Encouraging Effective Air Management in Water Pipelines: A Critical Review

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Abstract: Air can be entrapped in water and wastewater systems under a variety of conditions, and if such air is not managed properly, it can impose considerable operational penalties. To avoid these problems and the dangers associated with air pockets, several air management strategies have been routinely suggested. However, the devastating consequences of air pockets frequently documented in the literature imply the need for further development in this area. Improving air management obviously requires a thorough understanding of the current strategies and their shortcomings. This paper overviews the sources of air in pipes and key consequences associated with its presence. Current measures for managing air in water pipes are reviewed and critiqued. Finally, knowledge gaps that limit the efficient application of current air management strategies to real world problems are identified, and suggestions for future development are presented. DOI: 10.1061/(ASCE)WR.1943-5452.0000695. © 2016 American Society of Civil Engineers.

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Introduction

The presence of air in water pipelines can pose a threat to these crucial conveyance systems. Air can be present in water pipes either as small-scale bubbles or as large-scale air pockets. One of the principal ongoing sources of air in an operating pipeline is the small-scale air release from supersaturated water, typically when water is present at lower pressures or higher temperatures than at its equilibrium state. That is, dissolved air in saturated water—up to approximately 2% by volume (Dean 1999)—can be released when water temperature increases or when system pressures drop. Another source of air is the large-scale atmospheric entrainment through pump inlets, downstream of dropshafts, or at leaky valves. Furthermore, air can be entrapped downstream of check towers and during initial filling of pipelines (Colgate 1966). Finally, during transient-induced low pressures, large-scale air is sometimes intentionally admitted through air vacuum valves (AVVs) to limit negative pressures. In such conditions, after suppression of negative pressure, air should be removed from the pipe through the outlet of AVVs. However, under certain conditions, such valves can malfunction or close prematurely, or allow air to be swept downstream, often resulting in air entrapment, a potentially destructive outcome.

Problems induced by entrapped air range from mild (potentially costly) to severe (potentially devastating). The damage caused by the presence of air pockets is a function of air pocket location, size, mobility, system configuration, and flow regime (i.e., either steady-state or transient conditions, and the state of turbulence). In transient conditions, amplified overpressures can result during system start-ups because of the compression of the entrapped air. Also, both the movement of air pockets and rapid air release can induce the occurrence of high-pressure spikes. Even under steady flow conditions, a reduction in pump and turbine efficiency and a decrease of flow capacity often occur because of the concentrated head loss associated with the throttling of flow at the air pocket. This issue was verified by Escarameia (2007), whose results confirmed head losses as much as 25–35% across air pockets of 6 ml to 5 l at slopes of 2.5° and 3.4° in a 3-m long pipe with 150-mm diameter. Hence, to overcome the extra head loss and to maintain system discharge, pumps often operate at higher heads. This often leads to increased electrical consumption and inefficient performance. Also, air can influence the pipe material through corrosion, resulting in rapid deterioration of water infrastructure (Bowker et al. 1992) and perhaps water quality. In sewer systems, the presence of gas pockets facilitates creation of hydrogen sulfide pockets and the corresponding pipe corrosion. Understanding the places in which air pockets can accumulate helps to identify regions prone to corrosion. Walski et al. (1994) suggested predictive methods for identifying the locations along sewer mains at which the presence of such gas pockets can cause corrosion. The consequences of entrapped air pockets, therefore, justify a thoughtful and efficient air management strategy to prevent air entrainment or to remove entrapped air. Stated more positively, curbing entrapped air can enhance system control and boost both operational performance and energy efficiency.

Improving air management in water or wastewater systems and proposing innovative solutions benefit from an extensive review of current air management strategies and an identification of the gaps in existing knowledge. Previous reviews (Escarameia 2007, Lauchlan et al. 2005) focus on one air management strategy (i.e., hydraulically removing air from pipes) and specifically on the so-called clearing velocity of the fluid (i.e., the required velocity to transport air bubbles downstream). The current paper summarizes the issues created by air in water or wastewater systems, and two specific air management strategies are discussed and critiqued. Knowledge gaps that limit an efficient application of air management strategies to real-world applications are tentatively identified and suggestions for future work presented.
Sources of Air in Pipes

The air entrained into a system can be categorized either as small bubbles or larger air pockets. The entrained air bubbles tend to collect at high points along an undulating profile and, thus, can gradually accumulate to form larger air pockets.

Small Bubbles

A key source of free air is the up to 2% dissolved air (Dean 1999) in water, which can be released from solution as small air bubbles because of a pressure drop or temperature rise. Low-pressure zones tend to occur at high points along an undulating pipeline or within partially open valves. Dissolved air also comes out of solution because of turbulence and temperature increases because warmer water permits less dissolved air at saturation, and turbulence enhances the gas exchange process.

Large Volume Air in Water Distribution Systems

Large air volumes can occur in pipeline systems for a remarkable number of reasons. Air can enter pipes and be trapped at high points during rapid filling operations (Lauchlan et al. 2005). Sometimes air is admitted intentionally through AVVs to limit vacuum conditions and low pressures. When pressures rise, this admitted air should be removed; however, the premature closure of AVVs may hamper this. Air can enter through small cracks and broken pipes in regions of negative pressure. Air can be trapped downstream of check towers or in siphons and pipe bends (Colgate 1966). Air may enter through turbulence in several ways: from falling jets from the collectors in the pump sump (Fig. 1), at pump inlets because of free surface vortex generation (Denny 1956), or at drop chambers and dropshafts through plunging jets (Fig. 2). The air entrainment ratio depends on jet length and velocity, nozzle design and diameter, the angle of jet inclination, and the physical properties of liquid. An extensive survey of the early available experimental and theoretical studies on gas entrainment associated with plunging liquid jets (e.g., empirical formulas for gas entrainment rates) is presented by Bin (1993).

