour 2015; Zhou, Liu, and Karney 2013a,b) or numerical solutions of ordinary differential equations (Fuertes-Miquel 2001).

A numerical scheme based on approximate Riemann solvers can be used to study transition from pressurized flow to free surface flow and vice versa (Trindade and Vasconcelos 2006).

Table 3 presents a list of methods of resolution, where authors are mentioned. All methods of resolution are performed considering a constant friction factor, a non-variable polytropic coefficient, considering a known air pocket size, and the characteristics of air valves describe by manufacturers.

Table 3. Summary of methods of resolution.

Author	NS	MOC	FD	VOF	SPH
Coronado-Hernández et al. (2017, 2018c)	✓				
Liu, Zhang, and Yu (2018)		✓			
Wang et al. (2017)		✓			
Martins, Delgado, and Ramos (2017); Zhou et al. (2018b)				✓	
Fuertes-Miquel et al. (2016)	✓				
Tijsseling et al. (2016); Laanearu et al. (2012)	✓				
Hou et al. (2014)	✓				
Zhou, Liu, and Karney (2013a,b); Liu et al. (2011); Zhou et al. (2018a)		✓	✓		
Hou et al. (2012)					✓
Zhou, Liu, and Ou (2011)				✓	
Chaudhry and Reddy (2011)	✓	✓			
Malekpour and Karney (2011)		✓			
Lee (2005)			✓		
Zhou, Hicks, and Steffler (2002)	✓				
Fuertes-Miquel (2001); Izquierdo et al. (1999)	✓				
Liou and Hunt (1996)	✓				
Martin (1976)	✓				

Notes: NS = numerical solutions based on Runge-Kutta or Rosenbrock formula, MOC = method of characteristics, FD = finite-difference, VOF = volume of fluids, and SPH = smoothed particle hydrodynamics .

4. Uncertainty of current models and prospects

Current models for modeling filling and emptying processes consider the friction factor, the polytropic coefficient, the air pocket size, and the air valve behavior. However, there are sources of uncertainty in the selection of these parameters which can affect the determination of extreme pressures (maximum and minimum).

4.1. *Friction factor*

The friction factor changes during filling and emptying processes because water velocities vary owing to hydraulic events. Current models consider a constant friction factor during the transient flow (Izquierdo et al. 1999; Laanearu et al. 2012; Coronado-Hernández et al. 2017; Zhou and Liu 2013; Liou and Hunt 1996; Wang et al. 2017). Some expressions have been developed to consider a variable friction factor. Fuertes-Miquel (2001) demonstrated that the expression proposed by Brunone, Golia, and Greco (1991) can adequately fit the behavior of transient flow during these operations, expressed as:

$$J_u = J_s + \frac{k_3}{g}\left(\frac{\partial v}{\partial t} - \frac{\partial v}{\partial s}\right) \tag{11}$$

When a rigid water model is used, the convective acceleration is null, and then:

$$J_u = J_s + \frac{k_3}{g}\frac{dv}{dt} \tag{12}$$

A comparison between a constant and unsteady friction factor was conducted by Fuertes-Miquel (2001)) showing similar discrepancies of 1.31% (constant friction factor) and 1.05% (unsteady friction factor) between experiments and mathematical models as shown in Figure 9, during the filling operation in a metacrylate pipeline of internal diameter of 18.8 mm and a total length of 8.62 m. A similar analysis was conducted by Wang, Wang, and Lei (2018), where different models are presented to simulate an unsteady friction factor. Results show that both constant and unsteady friction factor can be used to simulate the filling operation; however, an unsteady friction factor improves results compared to a constant friction factor. This kind of analysis has not been performed in the emptying operation.

