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Insights and challenges associated with air in pressurized water conveyance systems

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Abstract

Air is present in pressurized water systems for a variety of reasons, including incomplete removal during filling, air entrainment at intakes of entrances, air admission during draining operations, or air exchanges due to transient events such as power failure or pipe burst. Each of these sources or events creates specific design and operational challenges, issues that often require thoughtful and sometimes expensive approaches to avoid serious upsets or accidents. Indeed, the design and operational challenges must collectively be blended to produce a robust and economical design that is valid for all foreseeable operational and emergency actions that might involve the presence of air, whether the air is admitted, expelled or introduced into the flow system. The current paper summarizes the key findings that relate to the presence of air in pressurized flow systems. The focus is on the available research and operational experience regarding the challenges and strategies for coping with residual air, for removing air, or for admitting air into the conveyance system. The emphasis is on practical recommendations but also highlights some of the key uncertainties that remain when dealing with the full range of design and operational challenges confronting the long-term performance of pressurized water conveyance systems. One of the persistent challenges is to select suitable design events since the conditions a pipeline will experience over life are inevitably uncertain.

INTRODUCTION

Hosted by the Hydraulic Structures committee, the Task Committee “Two-phase Flow in Urban Water Systems”, chaired by Jose Vasconcelos, has organized efforts to increase awareness of air-in-water systems broadly defined. The full committee has members from North and South America, Europe, and Asia, drawn from research institutions, consulting companies, and municipalities. A subset of the ASCE committee on two-phase air-water flows in water conveyance systems is specifically considering the challenges – and where possible recommended solutions – that air often presents in pressurized water conveyance systems.

Air, either as small bubbles or as entrapped pockets, is a common occurrence in pressurized water conveyance systems (Ramezani et al. 2016). Air may enter a liquid piping system at leaky joints or through air valves, when internal pressure falls below atmospheric, induced by the occurrence of cavitation for example. On the positive side, dispersed small bubbles or dissolved air attenuate the celerity of propagation of water hammer waves (Pothof and Karney 2012). However, the expulsion of entrapped air through over-sized air valves during transient events can result in dangerous secondary transient pressures (Tasca et al. 2021). Moreover, entrapped air pockets in pressurized systems generate localized head-losses with consequent undesirable reduction of conveyance capacity (Pothof and Clemens 2011, Ramezani et al. 2015). For fast transient events, accurately computing the evolution of air-water interfaces may become exceedingly challenging (Zhou et al. 2018). In summary, entrapped air in pipeline systems brings operational drawbacks and simulation complexities. In this sense, identifying the location of entrapped air in long undulating lines, for example, remains a challenge for practitioners and researchers (Edmunds 1979, Malekpour and She 2018).

A popular and often-effective strategy for air venting is to apply air valves in strategic locations. Air valves are divided in three main categories: air-release valves (ARVs), air/vacuum valves (AVVs), and combination air valves (CAVs). ARVs perform the role of venting accumulated air during normal operation, while AVVs are able to admit or expel large quantities of air during pipeline filling, draining or transient events (Ramezani et al. 2015). A dual body CAV is usually simply the connection of an AVV with an ARV, while single body CAVs have intricate internal mechanisms that allow air venting for both near atmospheric or relatively high operational pressures (AWWA 2016). Obviously, effective air management in pipeline systems requires adequate selection, sizing, installation and maintenance of air valves. With the aim of offering to practitioners general good practice recommendations and useful insights concerning air management in pressurized systems, the American Water Works Association (AWWA) developed the “Manual of water supply practices M51” entitled “Air valves: air-release, air/vacuum and combination”. This paper discusses the conceptual strengths and shortcomings associated with the M51 manual, with a preliminary indication of supplemental literature that might be of value to readers that seek a more nuanced understanding of air management issues.