Large Volume Air in Sewer Systems

In addition to the previous issues, there is a special air process in sewer systems. This is when air is trapped during a surcharge event or during the transition of gravity flow to surcharge flow. The three stages during which such a transition occurs are surge formation, interface instability, and transition to surcharged flow (Hamam and McCorquodale 1982). Also, air pocket formation is common when ventilation is inadequate. In such conditions, entrapment of an air pocket depends on inflow rates and system geometry. In particular, air entrapment is more likely at low inflow rates that cause open-channel bores and an air layer at the pipe crown. Reflection of such inflow fronts from system boundaries can cause air pockets to be trapped. To avoid air pocket formation, adequate ventilation should be provided (Vasconcelos and Wright 2006). One of the elements of urban drainage systems is the drop manhole in which the falling of storm water or wastewater causes severe turbulence and significant air entrainment. Inadequate ventilation in such application can lead to negative pressures with an increase in pool depths (Granata et al. 2015).

In conventional gravity-fed and siphonic roof drainage systems, significant air entrainment often occurs. Despite the negative effect of air entrainment on maximum system capacity, operational pressures, friction and form losses, and gutter water depths in siphonic systems, air entrainment tends to limit negative pressures in tall siphonic systems and controls the onset of cavitation in vertical downpipes (Beecham and Lucke 2015).

Consequences of Entrapped Air Pocket and Air Release

The large-scale air pockets trapped either during filling of water transmission pipelines or during surcharging of sewer systems
can be detrimental because of transient-induced high pressures. Also, release of such trapped air pockets, particularly if done thoughtlessly, sometimes creates high pressures. Of great importance are the pressure surges occurring because of compression of such entrapped air pockets during transient conditions and during sudden release through the nearby air vents. Such high-pressure surges often have destructive consequences on the built infrastructure.

**Transient Pressures because of Entrapped Air**

In sewer systems, factors affecting transient pressures because of the transition of gravity flow to pressurized flow and the resulting air entrapment are pipe size, shape, slope, material, water velocity, Froude number, relative depth of flow (i.e., depth of open channel flow to pipe diameter), venting arrangements, and boundary conditions (e.g., drop pipes, pumps, interceptors) (Hamam and McCorquodale 1982). Air pocket volume, initial flow rate, pipe slope and the degree to which flow is obstructed are other factors affecting this pressure peak and the shape of pressure history. The distance between the location of air pocket compression and the pressure relief location is also influential (Vasconcelos and Leite 2012). Moreover, the magnitude of peak pressure depends on whether the flow is fully or partially obstructed; partial obstruction usually results in lower peak pressures and fewer oscillatory pressure surges. There are several published numerical models for simulating flow regime transition in sewer systems by accounting for the effect of air pocket effects in the formulations. Vasconcelos et al. (2015) provided a comparative study of recent models that account for air effects and of previous models that neglect this feature.

The effect of trapped air on transient-induced pressures during rapid filling depends both on the length of initial water column and the initial water depth. Larger air pockets tend to mitigate pressure surges (Zhou et al. 2002a, b, 2004). Generally, start-ups (i.e., pressurization) of systems containing entrapped air require greater care. Challenging conditions occur during operation of intermittent undulating pipelines. The presence of air pockets can lead to high pressure spikes during start-up. A mathematical model for undulating pipelines containing trapped air confirmed that the more slowly the pipes are filled, the smaller the transient pressures (Izquierdo et al. 1999). Under start-up conditions, the initial volume of air pockets greatly influences the peak pressures. Also, ignoring elastic effects tends to overestimate the maximum pressure (Zhang and Vairavamoorthy 2006a). Furthermore, in rapid filling of systems with entrapped air, the effect of transient shear stress between the pipe wall and flow, and initial pressure of air pocket on transient pressures, is negligible (Zhang and Vairavamoorthy 2006b).

**Entrapped Air and Its Effect on System Dynamics**

The presence of air in water pipes can strongly influence system dynamics. For example, spectral analysis of experimental pressure time series confirms that air pockets increase the wave travel time because of a decrease in the wave speed. Reduction of the first peak in the frequency domain of the pressure time series verifies the increase in wave travel time. Of course, this depends on air pocket size and location, with larger pockets creating a greater increase in wave travel time (Covas et al. 2006; Lubbers and Clemens 2005a, 2007). The influence of air pockets farther from a pump is low. In a pumping system, the duration of low pressures at locations farther downstream reduces; thus, downstream air pockets experience low pressures for shorter periods and have smaller volumes. Hence, their effect on wave speed is lower compared to air pockets immediately downstream from the pump. This characteristic has been applied to detect the presence of air pockets along pipes by physical and numerical model studies and to explore whether the presence of air pockets accounts for capacity reduction of a pressure main (Lubbers and Clemens 2005a, 2007). However, such an approach requires prior knowledge of the location of the air pocket. However, recorded pressure spikes and the subsequent low pressure at air pocket locations, and the reduction in wave travel time, all can be used as indicators to estimate the location and size of air pockets in experimental facilities and real-life systems using an inverse transient solver (Covas et al. 2006). Such methods of air pocket detection have considerable potential for the design and operation of water pipes.

**Head Loss because of Entrapped Air**

Another consequence of entrapped air pockets is the increased head loss and energy consumption often associated with their presence. Because head losses are proportional to the square of the velocity, head loss is magnified at flow constrictions. For example, a 10% air volume in the pipe can cause a 20% increase in head loss (Stephenson 1997). Escarameria (2007) confirmed head losses across air pockets were 25–35% greater than in otherwise identical air-free pipes. Submerged hydraulic jumps at the terminal end of air pockets also can generate head loss; however, hydraulic jumps also can facilitate air removal. The transport capacity in wastewater systems is often reduced because of the presence of accumulated air pockets (Lubbers and Clemens 2005b). Under many conditions, the head loss associated with a gas pocket is easily estimated as

$$L_p = \frac{\sin \theta}{L_g},$$

where $L_p$ is the length of a gas pocket and $\theta$ is the pipe angle with horizontal (Pothof et al. 2013, Lubbers 2007).