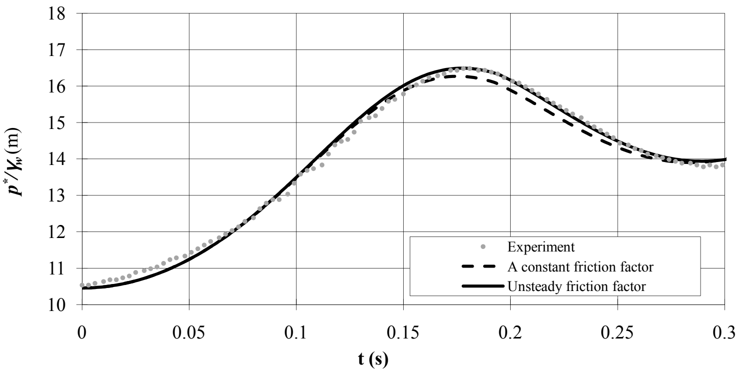


Figure 9. Comparison between a constant and unsteady friction factor [(Fuertes-Miquel 2001)]

4.2. *Polytropic coefficient*

Current models consider the polytropic coefficient during filling and emptying processes as constant. However, it can change during a hydraulic event, depending on the installation characteristics and the boundary conditions. In this sense, a transient flow can start with an isothermal condition ($n = 1.0$), but over time, an intermediate or adiabatic ($n = 1.4$) condition can be reached, and vice versa. Fuertes-Miquel et al. (2016) shows how the selection of a polytropic coefficient in isothermal ($n = 1.0$) or adiabatic ($n = 1.4$) conditions can induce significant differences of the maximum absolute pressure attained. Many studies use an intermediate polytropic coefficient of $n = 1.2$ considering the uncertainty of this value. The determination of a reliable polytropic coefficient is important during these operations. A filling process was analyzed in a 600-m-long pipeline (see example of Section No. 2), where the peak of the absolute pressure head was 31.6 m (for an isothermal condition), which is higher compared to the peak under adiabatic conditions of 30.1 m. Here, a difference around of 5 % was found.

A variable polytropic coefficient represents a challenge in current models (Wang, Wang, and Lei 2018; Izquierdo et al. 1999; Zhou, Liu, and Ou 2011; Martins, Ramos, and Almeida 2015), which has been implemented for modeling air vessels (Akpan et al. 2014).

4.3. *Air pocket size*

Air pockets, which directly affect filling and emptying processes, can accumulate in several parts in the system. In experimental facilities, different configurations regarding air pocket sizes have been conducted (Tijsseling et al. 2016; Coronado-Hernández et al. 2017; Zhou, Liu, and Karney 2013a,b). However, the air pocket size cannot be controlled in actual installations. It is very important to note that small air pockets are more dangerous than large air pockets during these operations when air valves are not acting. On the other hand, sometimes the gas phase volume is so large that the term pocket is not well descriptive, and rather flows should be seen as stratified.

Coronado-Hernández et al. (2018a) analyzed a 1200-m-long pipeline for filling and emptying procedures finding that the air pocket size is not sensitive over these events when air valves are acting. However, if there are no air valves along pipeline installations, the air pocket size can change remarkably the extreme values of absolute pressure. For instance, Izquierdo et al. (1999) shows a pipeline of a total length of 2000 m where a filling operation is analyzed. Results confirm that an air pocket size of 79 m produces a maximum absolute pressure head of 277 m, and considering an air pocket size of 140 m, the absolute pressure head is 191 m, which implies a difference of 30%.

4.4. *Air valves behavior*

Two sources of uncertainties were detected in the characterization of air valves produced by a lack of experimental tests of some manufacturers: (i) the first one corresponds to the air and vacuum flow rate curves, and (ii) the second one corresponds to the dynamic closure of air valves with entrapped air. Iglesias-Rey et al. (2014) analyzed discrepancies between manufacturer data and experimental tests considering different types of air valves.

On one hand, the development of experimental facilities to compute air and vacuum flow rate curves of air valves with large orifices is complex since an enough quantity of expelled/admitted air is required. Then, some manufacturers supply air and vacuum flow rate curves with discrepancies compared to experimental tests (Iglesias-Rey et al. 2014). An inappropriate characterization of air valves introduce an uncertainty in current models regarding inflow and outflow discharge coefficients.

On the other hand, the uncertainty associated to the dynamic closure with entrapped air in air valves is another deficiency of some manufacturers because they do not supply values of dynamic closure occurrence. The phenomenon occurs when outlet air velocity in air valves is too high (large volume of expelled air) producing a sustentation force on the float, which closes an air valve before the water arrives to this device and leaving a dangerous air pocket inside pipeline systems. The majority of air valves are prone to this phenomenon.

Table 4. Design of air valves during a filling maneuver.

