An Exploration of Transient Protection of Pressurized Pipelines using Air Valves

by

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Thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
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Abstract

The transient response associated with systems experiencing pump power failure having undulating profiles and containing air vacuum valves (AVVs) is systematically explored to characterize the critical high points where placing AVVs has the maximum influence on the resulting transient pressures. For this purpose, this work seeks to understand the principal function of AVVs and their relation to the geometry and hydraulic characteristic of the system. Semi-analytical formulas are developed for the time of air cavity growth and collapse, maximum air cavity growth, and the secondary transient pressures due to cavity collapse at AVV location. Such relations are developed considering an undulating pipeline with an exaggerated high point at an intermediate location with the assumption of sudden upstream flow curtailment. Through these semi-analytical formulas, it is shown how the presence of AVVs at particular high points influences the system’s transient response. Key characteristics of the high point – namely, its elevation and distance from the upstream and downstream boundaries – are explored and those values that lead to the most severe transient response are identified.

In order to numerically investigate those parameters most influential to a system’s transient response, the sensitivity of hypothetical pipeline systems to different input and design
parameters is systematically explored. To this end, a numerical model is developed to solve the water hammer governing equations in conjunction with the AVV boundary equations by application of the method of characteristics. This numerical model is also coupled to a Monte Carlo simulation procedure. Monte Carlo Filtering is applied to help isolate and understand the most influential parameters. Also, a variance-based method is applied to explore the main and interaction effects between the influential parameters and to map these as a function of the terms defining the AVV properties and the high point location.
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Chapter 1
Introduction

Transient events in pipe systems, such as those associated with power failure and valve closure, frequently occur and sometime generate pressures of high magnitude. If these transient pressures exceed certain limits—whether through overpressure or negative pressures—troublesome and even catastrophic failure can result, especially when the transient events occur frequently or are either intense or prolonged. To mitigate the induced transient pressures, various strategies are adopted and protective hydraulic devices installed. The protection devices run a large gamut of possibilities, ranging from expensive air vessels and surge tanks, to less expensive surge relief and air vacuum valves (AVVs). The size and location of these surge control devices are generally selected through computer analysis so that they will (ideally) be capable of limiting the positive and negative transient pressures within two prescribed limits: on the high side, the bound is the so-called pressure rating of the pipe and, to avoid negative pressures, the pipe elevation on the low side. This thesis is concerned with the role, risks, and possibilities created by the use (and abuse) of air vacuum valves.

1.1 Air Vacuum Valves (AVVs) as Surge Protection Devices

As opposed to air chambers and surge tanks which control transient pressure by exchanging water between the pipe system and an off-line temporary storage chamber, AVVs are (at least partly) designed to limit low pressures by admitting air into the pipe whenever vacuum conditions occur. After suppressing vacuum conditions and once the pressures have risen above atmospheric, AVVs are intended to gradually release the admitted air, and thus, to avoid the problems caused by allowing entrapped air to remain in the pipe. The design goal of AVV selection is easily stated but less easily achieved: to admit air in order to limit low pressures, thus preventing pipe collapse or the ingress of untreated water, but then to exhaust the admitted air so as to reduce any consequent flow interruption while controlling the subsequent system dynamics and possible high pressures. The primary motivation for using AVVs is that they are usually cheaper than alternative protection measures such as the effective but expensive air
chambers or surge tanks. Quite clearly, however, if vacuum conditions are to be effectively controlled, AVVs must be placed and sized properly, and there is considerable ambiguity in the literature about how this should be done, and of the consequences should this selection be done poorly.

According to the current design criteria, such as summarized in AWWA’s M51 manual, AVVs are placed at all the high points and at specific intervals along the pipe (i.e., every 800 m). Also, despite their effective role in controlling transient events, they are mainly sized and placed in water pipelines on the basis of filling and draining/pipe break scenarios; to remove air during filling scenario (Figure 1-1a) or admit air during draining/pipe break scenario (Figure 1-1b). Thereafter, these valves are too often neglected or forgotten and less attention is paid to their regular maintenance. Sizing outlet orifice of AVVs on the basis of a controllable scenario (e.g., filling) results in large outflow orifices. However, activation of these large, and often neglected, valves under uncontrollable transient events may cause destructive secondary transient pressures. Considering the fact that filling is a controllable event (i.e., operators can control how fast the line is being filled), the current AVVs design seems unreasonable. That is, designing on the basis of filling can potentially cause uncontrollable and destructive events under transient conditions resulting in pipe or valve destruction. Of course, the approach for sizing inlet orifices of AVVs on the basis of draining/pipe break is questionable if they are neglected and not maintained to perform well when required. Since they may also intrude contaminated flow into a pipe conveying potable water, and thus cause associated health risks, transient activation needs to be carefully managed. Unfortunately, there are millions of problematic AVVs around the world that no one is fully aware of their accumulated hydraulic effects. Moreover, there are few criteria as to how to select AVVs on the basis of transients. For example, it is seldom obvious that placing certain AVVs, properly sizing and maintaining them, is particularly important at certain high points. Or, how the horizontal and vertical locations of an AVV or its size affect the transient response of the system. This thesis aims to address such questions.
Figure 1-1 Air vacuum valve function during filling (a) and draining/pipe break (b) scenarios (DeZURIKvalves 2014)

1.1.1 Sizing AVVs

Air valves generally have two or three openings which connect, in a controlled way, the interior of the pipe with the atmosphere: one of these openings (usually the larger one) is designed to admit air if local pressures drop below atmospheric, and the second one, to gradually discharge the admitted air once pressures within the pipe return to positive values. The third, if present, is designed to remove small quantities of accumulated air that might occur at the air valve location.