Experimental data confirms that head loss is a function of conduit geometry (e.g., slope), air-packet length, and surface tension. Also, head loss increases with drag and turbulence (Lubbers and Clemens 2005b). Furthermore, air-pocket head loss has a reciprocal relationship with flow number and pipe Weber number, and a direct relationship with surface tension (Pothof et al. 2013). Surface tension influences head loss by enhancing the transport capacity of air in downward-sloping pipes or by reducing air accumulation. According to published experimental data, although the artificial reduction in surface tension of water (surfactant-added water) increases the air transport capacity of water, the reduced surface tension in real-world domestic wastewater (caused by proteins and surfactant additives) is usually insufficient to increase air transport in downward-sloping pipes (Pothof et al. 2013).

The consequence of entrapped air in water pipes under steady-state conditions (i.e., head loss) has received remarkably little attention in the literature. The available studies on air-pocket head loss (Posoz et al. 2010a; Lubbers and Clemens 2005b) cover only the low-operating pressure conditions that are more common in sewer systems than in pressurized water mains. Except for the limited measured air-pocket head losses reported by Escarameria (2007), other experimental data have been obtained under pressurized conditions slightly above atmospheric pressures (Posoz et al. 2010a; Lubbers and Clemens 2005b).

It is clearly questionable to apply the results of such low-pressure studies to pressurized water mains in which pressures are significantly higher. For example, in systems with a high point (Fig. 3), the size of the entrapped air-pocket volume at the high point and the associated head loss would be a function of the magnitude of pressure at the high-point location. However, such relationships have yet to be published and probably evolve over time because of gas dissolution and release.

To estimate the head loss because of an air pocket in pressurized conditions, the capacity of air accumulation in the most susceptible
locations along pipelines (i.e., high points) should be studied first. This could, in theory, be investigated numerically by applying sophisticated computational fluid dynamics (CFD) modeling, but it would require a systematic exploration of air-pocket volumes at high points with different slopes and geometries (Pothof et al. 2013).

However, to provide a first-order estimate, Fig. 3 depicts the steady-state hydraulic grade line (HGL) of a pressurized water main with an air pocket at the high point. In such systems, depending on the magnitude of pressure at the high points, air-pocket volume and the associated head loss would be expected to be different. In this paper, such a relationship is illustrated through an example by adopting some preliminary assumptions. Fig. 3 shows that before the pipe is filled, the air volume in the pipe is equal to the pipe volume under atmospheric pressure. It is assumed that all of this initial air is entrapped and distributed along the descending portion of the high point after the pipe is filled and a steady-state flow occurs. Neglecting local inlet and outlet losses, Fig. 3 shows the steady-state HGL. It is assumed that air expansion and compression follows polytropic relations, and that air-pocket head loss can be computed by trial and error for the steady flow and, consequently, the air-pocket head loss. In the system under study (Fig. 3), \(H_1\) (m), \(H_2\) (m), and \(f\) are 100, 50, and 0.017, respectively. Each pipe length \(L_1, L_2, L_3, L_4\), and \(L_5\) is 500 m. The steady-state discharge \((Q)\) and air-pocket head loss \(\left(h_f\right)_{\text{air}}\) are computed by Eqs. (3) and (2), respectively, at different high-point elevations.

The results of this operation are shown in Fig. 4. Air-pocket volume \(\left(V_{\text{air}}\right)\), its associated head loss \(\left(h_f\right)_{\text{air}}\), and the final steady-state discharge \((Q)\) are shown to vary for different high-point elevations. As the high-point elevation decreases, the pressure \(\left(H_p/\Delta H\right)\) increases, and therefore, both the entrapped air-pocket volume and the associated head loss are reduced. Although approximate, such quantification is helpful and justifies a more detailed and accurate study on this subject under pressurized conditions.

\[
P_{\text{air}} V_{\text{air}}^{1.2} = C \tag{1}
\]

\[
h_f = S_l^{1.2} \tag{2}
\]

where \(P_{\text{air}} = \) air-pocket pressure; \(V_{\text{air}} = \) air-pocket volume; \(C = \) constant; \(h_f = \) air-pocket head loss; \(S_2 = \frac{L_2}{L_1} = \) high-point slope; and \(l_{\text{air}} = \) air-pocket length

\[
H_1 - f \frac{L_1 Q^2}{D_1^2 g A_1^2} - f \frac{L_2 Q^2}{D_2^2 g A_2^2} - S_2 = 0
\]

\[
\times \left\{ \left[ \frac{C}{\left( H_1 - f \frac{L_1 Q^2}{D_1^2 g A_1^2} - f \frac{L_2 Q^2}{D_2^2 g A_2^2} - Z \right) \frac{H_1}{H_2} } \right]^{1/2} \right\}
\]

\[
-f \frac{L_3 Q^2}{D_3^2 g A_3^2} - f \frac{L_4 Q^2}{D_4^2 g A_4^2} - H_2 = 0 \tag{3}
\]

\[\text{Fig. 3. Steady-state HGL in a system containing entrapped air pocket at the high point and the associated head loss}\]

\[\text{Fig. 4. Effect of water pressure on air-pocket volume, the corresponding head loss, and the resulting steady-state flow in a pressurized water main as depicted in Fig. 3; } Q_0 \text{ is the steady-state discharge in the system without the presence of air pocket}\]

\section*{Geysering because of Air Release}

In storm or combined sewer systems, entrapped air might be released through partially filled vertical shafts (so-called manholes or gullies). This event is defined as geysering, and air interactions play key roles in its formation. That is, large air pockets with high upward velocities enter partially filled manholes. These air pockets entrain water droplets and carry them upwards forming a geyser (Wright et al. 2011). Geyser events may cause water jets to rise to a considerable height above ground level. In some cases, the associated pressure spikes have been known to reach up to 11 times the upstream pressure head (Zhou et al. 2004).