AWWA’s M51 MANUAL AS A KEY REFERENCE FOR AIR MANAGEMENT GUIDANCE

AWWA’s M51 manual is filled with insightful and relatively applicable information. The last version of the manual, in its initial section, overviews the occurrence of air in pipeline systems. The manual recommends, for example, use of volumetric solubility of air in water at standard conditions – 101 kPa and 16°C – of 2% for clean water, and of 5% for wastewater. The manual then describes the main types of air valves, and optional devices for transient control. The manual continues with suggestions regarding air valve location and sizing. According to McPherson (2012), however, the location and sizing suggestions found in the manual have the potential to be excessively conservative, leading to either too many or too-large air handling devices. Over-sized devices can lead to intense secondary transient waves, either during the filling process or after a pump trip event (Malekpour and Karney 2019, Tasca et al. 2021). After the considerations about air valve location and sizing, the manual discusses about air valves in the context of transients, recommending the use of numerical simulations for the assessment of system performance under unsteady flow. The manual then gives important and useful recommendations about air valve installation and maintenance. For example, air valves should be as close as possible to the main line according to the manual. In agreement with such recommendation, Beieler (2016) shows a practical example in which the installation of an air valve with too long connecting pipe would result in poor air venting performance. In the following, the evolution of the development of two important documents related to air valves is described: the M51 manual and the C512 standard.

About a decade before the first edition of the M51 manual in 2001, the first installment of the ANSI/AWWA C512 standard was released, namely, the C512-92 standard, entitled "Air-release, air/vacuum, and combination air valves for waterworks service". As mentioned by ANSI/AWWA (1999), the C512 standard has the goal of defining the "minimum requirements for air-release, air/vacuum, and combination air valves". To date, versions of the C512 standard were released in the following years: 1992, 1999, 2004, 2008 and 2015 (ANSI/AWWA 1992, 1999, 2004, 2008, 2015). To acknowledge the role of air valves as a means to avoid cavitation in pipelines, in the foreword of the C512-07 standard, the following section was added: "Pipeline water column separation protection". In the C512-07 standard, the minimum requirements for throttling and slow closing devices were included. This also reflects the increase of awareness regarding the whole of air valves in the context of unsteady flows. In the C512-15, the standard included specifications for the use of air valves in the context of wastewater pipe systems. This is evinced by the new title of the standard that now reads "Air-release, air/vacuum, and combination air valves for water and wastewater service".

Regarding the M51 manual, its new version released in 2016 made some advancements in relation to the previous edition. In the introduction section, the manual now includes a table with the required velocities for hydraulic removal of air from downward pipe segments and highlights the possibility of occurrence of wastewater gases in addition to regular air. In the "Types of air valves" section, the manual presents a rich set of air valve design conceptions, including air valves for wastewater applications, while also presenting the details of throttling and slow closing devices. In the "Design of valve orifice size" section, the new version of the manual changes the assumption of discharge coefficients from 0.7 to 0.6 and includes a sizing specification for partial rupture. In the "Installation, operation, maintenance, and safety" section, the new version of the manual gives a rich description of several types of air valve vaults for both above- and below-ground applications. Despite such improvements, something not so positive is also noticeable in the document: almost half of the documents referenced in the bibliography is from before 1990, showing clear disregard to more recent but important literature.

Both the M51 manual and the C512 standard were elaborated by committees that encompassed three types of professionals: general interest members, manufacturer members, and user members. Such diverse representation of various interests in the committees certainly resulted in a nuanced and good-quality text for the M51 manual and the C512 standard. However, the subject of air-water interactions in conveyance systems has gained considerable momentum in the scientific community – a category of professionals mostly absent in the aforementioned committees. Naturally, the scope of the M51 manual is mostly to provide practitioners with a basic understanding of air valve application, as stated in the preface of the 2016 version: "information contained in this manual is useful … for gaining a basic understanding of the use and application of air valves". However, insights and more in-depth explorations found in the scientific literature of the last years have the potential of improving the results of air management strategies applied by manufacturers and practitioners. The contribution of the remaining of this paper comes from its discussions about important "residual issues" related to air management, which are not presented with sufficient depth in the manual.