Both the inflow and outflow orifice sizes are considered as key design parameters in the selection of AVVs. If AVVs are not properly sized, they can actually induce or amplify transient pressures. Clearly, the inflow capacity must be sufficient to allow air to enter the pipe and avoid or limit negative pressures; if the valve orifice size is too small, too great a pressure drop occurs across the valve, and low pressures are poorly controlled. However, too great an inflow capacity
creates bulky and needlessly expensive valves. On the other hand, low outflow capacity may cause entrapped air (that air recently admitted to the pipe) to remain after the transient event and cause a variety of associated problems (e.g., overpressures and reduction in discharge are reported in Bergant et al. 2011 and Carlos et al. 2011). Moreover, if an air pocket is trapped between two water columns, or nearby to a closed valve, its presence can create high transient pressures during rapid acceleration of an adjacent water column (Martin 1976), making the pipe more vulnerable to later transient events. Yet, too large an outflow capacity is problematic too. High outflow capacity AVVs can cause secondary transient events as a result of sudden release of air (Lee and Leow, 1999; Lingireddy et al., 2004; Li et al., 2009). This phenomenon can be so severe as to damage the outflow mechanism and can even lead to air valve breakage (Li et al., 2009). However, AVVs can potentially be effective in mitigating transient conditions. For instance, AVVs with low outflow and high inflow capacity can effectively suppress peak pressures and avoid valve slamming while reducing negative pressures caused by transient events (Espert et al., 2008; Lee and Leow, 1999). Thus it is clear that the sizing of an air valve for surge relief requires a careful balancing of competing considerations.

Yet, interestingly, transient considerations are often treated as a secondary concern when AVVs are being selected. In fact, according to current practice, which is largely based on manufacturer’s recommendations, AVVs are often sized to be large enough to exhaust/admit large volumes of air when a pipeline is being filled, drained and during pipe breaks (AWWA 2001, Parmakian 1950). However, if such valves are activated under other transient events such as pump failure, the large outflow capacity can induce strong secondary transients as a result of sudden air release through the oversized AVV. And the large inflow capacity can cause the intrusion of contaminant flow into the pipe. In order to avoid such secondary transients and to effectively use AVVs for transient protection, at locations where transient conditions may cause an issue, their sizing should be based on transient considerations. This emphasis is logical and justified since the other functions of AVVs can be controlled by a variety of other means, such as strictly limiting filling or draining velocities (McPherson 2013).

1.1.2 Locating AVVs

The other AVV design parameter of direct relevance to the use of AVVs is the set of its locations for installation along the pipe. In order to be present where air is likely to accumulate
and for protecting the system against pipe breaks, AVVs are most commonly placed at all the local high points (or knees) in the pipeline profile (based both on manufacturer’s recommendations and AWWA 2001 guidelines). This can result in the occurrence of a large number of AVVs in undulating pipeline profiles. The recommended arrangement has the stated and almost exclusive goal of preventing the accumulation of entrapped air and its associated problems (i.e., overpressures and reduction in discharge) during operation and/or line filling, draining and pipe breaks. Thereafter, these valves are too often neglected or forgotten. Certainly, due to the relative inaccessibility of most AVV locations (often found in valve vaults requiring awkward confined space access procedures), the valves are often left exposed to weathering, physical damage, and wearing which eventually render them non-operational. Such problems sometimes justify replacing automatic AVVs with cheaper, manually-operated AVVs (i.e., pit cocks) if they solely control infrequent events such as filling, draining and pipe breaks (the City of Ottawa has largely taken this approach).

Yet, once an air valve is present, it will tend to be active whenever conditions are favourable. Thus, some of these same AVVs installed at some of the high points for filling, draining and pipe breaks will also be active under transient conditions such as the vacuum conditions frequently associated with pump trip or power failure. Design of such AVVs (specially their outlet size) should be based on transient considerations, with more care taken for their maintenance. Obviously, as has been suggested, the choice of such transient-activated AVVs requires additional consideration: careless placement and sizing of AVVs might make these valves either ineffective in controlling vacuum conditions or may even worsen the conditions by inducing secondary transients. However, in the literature to date, considerably less attention is paid to characterizing the locations where careful design and maintenance of AVVs is most or least beneficial in terms of transient conditions.

1.2 Thesis Objectives

As discussed so far, improper design of AVVs based on transient conditions has the potential to induce serious or even catastrophic consequences into water pipeline systems. However, in practice and in the available design guidelines, relatively little attention is paid to this issue. The main objective of this thesis is to pave the way for more rational and proper selection of AVVs for the transient protection of water pipelines. The overall goal is to characterize critical high
points and thus to help designers understand the critical locations along the pipeline profile where installing and the proper sizing of AVVs are crucial for protecting the system against secondary transient events. Subsequently, this information will serve as preliminary and practical recommendations for sizing and locating AVVs for transient protection. More systematically, this thesis aims to achieve the following objectives, often organized around answering specific questions:

1) To revisit the available literature in order to better appraise the benefits of proper air valve selection and the consequences of improper design considerations of AVVs. Attention will be given to the recognized challenges in achieving an appropriate design, and to operation and maintenance issues. This is performed with the expectation of provoking possible revision or rethinking about the design, operation and maintenance of AVVs. This primary objective is divided into the two following tasks forming Chapters 2 and 3:

- To review air-induced problems in water pipelines: as previously mentioned, the surge protection function of AVVs is based on admitting air into the system during draining and pipe break scenarios or vacuum conditions and to remove air from the system during filling scenarios or after suppression of negative pressure. In order to understand the consequence of the presence of entrapped air in pipes or sudden air release from the pipes which occurs either due to the absence or poor performance/malfunction of AVVs, an extensive survey of the literature is first performed. One specific facet of this review is to explore the available knowledge that might help to justify or challenge the large number of AVVs often recommended by the available guidelines. This survey has led to a selective critical review presented in Chapter 2. This critical review is directed to answering several key questions:

□ What are the consequences of entrapped air or sudden air release from water pipelines which potentially can occur in case of, the absence, malfunction, or improper design of AVVs?
What are the knowledge gaps regarding, the consequences of air pockets in both steady state and transient conditions that, if explored, can be applied for better design of AVVs?

What are the current air management strategies and the associated knowledge gaps that prevent these strategies from greater feasibility and applicability to real world problems?

- To review the current operating and maintenance issues as well as the present challenges in achieving an appropriate design of AVVs, the available knowledge regarding design, operation, maintenance, and simulation of air valves is critically reviewed. This critical review has formed the contents in Chapter 3. This chapter answers the following questions:

  - What are the design procedures for AVVs and the consequences of improper sizing of AVVs?
  
  - What are the knowledge gaps regarding proper sizing and locating of AVVs?
  
  - What are the operational and maintenance issues of AVVs documented either through experimental data or field records, and what are the current alternatives to prevent such problems?
  
  - What are the shortcomings in the numerical simulation of AVVs?

2) To systematically study the transient response of systems with undulating profiles containing AVVs in order to characterize the critical high points where improper sizing of AVVs has maximum influence on secondary transients in the system. This is the main objective of this thesis and dominates Chapters 4 and 5. To this end, the following studies are undertaken:

  - To physically understand the principal function of AVVs and its relation to the geometry and hydraulic characteristic of the system. This task is the focus of Chapter 4 which answers the following questions:
How can the function of AVVs be semi-analytically expressed both in frictionless and frictional systems?

To what extent are variations in the time of growth and collapse of an air cavity, its maximum size, and the secondary transient pressures due to cavity collapse, influenced by the location and elevation of the high point?

How does the presence of AVVs at particular high points influence the system’s transient response in both ideal (frictionless) systems and more realistic systems? What characteristics of a high point (e.g., elevation and distance to the upstream or downstream boundaries) imply that the presence and attributes of AVVs are crucial in maintaining system safety under transient-induced pressures? In other words, how can different locations of AVVs be ranked in terms of their potential to suppress or aggravate transient pressures?

How important or sensitive is the proper sizing of AVVs at different locations?

What are the preliminary and practical recommendations for the importance of properly sizing AVVs for transient protection at different high points?

Under what circumstances could the presence of AVVs under transient conditions be detrimental rather than protective?

• To numerically investigate the importance of the proper sizing of AVVs by studying the sensitivity of transient responses of hypothetical pipeline systems to different input parameters of the water hammer governing equations and design parameters of AVVs (e.g., inflow and outflow size) as well as the characteristics of high points (i.e., vertical and horizontal position). Through this process, the importance of sizing AVVs based on transient considerations at different high points is explored. Results of this study are illustrated in Chapter 5 which answer the following questions:
How do the hydraulic characteristics of the system (i.e., input parameters of water hammer governing equations) influence the simulation results? What are the most influential parameters and what are their key interaction effects?

How do inlet and outlet sizes of AVVs and the associated discharge coefficients affect the transient response of the system? What are the influential parameters and what are their main and interaction effects?

How does the location of AVVs change the influence or effectiveness of each parameter in the water hammer governing equations and design parameters of AVVs (i.e., inflow and outflow orifice sizes and discharge coefficients) on transient response of the system?

1.3 Thesis Scope and Framework

This section describes the underlying structure of the thesis. As has already been hinted, despite the wealth of research detailing the effects of AVV size on secondary transient events, and despite their acknowledged importance, there is still ambiguity, both in the literature and in practice, about what physical and hydraulic parameters of systems are most crucial in systems protected by AVVs. For instance, it is not yet physically clear how the system’s downstream driving head and the relative location of AVVs along a pipe affect the transient-induced pressures. Also, the importance of properly sizing AVVs, placed at particular high points, has not previously been systematically studied and elucidated. Such knowledge gaps motivate this research and contribute directly to its main objectives. In this thesis, a systematic study is performed with the direct goal of better understanding the role of AVVs, at each local high point, in protecting the system against negative pressures and in inducing secondary transients. This main objective is achieved in several steps with each forming a Chapter. It is planned that the 4 primary chapters constitute, or will eventually constitute, either a conference or a journal paper.

1.3.1 Chapter 2: A critique of air management in water pipes

As previously mentioned, surge protection using AVVs is based on the admission of air during vacuum conditions and the later expulsion of the same air. In order to understand the
consequences of the presence of air in pipe systems, and to review the published air management strategies and knowledge, an extensive survey of the literature is first performed in Chapter 2. This leads to a selective critical review regarding air management in water pipelines. Chapter 2 overviews the sources of air in both water and wastewater systems and the associated consequences of both entrapped air and air release. Also, the air management strategies are reviewed and the potential studies that make them more applicable to real world problems are explored. In this critical review, the consequences due to presence of air pockets in water pipelines are classified under steady state and transient headings. This Chapter summarizes the current open issues regarding the consequences of the presence or release of air in water pipelines either in steady state or transient conditions. Obviously, these challenges need to be addressed if the knowledge is going to be applied toward a rational design consideration for AVVs. Overall, this chapter implicitly illuminates the consequences of the absence, malfunction or improper design of AVVs.