Several kinds of events—high air-release velocity from manholes during surcharging, and geysering in sewer systems and from air vents during filling of water pipes—can damage hydraulic structures. For instance, high air-release rates because of rapid filling have been reported to have damaged trash racks at the outlet works of Dillon Dam in Colorado (Falvey and Weldon 2002). Hydraulic and structural analysis performed by Pozos-Estrada et al. (2015) confirmed that rapid filling and sudden air pocket release from the manhole caused severe pressure fluctuation inside the drainage tunnel of the western area of Mexico City, and led to the tunnel bursting and a fatality. Also, surcharging has led to associated destructive geysering in the Minneapolis storm water collection system (Wright et al. 2011) and at the Gallagher Hill Park manhole in the Bonnie Doon area of the City of Edmonton, Canada, drainage system (Zhou et al. 2004). Other examples include the blowing off of manhole covers in sewer systems of Amherstburg and Hamilton, Ontario, Canada, during high inflows (Hamam and McCorquodale 1982). Related events have occurred at hydropower plants because of entrained air within a hydraulic jump in a portion of pipes (Nielsen and Davis 2009). There are published sets of experimental data (Li and McCorquodale 1999) and field measurements (Wright et al. 2011) regarding geysering. Also, hydraulic behavior of a gully is presented through numerical and experimental data after pressurization of a sewer system (Lopes et al. 2015).

\section*{Studies of the Consequences of Air Release}

Air release from pipes has been the subject of several studies. Such studies have concentrated on air release into either an air or a water medium. The physics of flow between these two cases is markedly different. Experimental and numerical studies have been performed to understand the effect of air release into the atmosphere on the...
resulting pressure rises in rapidly filling pipelines (Zhou et al. 2004; Zhou et al. 2002a; Martin and Lee 2000; Lee and Martin 1999; Martin 1976). Also, photographic data regarding air-water behavior patterns in rapidly filling horizontal pipelines is presented by Zhou et al. (2002b). Published studies have tended to focus on the air release to the air medium.

Only a few studies have considered air release into a depth of water. In situations in which air is released through a submerged outlet structure, the induced pressures have negative consequences. For example, Falvey and Weldon (2002) studied air release from the outlet structure of the Dillon Dam in Colorado and determined that the drag force created by the air was high enough to move the 12.9 kN outlet trash racks. Such findings emphasize the need for research to explore influential parameters on such destructive consequences and to propose preventive measures, whether during design or operation. Establishing an efficient filling procedure and restricting air release can solve many of the problems resulting from air release from pipes or geysering through air vents.

**Transient Pressures because of Air Release**

According to the results obtained by Zhou et al. (2002b), the period of the pressure oscillation and magnitude of maximum pressure depends on the size of the entrapped air pocket during filling, the available hydraulic head, and the air-release rate. For instance, for high upstream head and small air volume, the period of pressure oscillation is short and peak pressures are high. For minimal and zero air release, water hammer effects usually can be neglected. For large air release, air-cushioning effects diminish and water-hammer effects dominate. However, for intermediate rates of air release, the water-hammer effect is usually quite small. Generally, the resulting high pressure depends on the orifice size of air release (Zhou et al. 2002a, b, 2004). This implies that size of ventilation structures should be selected carefully to prevent the destructive consequences associated with air. Also, sewer structures should be designed so that they withstand any high magnitude and frequency pressure peaks resulting from sudden air release (Vasconcelos and Wright 2006).

**Flow Patterns in Two-Phase Flow**

As the fraction of air transport is increased, flow patterns occurring in two phase flow are characterized successively as bubble flow, plug flow, stratified smooth flow, stratified wavy flow, slug flow, annular flow, and spray flow. These patterns are shown in Fig. 5 with the shaded regions accounting for the air. Each of these flow patterns has its special features and effects on the water flow (Escarameia 2005).

Bliss and May (1942) and Kalinske and Robertson (1943) classified three different flow regimes in air–water flow in downward-sloping pipes, in terms of the amount of air entrained by hydraulic jump and the air-removal capacity of the flow. They explained that in blow-back flow regimes, air entrainment by a hydraulic jump is greater than the air-removal capacity of the water flow below the jump. In their classification, transitional flow regimes follow the blow-back flow in which multiple air pockets and hydraulic jumps are created, and in which air pockets are still stable, which indicates that the air entrainment in the hydraulic jumps is approximately equal to the flow’s air-transport capacity. Lastly, full air transport occurs when air entrainment by the hydraulic jump is less than the air-removal capacity of the flowing water, resulting in the removal of all the entrained air. Therefore, the single hydraulic jump moves steadily up the pipe. In this flow regime, the amount of air removed from the pipe is related to the Froude number of the hydraulic jump.

Pothof and Clemens (2010) conducted several experiments over a range of downward-sloping pipe angles, lengths, and diameters, and observed the following four flow regimes: (1) stratified flow in which the air pocket filled the entire sloping section without surface entrainment, and the associated head loss was considerable; (2) blow-back flow in which one or more air pockets were present in the sloping reach, air entraining hydraulic jumps existed, and head loss was reduced with increasing water discharge; (3) plug flow in which a number of air plugs moved downward along the pipe sofit and head loss was 19 times less than the stratified flow regime; and (4) bubbly flow in which air was moved along the pipeline as small bubbles and head loss reached approximately zero. Moreover, transition from the blow-back flow regime containing multiple air pockets to plug flow regime depends on clearing flow, which is defined as $Fc = Qc / [A(gD)^{0.5}]$, in which $Qc$ is the water discharge, $A$ is the pipe cross section, $g$ is acceleration because of gravity, and $D$ is pipe diameter (Kent 1952; Wisner et al. 1975; Escarameia 2007).