PIPELINE FILLING

The M51 manual is objective and quite economical with its recommendations about pipeline filling. The rule of thumb of not surpassing a water filling velocity of 0.3 m/s for filling is suggested in the manual – with such velocity being relative to the whole cross-sectional area of the pipe. The essence behind such rule of thumb is that pipeline filling should be done slowly. As water enters a piping system in a controlled manner, an equivalent quantity of air volume should be vented out of the line. To achieve the goal of controlled pipeline filling, a variable speed pumping system and/or throttling mechanism could be used at the upstream end of the line. If water indeed enters the system in a sufficiently gradual manner, only a mild surge event will result from the water front reaching the far end of the line and thus being suddenly stopped. A common assumption for the differential pressure across an air valve during air expulsion is using a value of about 14 kPa. Such differential pressure, together with a discharge coefficient of 0.6 for the air valve, may be used to approximate the orifice size required for filling/venting. However, if a line is filled rapidly, either intentionally or by mistake, important transient pressure oscillations can occur. Nonetheless, the section of the manual regarding pipeline filling is rather short. In contrast, the literature about pipeline filling is rich, with several important examples published in the last few years – in this sense, just as examples, the following works could be mentioned: Fuertes et al. (2019), Tijsseling et al. (2019), Zhou et al. (2019), Zhou et al. (2020), Romero et al. (2020), Coronado et al. (2020).

To reveal some of the key aspects of the pipeline filling phenomenon, in the following, some of the experimental results obtained by Martins (2013) are analysed – with Figure 1(a) showing the experimental testing bench. The key components of the pipe filling tests include an upstream pressurized tank and valve, a downstream vertical pipe segment, a horizontal pipe segment connecting the tank to the vertical pipe segment, with a downstream entrapped air pocket at the vertical pipe segment. The quantities of interest in the experiments are as follows: pressure in the upstream pressurized tank p^*_{R0}, initial pressure in the downstream air pocket p^*_{a0}, length of the downstream air pocket L_{a0}, and maximum piezometric head in the system h^*_{max} during the transient phenomenon. From the experimental tests, it was verified that larger values of p^*_{R0} would result in higher amplitudes of the transient oscillations. Also, as L_{a0} increases, the frequency of oscillations decreases, which is nicely represented in Figure 1(b). However, as p^*_{R0} increases, the frequency of oscillations increases. For a given pressure at the upstream tank and initial pressure at the downstream air pocket, for example with

p^*_{a0} equals to 1.0 bar as in Figure 1(c), as the air pocket length L_{a0} increases, the maximum pressure h^*_{max} initially increases. However, as observed in Figure 1(c) for p^*_{R0} equals to 1.5 bar, for L_{a0} values beyond 0.5 m, h^*_{max} starts to decrease. Moreover, the behaviour of the air-water interface is strongly affected by the initial characteristics of the entrapped air pocket. Initial air pocket pressure p^*_{a0} plays a relevant role in containing the deformation assumed by the air-water front. The information depicted in Figure 1 gives some insight into the process of pipe filling without air venting, yet the design avoids the often-difficult complication of air motion that can be mobilized during certain transient events. Later in this paper, the also important phenomenon of pipeline filling with air venting is discussed.

In relation to modelling approaches that could be used to simulate the pipeline filling phenomenon, Fuertes et al. (2019) give a broad description of commonly used strategies – which include the rigid water column model (RWCM), the method of characteristics (MOC), and computational fluid dynamics (CFD). Malekpour and Karney (2019) for example used the Storm Water Management Model (SWMM) application to numerically simulate the filling process of a gravity pipeline.