1.3.2 Chapter 3: Critiquing the application of AVVs

The available knowledge regarding design, operation, and simulation of air valves (i.e., air release valves (ARVs) and air vacuum valves (AVVs)) are critically reviewed in Chapter 3. At this stage of the work, the main focus is on the application of AVVs and the operational and maintenance issues of AVVs documented in the literature either through experimental data or field records are presented. In addition, the available alternatives for preventing such problems are summarized and discussed. Furthermore, current AVV design procedures and shortcomings, the consequences of improper sizing of AVVs are reviewed and the challenges in achieving an appropriate sizing and the locating of AVVs are explained. Finally, the shortcomings in the numerical simulation of operating air valves are illustrated. Overall, this Chapter explores the knowledge gaps that limit the efficient application of air valves.

1.3.3 Chapter 4: Physical understanding of AVV performance under transient conditions

Following the extensive critical review in the previous two chapters, it is concluded that the literature still lacks a systematic study of the transient response of systems with undulating profiles containing AVVs. For this purpose, the principal function of AVVs and its relation to
the geometry and hydraulic characteristic of the system need first to be physically understood. This is the first part of the second objective of this thesis which is explored in Chapter 4. Understanding such fundamental physics of AVV function provides a tool for more proper decision making regarding AVV sizing with consideration of its location.

Chapter 4 documents a novel approach for understanding the physical behaviour of AVVs during a transient event. This chapter crucially explores how the presence of an AVV at particular high points influences the system’s transient response. To accomplish this, the key physical regularities associated with a sudden transient event within a system having a local high point and the possible AVV properties are semi-analytically investigated. Here, a high point is characterized by both a local geometry and its vertical and horizontal distance to various system features and boundaries (i.e., the vertical distance to the downstream reservoir head and the horizontal distance to the downstream reservoir in a reservoir-pipe-reservoir system). For simplicity, as is justified physically, the upstream and downstream portions of the high point are considered separately. First, the system is assumed to be frictionless and then the effects of friction is considered and explored.

The semi-analytical formulas lead to a better understanding of the variations in time of air cavity growth and collapse, maximum air cavity volume, and the secondary transient pressures due to cavity collapse at AVVs location. It is shown that installing AVVs in a given system with a hydraulic size and specific characteristics of the high point strongly influences its transient response. Also, the chapter discusses how secondary transient pressures vary with the characteristics of a high point (e.g., elevation and distance to the upstream or downstream boundaries). This leads to the distinction between various high point geometries where the presence of AVVs is most influential. For example, it is shown that there are high points where the presence of AVVs of improper size greatly exacerbates the system’s transient response. Overall, those circumstances under which the function of AVVs under transient conditions could be detrimental rather than protective are identified.

Such characterization gives preliminary and practical recommendations for selecting AVVs for transient protection especially in long and undulating profiles, and for eliminating unnecessary and possibly problematic devices. Such findings should help designers understand which AVVs should be sized based on transient conditions and which of them are infrequently active and
might be either avoided or replaced by cheaper devices. Obviously, careful design of AVVs at these locations can potentially help to protect the system against secondary transients and vacuum conditions.

1.3.4 Chapter 5: Sensitivity analysis

In order to better understand the importance of properly sizing AVVs on the transient protection of the system, the influential parameters on secondary transients in pipelines protected with only an AVV are numerically explored in Chapter 5. Three methods of sensitivity analysis are used: Monte Carlo Filtering (MCF), scatter plots, and the Variance-based Method. In this Chapter, the sensitivity of transient response of systems to design parameters of AVVs at each location and input parameters of the water hammer governing equations is presented. The sensitivity analysis numerically elaborates on the previously obtained semi-analytical results (Chapter 4) which are based on physical reasoning. Considering hypothetical pipeline systems, the sensitivity of transient responses to different input parameters of the water hammer governing equations and design parameters of AVVs (e.g., inflow and outflow size), and the characteristics of high points (i.e., vertical and horizontal distance to boundaries), are explored.

To accomplish this, a numerical model is developed to solve water hammer in conjunction with the air valve governing equations by applying the popular method of characteristics (MOC). Moreover, the numerical model is coupled with a Monte Carlo simulation. Monte Carlo Filtering, along with the visual clues from scatter plots, is applied to understand the influential design parameters of AVVs in producing the transient response surface of the system. Finally, the Variance-Based Method is applied to figure out the main effect of each hydraulic variable of the water hammer governing equations and design parameters of AVVs in producing the resulting transient response. Furthermore, the interactions of key variables are analyzed. Parameters with the most effects on the transient response of the system are distinguished. Through this procedure, the importance of sizing inflow and outflow AVV orifices is distinguished in different locations. This part of the work explores how the sensitivity of transient response of the system varies with inlet and outlet sizes of AVVs and variables such as wave speed, friction factor, and design discharge of the system. Also, the variations of sensitivity with changes in AVV location are explored.
1.4 Thesis Publications

The papers listed below are the accomplished or intended outcome of this thesis. Two of them are conference papers and the rest are either published, or provisionally accepted (“revision for editor only”) to be published, or being prepared to be submitted to a suitable journal. The contents of the papers reflect the contributions of this thesis.