**Air Management Strategies**

There are several strategies for managing air in pipes to decrease or prevent the devastating consequences of air pockets that are introduced either in wastewater systems during storms or in pressurized water mains because of entrance of air at the inlets of pipes and pumps during filling and through application of surge-protection devices, such as AVVs. Generally, the available air-management policies are categorized as follows: air prevention, consideration of hydraulically removing air bubbles or entrapped air pockets from

![Fig. 5. Flow patterns in air-water mixture (reprinted from Lauchlan et al. 2005, with permission from HR Wallingford)](image)
pipelines, and application of air-release devices, such as air valves or air vents. In this paper, the first two strategies are reviewed. Available knowledge and gaps in the literature regarding each method is discussed, and it is illustrated that further improvement is required to make these strategies feasible for real-world problems.

Preventing Air Admission

A significant hydraulic issue occurring at water pipe intakes is the formation of a free air-core vortex. In the absence of sufficient submergence (i.e., distance from upper level of intake to water level) at the intake, such a vortex potentially can introduce a substantial amount of air into pipes. Air-core vortices were illustrated by Gulliver et al. (1986). Several experimental and theoretical studies on the free-surface vortex were performed in pump intakes and at outflow nozzles (Daggett and Keulegan 1974 cited in Chang and Lee 1995; Jain et al. 1978 cited in Chang and Lee 1995; Anwar and Amphlett 1980 cited in Chang and Lee 1995). Such experiments are performed in still water and in uniform open-channel flow, and the intakes are either horizontal or vertically upward or downward with rectangular and circular shapes (Anwar 1965; Odgaard 1986; Yildirim and Kocabas 1995, 1998; Yildirim 2004; Denny 1956). Such geometries are commonly used in pump intakes and hydraulic structures. Pump performance depends primarily on whether proper approach conditions exist at pump intakes, and available guidelines should be consulted (Jones et al. 2008; Hydraulic Institute 1983) to prevent vortices, excessive swirling in the intake piping, poor velocity distribution at the entrance to the pump, and air entrainment in the pumped flow (Jones et al. 2008).

Pioneering studies by Denny (1956) revealed that a mere 1% air volume into the pump’s suction line through air-entrapping vortices can reduce a centrifugal pump’s efficiency up to 15%. Other studies show that air volumes greater than 3% significantly reduces pump performance, and in extreme conditions, damages mechanical components (Murakami and Minemura 1983; Patel and Runstadler 1978; Florajancic 1970). Hence, to prevent air entrainment at intakes, a critical submergence (Sc), at which air entrainment would begin, should be determined.

Sc has been studied in a vertically-oriented downward intake pipe in both still reservoir and open-channel flow for permeable (i.e., gravel with porosity = 0.77) and impermeable bottom (i.e., concrete with porosity = 0) by Kocabas et al. (2008). Diameter of the intake pipe, water velocity in the intake and channel, and permeability of the bottom of the intake tank are influential factors on the Sc ratio (i.e., the ratio of Sc to intake diameter) (Kocabas et al. 2008; Kocabas and Unal 2010). For a given channel velocity, the same Sc ratio occurs at higher intake velocities when sump bottoms are permeable. At a given channel velocity, the effect of permeability on the Sc ratio is lowered for high intake velocities. Overall, the Sc ratio decreases with channel velocity and increases with intake velocity in both permeable and impermeable bottoms.

Other factors influencing the Sc are the relative positions and dimensions of an intake (Yildirim et al. 2009), shape of the intake (e.g., flat- and bell-mouth shaped vertical intakes) (Durai et al. 2007), boundary friction (Tastan and Yildirim 2010), the ratio of intake water velocity to the channel water velocity (Ayoubloo et al. 2011), Froude number (Gulliver and Rindels 1987), Reynolds number, circulation number, Weber number of the intake (Jain et al. 1978 cited in Chang and Lee 1995; Gulliver and Rindels 1987), viscosity (Jain et al. 1978 cited in Chang and Lee 1995), and the impervious boundaries’ blockage effects (Yildirim et al. 2000, 2007). However, surface tension and viscous effects are insignificant for some limit values of Froude number, Weber number, and Reynolds number. Such limiting values differ for each system because of the difference in configuration under study and flow conditions (Tastan and Yildirim 2010). Also, Sc has a direct relationship with circulation at the intake (Kocabas and Yildirim 2002). A comparison by Li et al. (2008) on empirical formulas relating Sc to intake Froude number (Reddy and Pickford 1972; Odgaard 1986) showed that the Sc was dependent on boundary effects (e.g., flume size).

Furthermore, Sc depends on whether the intake is dual pipe or single pipe, with the former requiring a larger Sc under identical conditions (Yildirim et al. 2009). For example, experimental studies by Denny et al. (1957) for single, double, and triple intakes in a pump sump show an increase of 1 to 4 times in downstream Sc because of the existence of upstream intakes. The Sc should be larger in dual intakes because of the disturbances and blockages they impose (Yildirim et al. 2012). Furthermore, it is experimentally and theoretically explored that in a multiple intake configuration, intake geometry influences the discharge into each individual intake and, therefore, larger Sc compared with a single isolated intake becomes necessary (Yildirim and Tastan 2009).