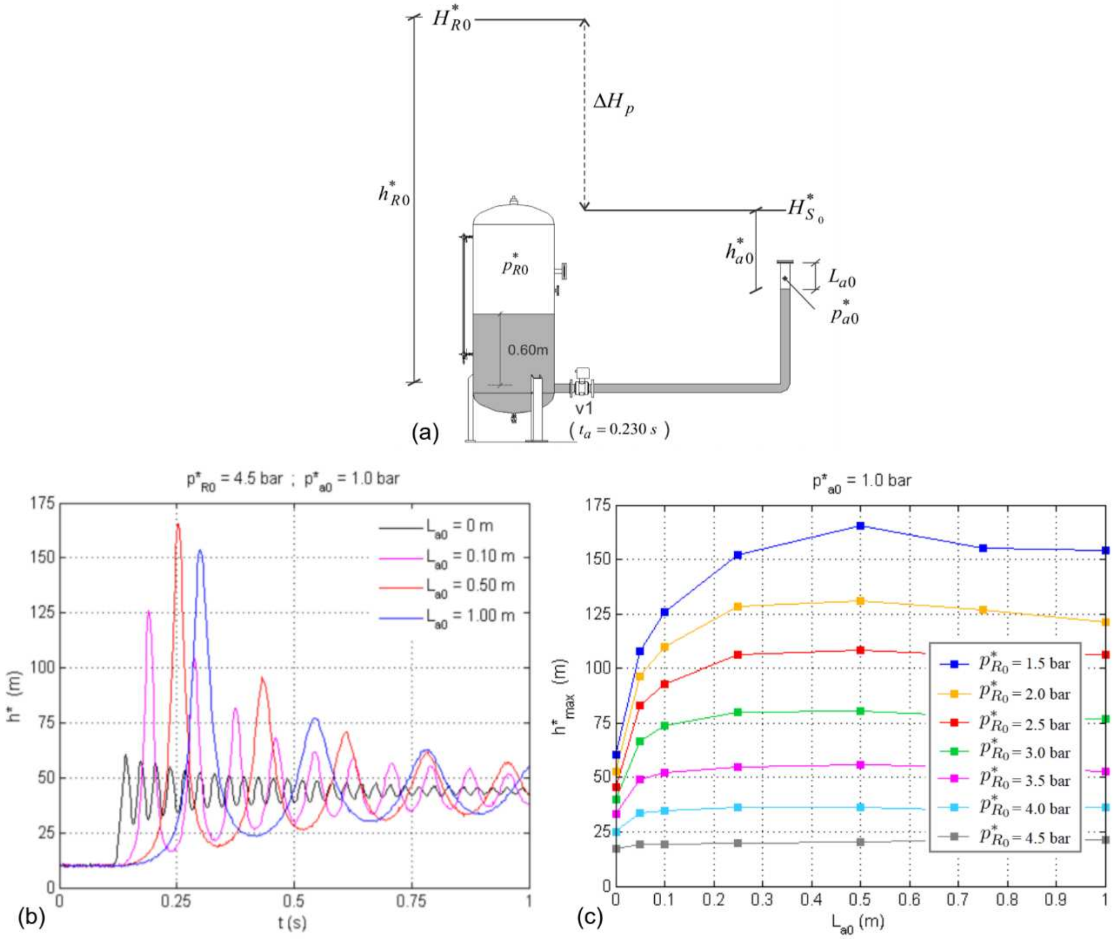

Figure 1. Confined pipe filling with entrapped air pocket: (a) experimental scheme; (b) transient piezometric heads; (c) maximum piezometric head for different filling pressure loads as a function of entrapped air size – adapted from Martins (2013).

PIPELINE DRAINING

M51 recommends a maximum water draining velocity from 0.3 to 0.6 m/s with air valves installed at the highest point close to a drainage valve. The valve should be able to admit air at the same volumetric rate as the rate with which water is expected to leave the line. In addition to regular controlled draining, the manual presents some useful information regarding pipeline drainage in the context of gravity flow and partial pipe rupture. Gravity water flow, in particular, may become problematic for systems with large-diameter pipes with low stiffness. Such systems must be protected against sub-atmospheric pressures, which could be achieved with sufficiently sized air valves or well planned and accurate drainage procedures. The manual, despite giving considerable attention to pipeline draining, fails to address some important issues: the phenomenon of backflow air intrusion, and the influence of initial air pocket size and drainage valve maneuver on pressure fluctuations. Such issues should be carefully considered, especially in the context of gravity draining operations for which water columns tend to drop rapidly (Besharat et al. 2018).

As the draining process starts, the pressure of the entrapped air pocket starts to decrease, leading to a minimum pressure value that is mostly dependent on air pocket size and pipeline slope. Low pressure values, however, may happen again in the following oscillations. Pressure fluctuation is mostly dependent on how the draining operation proceeds in terms of the backflow air intrusion. Backflow air intrusion is highly dependent on the opening percentage of the drainage valve. For partial openings, backflow air intrusion is not considerable. But for the full opening of the draining valve, a significant amount of air may enter the pipeline from the downstream end. Simulations using CFD models show that the draining process with backflow air intrusion is characterized by consecutive expansion and contraction of the entrapped air pocket – pulsatile flow. Downstream air intrusion can be considered beneficial for line safety. Air intrusion is especially important for the draining of systems with faulty or absent air valves. Nevertheless, for a draining situation with a partially opened drainage valve that only allows slow draining velocities, the absence of backflow air intrusion is not expected to be problematic.