Ramezani, L. and Karney, B. W., 2013. Water column separation and cavity collapse for pipelines protected with air vacuum valves: understanding the essential wave processes. Hydraulic surge and air control symposium # 1. 9-10 April 2013, Israel. (Chapter 4)

Ramezani, L. and Karney, B. W., 2015. Water column separation and cavity collapse for pipelines protected with air vacuum valves: understanding the essential wave processes. As of August 2015, this paper is in the process of “Revision for Editor Only” to be published in the Journal of Hydraulic Engineering, ASCE. (Chapter 4)


Ramezani, L., Karney, B. W., 2015. Application of sensitivity analysis methods to understand the importance of proper design of air vacuum valves. In preparation to be submitted to the Journal of Hydraulic Engineering, ASCE. (Chapter 5)

Ramezani, L., Karney, B. W. and Malekpour, A., 2015. The challenge of air valves: a selective critical literature review. Journal of Water Resources Planning and Management, ASCE. Published online in March 18, 2015 (Chapter 3)


As the primary author, I drafted the first versions of all the above mentioned papers and performed all the associated numerical and conceptual studies and detailed analyses. Professor Bryan W. Karney, as my PhD supervisor, provided academic advice, conceptual ideas, detailed
reviews and comments as well as editorial suggestions to improve the work. I have also received some helpful suggestions from recently completed Dr Ahmad Malekpour, an experienced colleague in this field, who helped elaborate on practical and experiential issues on the two review papers with which he is associated. Also, the papers under submission and review have benefitted from the comments of the various anonymous reviewers who have read and thoughtfully commented on the work.
Air is entrapped in water and wastewater systems under several conditions. Entrapped air, if not properly managed, imposes operational problems. In order to avoid these problems and the dangers due to air pockets, several air management strategies have been 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 chapter overviews air sources in pipes and those consequences associated with its presence. Furthermore, 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.

2.1 Introduction

The presence of air in pipes can often pose a great threat to pipeline systems. Air can be present in water pipes either at a small-scale (e.g., bubbles) or at a large-scale (e.g., large air pockets). One of the principal on-going sources of air in an operating pipeline is the small-scale air release from supersaturated water, typically at lower pressures or higher temperatures than at its equilibrium state. That is, dissolved air in saturated water – up to about two percent by volume (Dean 1999) – can be released when water temperature increases, or when pressures drop in the system. Another source of air is the large-scale air entrained from the atmosphere into the flow 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 intentionally admitted into the pipe through air vacuum valves (AVVs) in order to prevent negative pressures and the resulting pipe collapse. In such conditions, after suppression of negative pressure, air should be removed from the pipe through the outlet of AVVs. However, there are certain conditions in which valves
malfuncon or close prematurely, or under which air is swept downstream, resulting in air entrapment under the AVVs. Certainly, entrapped air in the system, either on a small-scale or a large-scale basis, can be potentially destructive.

Problems induced by entrapped air range from mild (but potentially costly), to severe and potentially devastating. The damage caused by 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 pump start-ups due to the compression of the entrapped air. Also, movement of air pockets and rapid air release from the pipe can both cause high pressure spikes. Moreover, even under steady state conditions, disruption of the flow, reduction in pump and turbine efficiency and the decrease of flow capacity often disrupt pipelines containing air. That is, the entrained air introduces operational problems in the form of concentrated headloss due to throttled flow. This problem is 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, in order to overcome the extra headloss and to maintain system discharge, pumps often operate at higher heads. This leads to increased electrical consumption and inefficient performance. Also, air influences the pipe material through corrosion, resulting in rapid deterioration of water infrastructure (Bowker et al. 1992) or perhaps over water quality. The consequences of entrapped air pockets therefore justify a thoughtful and efficient air management strategy to prevent air entrainment or to remove the entrapped air from the pipe.

Stated another way, curbing entrapped air boosts the operational and energy efficiency of pipe systems, and air management in water pipelines is therefore of crucial concern to engineers. With emphasis on energy conservation while still achieving a desirable system performance, attention has been given to efficient removal of entrained/entrapped air pockets from the system, decelerating deterioration of pipes due to air-induced corrosion, and preventing sewer systems from explosive events and damage. Achieving sustainability is a major challenge that will require transformational changes in approaches to managing air in water networks. Such consideration requires that air behaviour in pipes be explored and effective (and possibly innovative) air control measures be proposed.
Improving air management in water or wastewater systems and proposing innovative solutions requires an extensive review on current air management strategies and an exploration of the gaps in existing knowledge. Previous reviews (Escaramellia 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 water (i.e., the required velocity to transport air bubbles downstream). The current chapter summarizes the issues created by air in water or wastewater systems, and two air management strategies are discussed and critiqued. Knowledge gaps which limit an efficient application of air management strategies to real world problems are explored, and suggestions for future works are presented.

2.2 Sources of air in pipes

The air entrained into the system can be categorized as small-scale and large-scale air. The entrained air bubbles would collect at high points along the pipeline in an undulating profile and create larger air pockets.

2.2.1 Small-scale air

One key source of air in pipes is the dissolved air in water, which is up to 2% by volume (Dean 1999), which can come out of the solution as small air bubbles due to a pressure drop in the system. Such low pressure zones are introduced into the system at high points along an undulating pipeline or at partially open valves. Also, dissolved air comes out of solution due to turbulence and temperature increases, since warmer water permits less dissolved air at saturation, and turbulence promotes the exchange process. Although initially in the form of small air bubbles, over time the released air tends to collect at pipe summits and can result in severe consequences.