No reliable relation has been found yet between parameters affecting Sc. Experimental and theoretical studies in the literature have led to proposing several empirical equations to predict Sc of intakes primarily in an open channel. Such empirical formulas are on the basis of prototype and physical model studies, and relate the relative Sc (Sc/Dd, in which Dd is the tunnel or intake diameter) either to flow velocity in the tunnel (Denny et al. 1957) or to Froude number of the tunnel (Amphlett 1976; Berge 1966; Gordon 1970; Reddy and Pickford 1972). Other empirical relationships and charts available in the literature (Kocabas and Yildirim 2002; Odgaard 1986; Reddy and Pickford 1972) mostly estimate Sc as a function of Froude number, Reynolds number, Weber number, circulation, and the vertical height of intakes. Other studies have proposed equations that relate Sc/D to a nondimensional circulation number defined as \( \Gamma/\sqrt{2D} \), in which \( \Gamma \) is the vortex circulation defined as \( \Gamma = 2\pi v_0 r \), Sc is the critical submergence, \( D \) is the intake diameter, \( v_0 \) is acceleration because of gravity, and \( v_0 \) is the tangential velocity at a distance \( r \) from the vortex axis (Anwar et al. 1978; Jain et al. 1978 cited Chang and Lee 1995; Odgaard 1986; Sarkardeh et al. 2010). Because of the complexity of the process, such conventional formulas on the basis of regression approaches may not be good representatives for estimating Sc.

Several empirical formulae exist for estimating Sc. Due to their flexibility, ability to generalize and power to approximate nonlinear and complex systems, soft computing and data mining techniques such as classification and regression tree (CART) and artificial neural network (ANN) are widely used to estimate Sc. Sc is predicted using empirical equations, nonlinear regression, back propagation ANN, M5 model tree-based modeling (Goel 2012), and CART for different clearances (i.e., vertical distance of intake to bottom of tank) (Ayoubloo et al. 2011), either for horizontal intakes or for intakes in channels with permeable and impermeable bottoms (Kocabas et al. 2008). Also, potential flow theory and dimensional analysis is applied to determine Sc for intakes from both an open-channel flow and from still-water reservoirs (Yildirim and Kocabas 1995, 1998, 2002; Yildirim et al. 2000, 2009; Yildirim and Tastan 2009).

Although these results help to understand the effect of different features of intake geometry and flow characteristics on Sc of the intake, they cannot be used as design criteria. For example, through an extensive model-prototype evaluation, Hecker (1987) recognized the poor correlation with published guidelines. Hence, such results obtained from physical model studies may contribute only partially to the development of a general design methodology because they do not provide quantitative information that could
be applicable to all geometries and operating conditions. However, financial and time constraints for a physical model study in engineering projects justifies developing a design criteria for Sc in multiple intakes.

Another air prevention strategy is to avoid intake vortices. The available alternatives are illustrated in Gulliver et al. (1986) and include guiding the far field flow and reducing the intake velocity or installing antivortex devices, such as funnels (Trivellato 2010) or horizontal (perforated or solid) plates at the top of intakes (Amiri et al. 2011). CFD progressively is playing a role of estimating such terms, although it remains expensive and often difficult.

**Air Removal by Hydraulic Means**

Understanding the movement of air-water mixtures started to be of great concern to researchers as early as 1950. Different flow patterns are created when different proportions of air and water are transported in the pipe. The properties of the fluids, the gas and liquid mass flow rates, and the pipe slope and diameter are the factors affecting flow patterns (Escarameia 2007). Rouhani and Sohal (1983) provided reviews of the two-phase flow patterns.

In theory, the following three primary forces acting on an air pocket should be considered to find the criteria for air movement: (1) buoyancy, (2) drag, and (3) equilibrium in surface tension. The magnitude of the resultant force determines the tendency of the air pocket to remain stationary and grow in size or move in the direction of the resultant force. In pipe sections with upward slopes, buoyancy will force air pockets of all sizes and shapes to travel to peaks along the pipeline. The movement of air pocket in pipes with downward slopes is more complicated. If buoyancy exceeds drag, air pockets will travel upward. But if the drag force is dominant, air pockets move in the direction of flow (Falvey 1980; Lubbers and Clemens 2005a, b). However, the complexity of two-phase flow problems has limited the number of theoretical works on this subject. Consequently, most of the published knowledge regarding the criteria for movement of air bubbles/pockets is on the basis of experimental observations. Such work has explored the two possible ways through which the hydraulic removal of air pockets from a pipeline takes place: sweeping (i.e., the movement of the whole air pocket while critical water velocity is reached), and generation and entrainment (i.e., air moves by the hydraulic jump formed at the end of the big air pocket) (Wisner et al. 1975). Studies on either of the subjects are available, with less data on the latter.

**Sweeping**

Much published work on air removal has been experimental in focus, in which the study’s primary focus is on recording the critical velocity of flow that is able to remove air from the pipe. The mechanism of air-pocket movement has been studied widely, leading to the introduction of the critical velocity of water by which air pockets are observed to move downstream. Applying these criteria can predict and solve air-binding problems in pipeline systems. On the basis of dimensional analysis, critical velocity is a function of Froude number, Reynolds number, surface tension, and pipe slope (Bendiksken 1984; Falvey 1980; Wisner et al. 1975; Kalinske and Bliss 1943). However, the effects of viscosity and surface tension are less pronounced in pipes of 175–200-mm diameter or larger (Pothof and Clemens 2010; Viana et al. 2003; Zukoski 1966). Thus, it is often assumed that the critical velocity for a given pipe slope is proportional to \( \sqrt{gD} \), in which \( g \) is acceleration because of gravity and \( D \) is the pipe diameter. However, the proposed formulas are valid for a specific range of pipe slope. Generally, such formulas have related the pipe slope with a dimensionless number \( V/\sqrt{gD} \), in which \( V \) is the average velocity. According to the formulas, the steeper the downward slope is, the smaller the air pocket velocity/critical flow velocity ratio becomes (Escarameia 2007).