For the draining of systems protected by air valves, pressure oscillations will be dependent on line characteristics and air valve capacity. Figure 2 shows the time evolution of pressure for the draining process of a system with a distinct high point with an air valve. In Figure 2(a), the drop in pressure as the draining valve is opened is sharp and much more pronounced than for the case depicted in Figure 2(b). Such difference in system behaviour is caused by two main reasons. First, for the case depicted in Figure 2(a), the air valve is rather small, while for the case in Figure 2(b), the air valve is large. As air valve capacity increases, pressure fluctuations are attenuated. Also, the volume of the entrapped air pocket is negligible for the case depicted in Figure 2(a) but is considerably large for the case depicted in Figure 2(b). For larger initial volumes of entrapped air, more attenuated pressure oscillations are expected.

To numerically simulate pressure and velocity oscillations during the draining process in an undulating pipeline, one of several numerical approaches could be chosen. Despite the natural disposition of detailed and complex numerical approaches of giving very accurate results, the use of rather simple models might be sufficient for engineering applications. Coronado et al. (2017) show that the RWCM can predict with reasonable accuracy the pressure and velocity fluctuations during pipeline draining events. If a more in detail analysis is desired, as shown by Besharat et al. (2020), CFD could be used to simulate pipeline draining. As discussed here and highlighted by Besharat et al. (2021), as well by Rokhzadi and Fuamba (2021) who applied the modified Saint-Venant equations with the polytropic relationship to study pipeline draining, each numerical approach has its own strengths and disadvantages, and thus the suitability of a numerical approach must be evaluated considering the main simulation objectives.

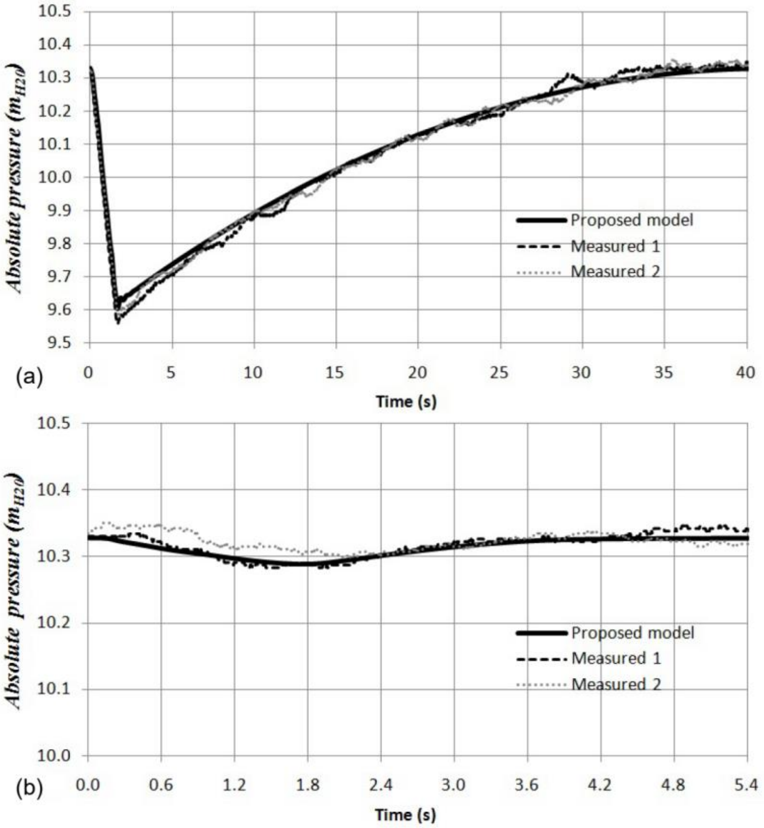

Figure 2. Comparison between model and measurement for the draining process of a test pipeline: (a) line with small air valve; (b) line with large air valve – adapted from Coronado et al. (2017).