2.2.2 Large-scale air in water distribution systems

In addition to small-scale air, large-scale air can get into pipes or be trapped at specific locations along pipelines. For example, large air pockets may become trapped at high points in the system during rapid filling of pipelines with undulating profiles (Lauchlan et al. 2005).
Another source of large-scale air is intentionally discharging air into pipes through air vacuum valves (AVVs) to protect the system from collapse due to vacuum conditions and low pressures. After suppression of vacuum conditions and when pressures reach above atmospheric, air should be discharged from the pipe. However, the malfunctioning of AVVs (i.e., their premature closure) may prevent the air pockets from being completely discharged, entrapping them at AVV locations. Also, air can penetrate into system through small cracks and broken pipes. It can be trapped downstream of check towers or in siphons and pipe bends (Colgate 1966).

Furthermore, a large amount of air may enter the pipe through existing turbulence due to falling jets from the collectors in the pump sump (Figure 2-1). Also, large volumes of air can sometimes be entrained from the atmosphere into the flow at pump inlets due to free surface vortex generation (Denny 1956) or at drop chambers and dropshafts through plunging jets (Figure 2-2). The air entrainment ratio depends on jet length and velocity, nozzle design and diameter, angle of jet inclination and physical properties of liquid (e.g., viscosity). An extensive survey of the early available experimental and theoretical studies on gas entrainment by plunging liquid jets (e.g., empirical formulas for gas entrainment rates) is presented by Bin (1993).

![Figure 2-1 A plunging jet of wastewater into a wet well, entraining air at the pump's intake (Zlochower 2010 with permission from ASCE).](image-url)
2.2.3 **Large-scale air in sewer systems**

In sewer systems, air is trapped during a surcharge event or 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 surcharge flow (Hamam and McCorquodale 1982). Also, air pocket formation is common where ventilation is inadequate. In such conditions, entrapment of air pocket depends on inflow rates and system geometry. In particular, air entrapment is more likely at low inflow rates which cause open channel bores and an air layer at the pipe crown. Reflection of such inflow fronts from system boundaries causes air pockets to be trapped. In order to avoid air pocket formation, adequate ventilation should be provided (Vasconcelos and Wright 2006).

2.3 **Consequences of entrapped air pocket or air release**

The large-scale air pockets trapped either during filling of water transmission pipelines or during surcharging of sewer systems can be detrimental due to the transient-induced high pressure. Also, release of such trapped air pockets, if done carelessly, sometimes creates high pressures. Of great importance are the pressure surges occurring due to 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 for the infrastructure.

2.3.1 Geysering due to air release

In storm or combined sewer systems, entrapped air might be released through partially-filled vertical shafts (so-called “manholes”). 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). Geysers may cause water jets to rise through manholes 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 such as pipes and manholes. For instance, high air-release rates due to rapid filling have been reported to have damaged trash racks at the outlet works of Dillon Dam in Colorado (Falvey and Weldon 2002). Also, surcharging and the associated destructive geyser through the manhole 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 drainage system (Zhou et al. 2004) are reported. Other examples include the blowing off of manhole covers in sewer systems of Amherstburg and Hamilton, Ontario during high inflows (Hamam and McCorquodale 1982). Furthermore, such events have occurred in hydropower plants due to entrained air within a hydraulic jump in a portion of pipes (Nielsen and Davis 2009). Sets of experimental data (Li and McCorquodale 1999) and field measurements (Wright et al. 2011) regarding geysering are reported in the literature.

2.3.2 Studies on 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, photographical data regarding air-water behaviour pattern 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.

The study of air release into a depth of water is comparatively rare in the literature. In situations where 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 trash racks at the outlet structure. Such findings emphasize the need for research in order to explore influential parameters on such destructive consequences and to propose preventive measures, whether during design or during 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.

2.3.3 Transient pressures due to air release

According to the results obtained by Zhou et al. (2002b), the period of the pressure oscillation and magnitude of maximum pressure depend on the size of the entrapped air pocket during filling, the amount of available hydraulic head in the system, and the air release rate. For instance, for high upstream head and small air volume, the period of pressure oscillation is short and the peak pressure is high. For minimal and zero air release, water hammer effects can be neglected. For large air release, there is no air-cushioning effect, and therefore, the water hammer effect is dominant. However, for intermediate air release, the water hammer effect is mitigated. Generally, the resulting high pressure depends on the orifice size of air release (Zhou et al. 2002a, b, c). This implies that size of ventilation structures should be carefully selected 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).

2.3.4 Transient pressures due to entrapped air

In sewer systems, factors affecting transient pressures due to the transition of gravity flow to pressurized flow and the resulting air entrapment are pipe size, shape, slope and material, as well as 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 totally or partially obstructed; partial obstruction usually results in lower peak pressures and fewer oscillatory pressure surges.

In water pipes during rapid filling, the effect of trapped air on transient-induced pressures depends on the length of initial water column and water depth. For instance, larger air pockets tend to mitigate pressure surges (Zhou et al. 2002a,b,c). Generally, start-up (i.e., pressurization) of pipes containing entrapped air should be accomplished with great care. Challenging conditions occur during operation of intermittent undulating pipelines. The presence of air pockets in pipelines often creates high pressure spikes during pipeline start-up (i.e., pressurization). A mathematical model for undulating pipelines containing trapped air showed that the more slowly the pipes are filled, the smaller are the transient pressures that are introduced into the system (Izquierdo et al. 1999). Under start-up conditions, the initial volume of air pockets greatly influences the peak pressures. Also, ignoring elastic effects overestimates the maximum pressure (Zhang and Vairavamoorthy 2006a). Furthermore, in rapid filling of pipelines 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).