Falvey (1980) and Escarameia (2007) combined all the available criteria in a single graph. They included the criteria for which air pockets remain stationary or move either downstream or upstream. However, for the same pipe slope, critical velocity depends on air-pocket size. For instance, larger air pockets are associated with higher critical velocities. Escarameia (2007) took account of this by defining a nondimensional air-pocket size parameter, \( n \), previously used by Kent (1952), in which \( n = 4V_{air}/\pi D^2 \), \( V_{air} \) is air-pocket volume, and \( D \) is pipe diameter. Also, she accounted for uncertainties related to air movement in pipes by considering a safety factor in such formulas. However, she observed a discrepancy among the curves proposed by different studies, such as whether the curves were either convex or concave.

Despite a few experiments by Escarameia (2007) in mild slopes (less than 22.5°) to explore air pocket movement, most of the experimental works have investigated bubble motion in small diameter tubes using steep slopes and small-sized air bubbles in stationary liquids, all conditions that are not particularly relevant to operating engineering pipelines. Various researchers carried out the experiments in a single diameter pipe and steep slopes, and yet, suggested a wide range for applicability of their formulas by relating the critical velocity of flow with pipe diameter and slope, and with acceleration because of gravity. However, dependence on \( D \) is questionable because of insufficient experimental data (Lauchlan et al. 2005). Furthermore, all of these data and criteria originate from case-specific studies and their general application necessitates more physical insight into air movement, including consideration of scale effects. For example, applicability of the formula proposed by Escarameia (2007) is for air-pocket sizes of \( n = 0.0002 \) to 2 (i.e., \( n \) is a nondimensional parameter as defined in the previous paragraph). Also, the focus of her study is on bubble-to-plug flow regimes, in which relatively low airflow rates are moving with the water. However, smaller air-flow numbers are found to result in smaller clearing flow numbers (Pothof and Clemens 2010). Hence, considering such scale effects is necessary to efficiently generalize experimental data.

**Hydraulic Jumps and Air Entrainment**

Air entrainment by hydraulic jumps is regarded as a mechanism for removing air pockets from downward-sloping water pipes. That is, large air pockets break up into small air bubbles because of air entrainment by the hydraulic jump. Then, these small bubbles will be transported downstream if the flow velocity exceeds the critical velocity for removing air bubbles. Published experimental studies address the issue of hydraulic jump; Chanson and Qiao (1994) provided a summary of the previous work in this area, whereas Ervine (1998) summarized the literature on air entrainment at hydraulic jumps. Additional studies by Escarameia (2007) and Pothof and Clemens (2010) add to these findings.

In closed conduits, hydraulic jumps occur at a change in bottom slope from mild to steep, at siphons, downstream of a sluice gate or control gate, and downstream of an entrapped air pocket at high points or along a downward slope during a pressurized flow (Fig. 6). Furthermore, hydraulic jump occurs during the transition from supercritical to subcritical flow (or pressurized flow in closed conduits). This hydraulic event produces considerable local turbulence leading to energy dissipation and air entrainment. The entrained air bubbles may be transported downstream or returned upstream because of their buoyancy depending on the flow’s transport capacity. In sewer systems, air entrainment enhances ventilation of conduit flow and reduces cavitation damage (Hager 2010). However, the occurrence of pulsating slug flow, discharge reduction (Lubbers and Clemens 2005a, c), and sudden air outflow (geysering) (Zhou et al. 2002b) are the common disadvantages.
The three characteristics of a hydraulic jump (Hager 2010) are: (1) the roller length (i.e., the distance from the toe of the jump to the stagnation point at the free surface); (2) aeration length (i.e., the distance from the toe of the jump to the section at which air bubbles have left the flow); and (3) jump length [i.e., the distance from the toe of the jump to the point at which the jump profile meets the system hydraulic grade line; i.e., \( L_j \) in Fig. 6(e)]. The location of the hydraulic jump depends on the flow conditions at the upstream and downstream reaches. Wang and Chanson (2015) investigated the physical modeling of hydraulic jumps with developed inflow conditions. They measured time-average free-surface profiles, free-surface fluctuations, and air-water flow properties (e.g., distribution of void fraction, bubble count rate, and interfacial velocity) in hydraulic jump rollers, and they estimated air entrainment.

Air transport through hydraulic jumps has been studied in rectangular cross sections (Rabben et al. 1983; Rajaratnam 1967; Wisner et al. 1975; Ahmed et al. 1984) or horizontal circular pipes (Kalinske and Robertson 1943), and in circular pipes with downward and upward slopes (Escarameia 2007; Falvey 1980; Pozos et al. 2010b). An air pocket moves downstream without changing its shape if water discharge is high. However, if some of the air is removed from the system, the air-pocket size is reduced sufficiently in a downward-sloping pipe, and the hydraulic jump moves upstream. However, the shape of the air pocket in the upstream section of the pipe remains constant (Escarameia 2007). Criteria for air movement have been proposed by considering the effect of hydraulic jumps in the formation of air pockets and their movement. For example, a criterion for a stationary air pocket is \( Q^2/gD^5 = S_0 \), in which \( Q \) is the water discharge, \( g \) is acceleration because of gravity, \( D \) is pipe diameter, and \( S_0 \) is pipe slope (5° to 60°) (Pozos et al. 2010b). More specifically, the critical flow number is a function of pipe diameter, pipe angle, viscosity, and air discharge (Pothof and Clemens 2010). Equations for calculating air entrainment rates are given for circular pipes with downward pipe slope of 4% and Froude numbers 4–12 (Mortensen et al. 2012).