Type of design	Description of an air valve behavior	Consequence
Undersized	The quantity of expelled air flow by air valves is lower than a filling water flow.	Air valves are capable to reduce air pocket pressure compared to the situation without air valves.
Well-sized	This situation is reached when a similar ratio of water and air flow is presented.	Air valves offer a reliability protection of pipelines against pressure surges occurrence.
Oversized	The capacity of expelled air flow is so high in comparison with a filling water flow. This condition produces an additional pressure surges, where the phenomenon is named as "air slam" (Lingireddy, Wood, and Zloczower 2014).	The most risky condition of pressure surges is presented for this scenario. Air pocket pressure can be greater even if air valves have not been installed.

5. Practical considerations

5.1. *General practices*

In water pipelines, pressure surges and troughs of sub-atmospheric pressure can occur during filling and emptying processes, respectively, which are generated by entrapped air pockets in hydraulic systems. Air/vacuum valves (AVVs) should be installed along pipelines to prevent pressure surges, by exhausting air during filling processes and injecting a sufficient quantity of air during emptying processes, thus preventing sub-atmospheric conditions (AWWA 2001; Ramezani, Karney, and Malekpour 2016). However, if AVVs are not correctly sized and well-maintained, problems can continue in installations (Ramezani, Karney, and Malekpour 2015; Stephenson 1997; Fuertes-Miquel 2001; Tran 2016).

Filling processes should be executed carefully, through slow maneuvers in the operation of discharge valves to produce an adequate expelled airflow rate. A pressure differential of 2 p.s.i (13.79 kPa) is recommended by the AWWA (2001) during this process. Water flow should be similar to air flow (Q_a) through AVVs with a water velocity of 0.3 m/s.

By contrast, a controlled emptying process should be performed replacing the water volume by an admitted air volume with a similar ratio to avoid dangerous troughs of absolute pressure (Coronado-Hernández et al. 2017; Fuertes-Miquel et al. 2019). (AWWA 2001) recommends both water velocities from 0.3 to 0.6 m/s and a pressure differential of 5 p.s.i (34.5 kPa). If air valves are not installed or are undersized, then dangerous troughs of sub-atmospheric pressure occur, and hydraulic systems cannot be drained.

5.2. *Air valves selection*

The air valve selection during the air expulsion phase considers different scenarios (Ramezani, Karney, and Malekpour 2015; AWWA 2001), as shown in Table 4.

At the end of a filling process when the water reaches the air valve position, the air valve closes rapidly, producing a water hammer in a single-phase (water). Another consideration is the dynamic closure of air valves, which is typically not provided by manufacturers. When an air valve closes without expelling the entrapped air pocket completely, the water column compresses it, producing a dangerous pressure surge.

On the other hand, during the emptying process, the air valve should be selected to protect the system from the troughs of sub-atmospheric pressure. In this sense, a larger air valve size reduces the lowest values of sub-atmospheric pressure.

5.3. *Typical pipe selection practices*

The pressure surges and troughs of sub-atmospheric pressure can be caused by a change in the water velocity during the filling and the emptying process, respectively (Wang et al. 2017; Coronado-Hernández et al. 2017). To select the pressure and the stiffness class in pipelines, the water hammer effects should be computed not only for these operations but also for hydraulic events such as the stopping of pumps (power failure), the rapid opening or closing of valves, and pipe failure, among others. Extreme values of absolute pressure should be selected to design the pipe characteristics.

The highest peak of the pressure surge reached in the aforementioned hydraulic events should be used to select the pressure class in pipelines. Pipe manufacturers usually specify the pressure class of water distribution networks depending on pipe material with typical values varying from 6 to 16 bar (Mays 1999). In other installations pressure class can be different.

The stiffness class is selected according to the following conditions: (i) burial conditions given by native soil, type of backfill, and cover depth, and (ii) the troughs of sub-atmospheric pressure in the system. In this sense, designers can select the stiffness class based on manufacturer data, for instance, SN2500, SN5000, or SN10000.

6. Future research

This section provides future developments that should be considered to continue working in this field, which are mentioned as follows:

(1) Computational Fluid Dynamics (CFD) can be used to understand better the behavior of air pockets considering, among other things, the following circumstances: (i) the entrance of backflow air by drain valves during the emptying process, (ii) complex shapes of air-water interface, (iii) the variation of entrapped air pockets during these processes, (iv) the variation of thermodynamic proprieties of air inside air valves (García-Todolí et al. 2018), (v) the determination of absolute pressure caused by oversized air valves, and (vi) how an entrapped air causes a reduced cross section in pipelines.