2.3.5 Entrapped air and its effect on system dynamics

The presence of air in water pipes sometimes strongly influences the system dynamics. For example, spectral analysis of experimental pressure time series at locations along pipes reveals that air pockets increase the wave travel time due to 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 the size and location of the air pocket with larger air pockets creating a greater increase in wave travel time (Covas et al. 2006, Lubbers and Clemens 2005a, 2007). The effect of air pockets farther from a pump is low. In a pumping system, the duration of low pressure at locations farther downstream is less, and therefore, air pockets at
those locations experience low pressures during a shorter period 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 in order to explore whether the presence of air pockets accounts for capacity reduction of a pressure main (Lubbers and Clemens 2005a, 2007). However, this method requires prior knowledge of the location of the air pocket. On the other hand, the pressure spike and the subsequent low pressure at air pocket locations, as well as the reduction in wave travel time, can be used 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 detections are crucial for the design and operation of water pipes.

2.3.6 Headloss due to entrapped air

Another consequence of entrapped air pockets in pipelines is the head loss and the associated increase in energy consumption for pumping a desired flow. In the presence of air pockets, pipe carrying capacity is reduced. That is, the effective flow area in the pipe is reduced and the flow encounters more resistance and head loss. In such conditions, since friction loss is proportional to the square of the flow rate, head loss is magnified. For example, a 10% air volume in the pipe can cause a 20% increase in head loss (Stephenson 1997). Escarameia (2007) confirmed head losses across air pockets were 25-35% more than the identical water pipes without air pockets. Submerged hydraulic jumps at the end of air pockets are other causes of headloss. However, hydraulic jumps can be beneficial by enabling air removal. Also, in wastewater systems, the transport capacity is often reduced due to the presence of accumulated air pockets (Lubbers and Clemens 2005b). Under such conditions, gas pocket headloss is reported to be equal to $L_g \sin \theta$, where $L_g$ is the length of air pocket and $\theta$ is pipe angle with horizontal (Pothof et al. 2013, Lubbers 2007).

Furthermore, experimental data validates that headloss is a function of conduit geometry (e.g., slope), air pocket length and surface tension. Also, headloss increases with drag and turbulence (Lubbers and Clemens 2005b). Furthermore, air pocket headloss 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 headloss 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) is shown to be effective in increasing the air transport capacity of water, the reduced surface tension in real world domestic wastewater (caused by proteins and surfactant additives) is not sufficient to observe such an increase in transport in downward sloping pipes (Pothof et al. 2013).

Note that the consequence of entrapped air in water pipes under steady state conditions (i.e., head loss) has received little attention in the literature. The available studies on air pocket headloss (Posoz et al. 2010a, Lubbers and Clemens 2005b) cover only the low operating pressure conditions which are more common in sewer systems rather than in pressurized water mains. Except for the limited measured air pocket headlosses reported by Escaraemia (2007), other experimental data has been obtained under pressurized conditions slightly above atmospheric pressures (Posoz et al. 2010a, Lubbers and Clemens 2005b). Obviously, it is questionable to apply the results of such studies to pressurized water mains where pressures are significantly higher. For example, in systems with a high point (Figure 2-3), 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.

![Figure 2-3 Steady state HGL in a system containing entrapped air pocket at the high point and the associated headloss](image)

In order to quantify the headloss due to an air pocket in pressurized conditions, the capacity of air accumulation in the most susceptible locations along pipelines (i.e., high points) should first be studied. This can be investigated numerically by applying sophisticated CFD modelling. It is
necessary to explore air pocket volumes accumulated at high point locations with different slopes and lengths and the associated headloss as a function of pressure. Figure 2-3 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 headloss are different. Here, such a relationship is illustrated through an example by adopting some preliminary assumptions.

Figure 2-3 shows the system under study. 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 distributes along the descending portion of the high point after the pipe is filled and steady state flow occurs. Neglecting minor inlet and outlet losses, the steady state HGL (hydraulic grade line) is shown in Figure 2-3. It is assumed that polytropic air expansion and compression (Equation (2-1)) occurs and air pocket headloss can be estimated by Equation (2-2) presented by Pothof et al. (2013). Summing up friction losses and air pocket headloss, a nonlinear equation as a function of steady state discharge (Equation (2-3)) is derived which can be solved by trial and error for the steady flow and, consequently, the air pocket headloss. In the system under study (Figure 2-3), \( H_1 \) (m), \( H_2 \) (m), and \( f \) are 100, 50, and 0.017, respectively. And, each pipe length (\( L_1, L_2, L_3, \) and \( L_4 \)) is 500 m. The steady state discharge (\( Q \)) and air pocket headloss (\( h_{f,air} \)) are computed by Equations (2-3) and (2-2), respectively, at different high point elevations. Results are shown in Figure 2-4. According to this Figure, air pocket volume (\( V_{air} \)), its associated headloss (\( h_{f,air} \)) and the final steady state discharge (\( Q \)) varies at different high point elevations. As the high point elevation decreases, the pressure (\( H_P/\Delta H \)) increases, and therefore, both the entrapped air pocket volume and the associated head loss are reduced. Although quite approximate, such a quantification of the effect of pressure on air pocket-induced headloss is helpful and justifies a more detailed and accurate study on this subject under pressurized conditions.