AIR VENTING STRATEGIES WITH AIR VALVES

Several sizing hypotheses need to be balanced when developing an air venting solution for a pipeline system – pipeline filling, controlled and uncontrolled draining, and transient flow scenarios. As these operational issues vary so profoundly, competing needs are thus almost inevitable in the sizing process and need to be effectively resolved. For draining, the manual gives sizing indication for controlled draining, gravity flow and partial rupture. Between these three sizing scenarios, gravity flow is expected to lead to the largest recommendations for AVV orifices. However, large orifices are generally detrimental for venting performance during transient events, though they are generally adequate for slow pipeline filling. From the impossibility of effectively resolving conflicting needs with a usual AVV design, manufacturers developed air valves with internal anti-slam mechanisms, and optional devices for transient control to be installed at the inlet or outlet of air valves. AVVs with internal anti-slam mechanisms are designed to admit air through the large orifice when under near atmospheric pressures but restrict outflow if the internal pressure surpasses a certain threshold. Ramezani and Daviau (2021) numerically explore the efficacy of air valves with internal anti-slam mechanisms against hydraulic transients. Experimental research shows that the expulsion of air – pushed by a moving water column – through small orifices can be beneficial for transient attenuation (Zhou et al. 2002).

WATER HAMMER AND AIR POCKETS

M51 gives general recommendations regarding the application of air valves in the context of hydraulic transients. According to the manual, air valves should be considered at the discharge of vertical turbine or deep-well pumps, before respective check valves, to expel air upon pump start-up and admit air upon pump shut-off. The duality of air pocket behavior is highlighted by the manual: air pockets may be responsible for transient pressures as they move throughout a line, but can also function as inline accumulators, attenuating transient pressures. Given the limited scope of the manual, not much detail is given about the specifics of transient events with air in pressurized systems. In the following, the influence of air in the context of unsteady pipeline flow is briefly explored in three ways: filling of a pipeline with confined air pocket, filling of a pipeline with entrapped air pocket and downstream orifice, water hammer event due to a pump trip scenario in a hilly pipeline with protective air valve.

For only one confined air pocket during the rapid filling of a pipeline, abnormal pressures may occur, which have the potential of damaging the structural integrity of the system (Zhou et al. 2013). Maximum pressure occurs during the first compression of the entrapped air pocket, with subsequent pressure peaks being gradually dampened. Zhou et al. (2018) did both experiments and simulations of the phenomenon of filling for a horizontal-vertical test pipe. It was found that temperature variations in the air phase are important during fast transients. A representative set of the results from such research is depicted in Figure 3. In Figure 3(a), it can be observed for example that the air-water interfaces do not occur according to the commonly assumed piston-flow shape. Also, for $t = 0.95$ s, air-water mixture is meaningful, and thermal conduction and convection between the air and water phases have an important role in the phenomenon. Figure 3(b) shows the time evolution of pressure values according to experimental and CFD results. The agreement is excellent between measurement and theory, especially for the first two pressure peaks. Employing CFD techniques for the numerical simulation of large-scale systems, however, might not always be practical, given the relatively extended time and spatial scales that need to be considered. In summary, the information depicted in Figure 3 can be interpreted in two somewhat opposing ways: first, air-water interactions can be exceedingly complex, often appearing to occur in a rather random manner; second, despite such complexity, it is possible – not necessarily practical – to compute with good accuracy the important parameters of air-water interactions during fast line filling.