(2) The analysis of filling and emptying operations of water distribution networks has not been conducted neither numerically nor experimentally. The majority of experimental facilities correspond to single pipes or pipelines of undulating profiles. Also, the behavior of air in pipelines bifurcations needs to be analyzed since there are no studies related to the quantification of air volume fraction flowing to the downstream two pipe branches.

(3) Current works consider the positing of air valves in high points of water pipelines; however, AWWA (2001) considers others locations of air valves which needs to be studied in points such as horizontal pipe branches, at vertical pumps, long descents and ascents, among others.

(4) Many studies show that the determination of air and vacuum flow rate curves supplied by some manufactures is inadequate, as well as they do not supply reference values of dynamic closure occurrence. The correct air valves characterization is very important to analyze filling and emptying processes.

(5) Current models of filling and emptying operations consider that polytropic model

can be applied. However, there are some limitations of the polytropic model as reported by Graze, Megler, and Hartmann (1996).

(6) The majority of 1D models consider a piston flow to simulate the air-water interface. In this sense, the incorporation of more complex air-water interactions in 1D modeling frameworks can help to have a better approach of filling and emptying processes.

(7) In some situations transitions from pressurized flow to free surface flow can be occurred, which should be studied through better numerical methods and non-linear numerical schemes, particularly the latter.

7. Conclusions

This research presents current knowledge regarding the transient phenomena related to filling and emptying processes in water pipelines. A literature review was conducted on various mathematical models for the water phase, air-water interface, and air phase. Advantages and disadvantages of water phase models were described, as well as an identification of actual researchers. Air-water interface criteria are described, and the air phase and air valve characterization are explained. Four sources of uncertainty that need to be studied further, including the necessity to include a variable value for the polytropic coefficient and the friction factor, as well as the air pockets sizes and air valves selection in the system, were identified in current models. Typical practices about the air valve selection and the pressure and stiffness class in pipelines are summarized showing how emptying and filling operations should be considered for selecting them in hydraulic systems. Finally, future research on filling and emptying processes in pressurized pipelines have also been presented in this work.

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Nomenclature/Notation

a	= wave speed (m/s)
A	= cross-sectional area of pipe (m^2)
AV	= air valve (–)
A_{adm}	= cross sectional area of the air valve when air is admitted (m^2)
A_{exp}	= cross sectional area of the air valve when air is expelled (m^2)
C_{adm}	= inflow discharge coefficient (–)
C_{exp}	= outflow discharge coefficient (–)
c	= speed of sound (m/s)
D	= internal pipe diameter (m)
D_{av}	= air valve size (mm)
E	= internal energy (J)
f	= friction factor (–)
g	= gravity acceleration (m/s^2)
H	= piezometric head (m)
H_u	= upstream piezometric head (m)
H_d	= downstream piezometric head (m)
K	= polytropic coefficient in adiabatic conditions for air with a value of $K = 1.4$ (–)
K_d	= resistance coefficient of drain valve (m/(m^{3}s^{-1})^2)
K_u	= resistance coefficient of discharge valve (m/(m^{3}s^{-1})^2)
L	= length of the water column (m)
L_t	= total length of the pipe (m)
n	= polytropic coefficient (–)
m_a	= air mass (kg)
p_a^*	= absolute pressure of the air pocket (Pa)
p_{atm}^*	= atmospheric pressure (Pa)
t	= time (s)
T	= temperature ($^\circ K$)
R	= constant air (287 J / kg / °K)
Q_e	= net quantity of heat (J)
Q_a	= air flow (m^3/s)
Q_w	= water discharge (m^3/s)
X	= distance along of a pipe (m)
x_0	= initial air pocket size (m)
V_a	= air volume (m^3)
v_w	= water velocity (m/s)
v_a	= air velocity (m/s)
W	= work done by the system (J)
ρ_a	= air density (kg/m^3)
θ	= pipe inclination (rad)
Δz	= difference elevation (m)
0	= refers to an initial condition

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