Obviously, viscous and surface tension can affect air entrainment rates (Chanson and Gualtieri 2008). Consequently, surface tension influences the transport capacity of air in downward-sloping pipes (Pothof et al. 2013). Escarameia (2007) found that key parameters generally influencing air transport along a closed conduits are air entrainment rate, upstream Froude number, pipe cross section, flow condition downstream of the shear region in a hydraulic jump, the downstream pipe length, and the downstream exit condition (i.e., open channel or pipe-full flow). For example, according to a summary provided by Escarameia (2007), in short conduits \( L/D < 5 \), air entrainment is equal to air transport. Also, in intermediate length pipes \( L/D = 5–20 \), air transport is a portion of air entrainment because some of the air bubbles collect at pipe soffits producing small air pockets. This phenomenon depends on the conduit full-bore velocity and bubble-rise velocity in still water. However, in long conduits \( L/D > 20 \), air bubbles are more likely to coalesce into larger air pockets. This can allow them to be transported downstream if sufficient flow capacity is present. Otherwise, air pockets grow until they eventually blow back upstream. Furthermore, Pothof and Clemens (2010, 2011) found that air transport for various flow regimes depends on water flow number, pipe slope, and surface tension. However, pipe slope does not affect the air transport capacity of hydraulic jumps in circular pipes (Escarameia 2007; Hager 2010). Also, the influence of bottom slopes smaller than approximately 5% is negligible in rectangular ducts (Hager 1992). Hence, cross section, length of the pipe, and flow characteristics are the factors that should be considered when accounting for air removal by hydraulic jump at the design stage.

Furthermore, an air relief system, such as an air vent, is required to be installed downstream of hydraulic jumps. In such cases, the location of the hydraulic jump affects the rate of air entrainment in closed-circular conduits (Mortensen et al. 2012) or in a high-head rectangular conduit (Sharma 1976). For example, according to experimental data, the air entrainment rate is dependent on the upstream Froude number and is independent of jump location if total length of the hydraulic jump is less than the pipe length downstream of the jump (Mortensen et al. 2012). However, the location of the hydraulic jump influences the air entrainment rate if the hydraulic jump is not fully developed within the pipe. The closer the toe of the jump to the air-release structure, the more the air-entrainment rate. This is an implication for more careful design of air-control devices, such as air vents.

At times there may be several hydraulic jumps in a pipe reach downstream of the primary hydraulic jump. For example, secondary hydraulic jumps form if the primary hydraulic jump is too far from the downstream air-release structure (Mortensen et al. 2011, 2012; Kalinske and Robertson 1943). In such cases, the number of secondary hydraulic jumps does not affect the air-entrainment rate \( Q_{air}/Q_w \) as long as downstream pipe length is greater than the aeration length of the primary jump. Otherwise, air entrainment varies slightly independent of the Froude number. This independence of the Froude number is more pronounced if the downstream pipe length is less than the rolling length of the hydraulic jump (Mortensen et al. 2012).

To safely apply the air-entrainment rate equations to air-control system design, scale effects because of pipe size and water temperature should be considered. According to experimental data by Mortensen et al. (2011), scale effect can be neglected only if downstream pipe length is more than the hydraulic jump length. However, there is a significant reciprocal relationship between water temperature and the air-entrainment rate. Hence, further research is required to address any possible scaling effects of transposing results from laboratory investigations to pipes with diameters of more than 1 m. For example, to apply the available air-entrainment rates to designing air-control devices, pipe shapes, downstream flow...
conditions (Escarameia 2007), and water temperature (Mortensen et al. 2011) should be the same in model and prototype.

As illustrated, bubble motion rather than air-pocket motion has received more attention in the literature. Significantly, though published experimental works only rarely consider scale effects, such effects must be accounted for if one is to generalize and apply such empirical formulas to real-world problems, and if one is to provide design guidelines for hydraulically managing air in pipes. Clearly, though, the study of air pocket movement justifies continued study.

Summary

Both chronic and devastating consequences are sometimes associated with entrapped air. This reality justifies a review of air-management strategies to understand the current available practice and improvements, and justifies the possibility of further research and development. This paper overviews the literature concerning air in both water and wastewater systems, and the associated consequences, providing a critical review on two air-management strategies. Advancements in the literature are discussed along with the gaps that prevent management strategies from greater acceptance and success.

Consequences of air pockets are categorized into steady-state and transient conditions, with more available research on the latter. In transient conditions, the peak pressures induced by entrapped air pockets or air release from pipes, and the pressure oscillation patterns are of interest. Whereas most of the studies deal with air release into an air medium, the study of air release into water is seldom considered. Therefore, further studies are necessary to explore influential parameters on destructive consequences of air release into water and to propose preventive measures whether in the design stage or in operation protocols. In steady-state conditions, a limited number of studies have been performed regarding the capacity reduction because of the presence of entrapped air in wastewater systems under low operating pressures. However, there are still knowledge gaps regarding the ability of air pockets both to accumulate at most susceptible locations along pipelines (i.e., high points) and to reduce pipe capacity in pressurized water mains.

The prevention of air entry is one of the air-management strategies reviewed. Research has experimentally explored the Sc of intakes with different geometries to prevent air intrusion because of the entrance vortex. However, almost all of these studies are case specific, providing few general guidelines. A clear understanding of scale effects is still lacking. Obviously, the financial and time constraints for a physical model study in most projects justifies developing a set of design criteria for Sc, especially for multiple intakes. CFD approaches are developing quickly, but they remain expensive, case specific, and infrequently used.

Finally, there are strategies for hydraulically removing air from systems. The two mechanisms of removing air bubbles by sweeping and by hydraulic jumps through generation and entrainment are illustrated. Bubble motion, as opposed to air-pocket motion, has received noticeably more attention in the literature. Again, generalization of results obtained from sweeping mechanism requires further studies on scale effects. To safely apply the empirical air-entrainment rates by hydraulic jumps at the design stage to real-world problems remains challenging because of scale effects (e.g., pipe size and water temperature). Establishing a general design guideline for air management in water pipes requires physical understanding of air behavior in water pipes through an informed theoretical, experimental, and numerical exploration, and thus, remains a challenging and partly open question.

References