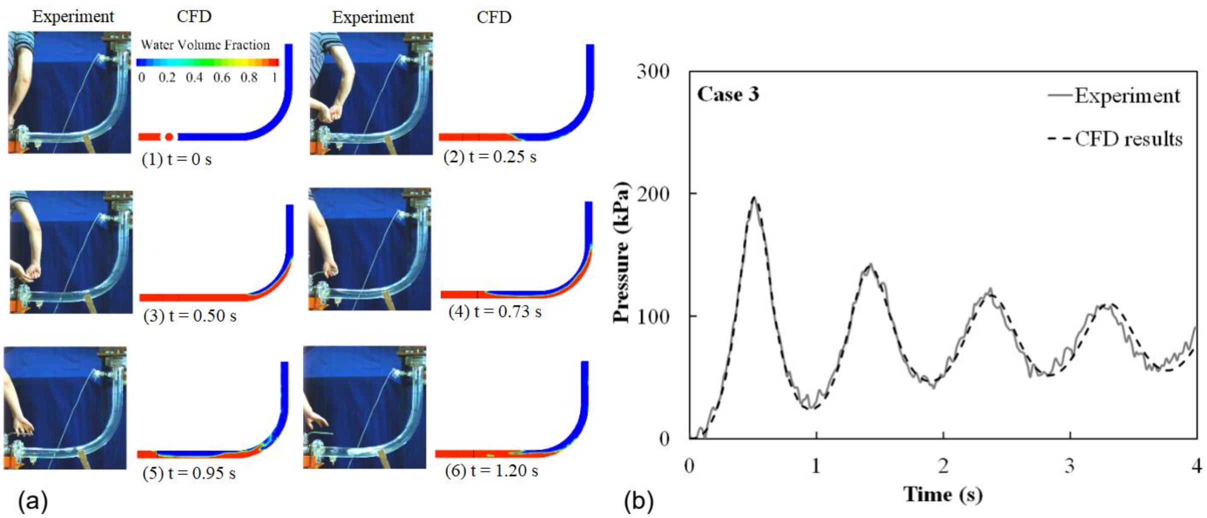

Figure 3. Air-water interaction in horizontal-vertical pipe: (a) pictures taken during the tests with corresponding CFD results; (b) measured and computed pressure oscillations – adapted from Zhou et al. (2018).

For pipeline filling with air venting, the transient phenomenon has some peculiar characteristics, which were classified by Zhou et al. (2002) in three categories: negligible water hammer effect for small downstream orifice less than 0.086*D* (with *D* as the diameter of the pipe); mitigated water hammer effect for intermediary sizes of downstream orifice (between 0.086*D* and 0.2*D*); and water hammer dominated event for downstream orifice beyond 0.2*D*. The highest peak pressures, up to 15 times the upstream head, were observed at a critical orifice size around $d/D = 0.2$. Indeed, Albertson and Andrews (1971) did report that the rapid air expulsion from an air valve may cause dangerous transient pressures during the filling process of a pipeline. Interestingly, for medium orifice sizes near the critical value, the explanation of Zhou et al. (2002) that the impacting water hammer causes the pressure peaks is notably different from the "rapid air compression" arguments of Martin and Lee (2000, 2012) and Lee (2005). As mentioned by Lingireddy et al. (2004), reducing the size of the outlet orifice of an air valve for expulsion may be advantageous for controlling secondary water hammer pressure waves during hydraulic transients. For inflow, however, the size of the outlet orifice of the air valve should be large enough to admit air freely, thus avoiding cavitation if pressure becomes sub-atmospheric at the air valve location.

If an upstream flow is quickly curtailed, say due to a failing pump or a suddenly closed valve, a wave of reduced pressure is initiated and propagates downstream. If the down-surge is not attenuated by the action of a protection device – a hydropneumatic tank for example – and there is a distinct high point in the profile, the reduced pressure wave has the potential to cause sub-atmospheric pressures at such high elevation point. Usually, for a situation as the one presented in Figure 4, if the down-surge is intense, both the upward pipe segment upstream of the high point and the upstream segment near the downstream reservoir are expected to experience sub-atmospheric pressures. Nevertheless, the presence of an air valve at the high point has the potential of mitigating transient events with down-surges (Ramezani and Karney 2017). Figure 4 shows the difference in behavior between a line without air venting and a line protected by the presence of air valve at its high point. In Figure 4(b), for the line with air valve, the hydraulic grade line right before air valve closure is well behaved, while in Figure 4(a), for the line without air valve, the hydraulic line is quite erratic (Tasca et al. 2021).

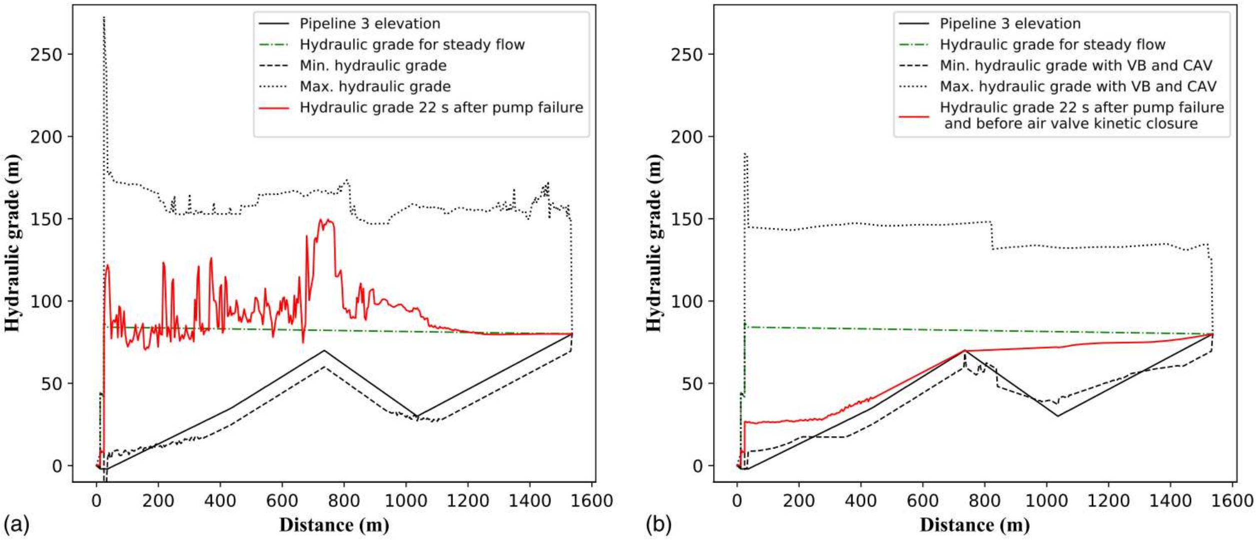

Figure 4. Hydraulic grade line after a pump trip event in a water rising pipeline: (a) line without air valve at high point; (b) line with air valve at high point – from Tasca et al. (2021).

EMPLOYING SIMPLE SOLUTIONS TO COMPLEX AIR-RELATED ISSUES IN PRESSURIZED SYSTEMS

Even when considering the hypothesis of well-defined initial conditions for transient events with important air-water interactions, eventual simplifications and limitations of numerical models may result in inaccuracies in the outcome of numerical simulations. To make matters worse, in general, well defined initial conditions are only assured in the context of controlled experimental setups. Usual sources of uncertainty in pipeline simulations are wave speeds, friction factors, and location of leaks. Examples of air-related sources of uncertainty in pipeline simulations are the location and size of air pockets, amount of dissolved air in water, and whether specific air valves are active or functioning as expected. Thus, it is important to evaluate the sensitivity of a system's transient behaviour to the uncertainty of input parameters and limitations of computer models. Commonly applied air management strategies, however, are often guided by simplistic sizing criteria applied to narrowly defined conditions. For example, the air valve sizing result obtained to comply with a given loading condition may very well get in conflict with the sizing result obtained for a complementary condition. Therefore, an important goal of future research is the development of sound integrative air management solutions – solutions that consider the complexities and uncertainties in transient events with air-water interactions, a sufficiently wide range of expected air-related loadings, and limitations of numerical modeling approaches used in pipeline design and assessment.

SUMMARY

The analyses summarized in this paper give a glimpse into the complexity of air-water interactions in pressurized pipeline systems. The presence of air and water is often problematic and sometimes the recommended practices for the different operational requirements are in conflict. This paper particularly overviews some of the operational challenges related to entrapped air pockets in pressurized pipeline systems. Special attention is given to air management strategies that include the application of air valves. Specifically, the paper explores the strengths and weakness of the M51 manual by AWWA, a central and widely used reference document. The paper also discusses the C512 standard by ANSI/AWWA, which is a complementary document to the M51 manual. The paper explores, illustrated by examples from the literature, some of the important air related operational issues including pipeline filling and draining, application of air valves, and the influence of air pockets during transient events. Overall, the present work can be viewed as a "next step investigation" into the residual air-related issues that are not fully resolved in the M51 manual. The ideas presented in this paper are to be further elaborated in the upcoming monograph developed by the Task Committee "Two-phase Flow in Urban Water Systems".

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