\[
P_{air}V_{air}^{1.2} = C \tag{2-1}
\]

\[
h_{f,air} = S_{2}l_{air} \tag{2-2}
\]
where, $P_{air}$ is the air pocket pressure, $V_{air}$ is the air pocket volume, $C$ is a constant, $h_{f,air}$ is air pocket headloss, $S_2 = \frac{Z}{L_2}$ is the high point slope and $l_{air}$ is air pocket length

$$h_1 - f_1 \frac{Q^2}{2gD_1^2} - f_2 \frac{Q^2}{2gD_2^2} - S_2 \times \left( C \left( h_1 - f_1 \frac{Q_1^2}{2gD_1^2} - f_2 \frac{Q_1^2}{2gD_2^2} - Z \right) \right) \frac{1}{2} - f_3 \frac{Q^2}{2gD_3^2} - f_4 \frac{Q^2}{2gD_4^2} - h_2 = 0$$

(2-3)

Figure 2-4 Effect of water pressure on air pocket volume, the corresponding headloss, and the resulting steady state flow in a pressurized water main as depicted in Figure 2-3, $Q_0$ is the steady state discharge in the system without the presence of air pocket

2.4 Air management strategies

There are several strategies for managing air in pipes in order to decrease or prevent the devastating consequences of air pockets which are introduced either in wastewater systems during storms or in pressurized water mains due to entrance of air at the inlets of pipes and pumps, during filling, and through application of surge protection devices such as air vacuum valves (AVVs). Generally, the available air management policies are categorized as follows: air prevention, consideration of hydraulically removing air bubbles or entrapped air pockets from pipelines, and application of air release devices such as air valves or air vents. In this chapter, 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.
2.4.1 Air prevention strategy

A significant hydraulic issue occurring at water pipe intakes is the formation of 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 can potentially introduce a substantial amount of air into pipes. Air-core vortices have been illustrated by Gulliver et al. (1986). Several experimental and theoretical studies on the free surface vortex have been 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, uniform open channel flow, and the intakes are either horizontal or vertically upward or downward with rectangular and circular shapes (Anwar 1965, Odgaard 1986, Yidrim and Kocabas 1995, 1998, Yildrim 2004, Denny 1956). Such geometries are commonly used in pump intakes and hydraulic structures.

Pioneering studies by Denny (1956) revealed that a mere 1% air volume into the pump’s suction line through air entraining vortices can reduce a centrifugal pump performance up to 15%. Other studies show that air volumes greater than 3% significantly reduces pumps performance, and in extreme conditions, damages its mechanical components (Murakami et al. 1969 cited in Chang and Lee 1995, Patel and Runstadler 1978 cited in Chang and Lee 1995, Florajancic 1979 cited in Chang and Lee 1995). Hence, to prevent air entrainment at intakes, a critical submergence (Sc), at which air entrainment would begin, should be determined.

Critical submergence (Sc) has been studied in a vertically-oriented downward intake pipe in both the still reservoir and open channel flow for permeable and impermeable bottom by Kocabas et al. (2008). Diameter of the intake pipe, and water velocity in the intake and channel as well as permeability of bottom of the intake tank are influential factors on critical submergence ratio (i.e., the ratio of critical submergence to intake diameter) (Kocabas et al. 2008, Kocabas and Unal 2010). For a given channel velocity, the same critical submergence ratio occurs at higher intake velocity in permeable bottoms compared to impermeable ones. At a given channel velocity, the effect of permeability on critical submergence ratio is lowered for high intake velocities. Overall, critical submergence ratio decreases with channel velocity and increases with intake velocity in both permeable and impermeable bottoms.
Other factors influencing the critical submergence 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 (Re), Circulation number, Weber number of the intake (Jain et al. 1978 cited in Chang and Lee 1995, Culliver and Rindels 1987), and viscosity (Jain et al. 1978 cited in Chang and Lee 1995), as well as impervious boundaries’ blockage effects (Yidririm et al. 2000, 2007). However, surface tension and viscous effects are insignificant for some limit values of Froude number ($Fr$), Weber number ($Wb$), Reynolds number ($Re$). Such limiting values differ for each system due to 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 Yeldirim 2002). A comparison by Li et al. (2008) on empirical formulas relating critical submergence to intake Froude number (Reddy and Pickford 1972, and Odgaard 1986) showed that the critical submergence 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 critical submergence 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 critical submergence due to the existence of upstream intakes. The critical submergence should be larger in dual intakes due to 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 critical submergence compared with a single isolated intake becomes necessary (Yildirim and Tastan 2009).

In hydraulic systems, it is hard to find an exact relation between parameters affecting critical submergence ($Sc$). And, experimental and theoretical studies in the literature have led to proposing several empirical equations to predict critical submergence of intakes mainly in an open channel. Such empirical formulas are based on prototype and physical model studies and relate the relative critical submergence ($Sc/D_i$, where $D_i$ 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 (Kocaabas and Yidirim 2002, Odgaard 1986, Reddy and Pickford 1972) mostly estimate Sc as a function of Froude number, Reynolds number, Weber number, and circulation as well as the vertical height of intakes. Other studies have proposed equations that relate $Sc/D$ to a non-dimensional circulation number defined as $\Gamma/(2\pi g l/2D^{3/2})$, where $\Gamma$ is the vortex circulation defined as $\Gamma=2\pi rv_\theta$; and $Sc$ is the critical submergence; $D$ is the intake diameter; $g$ is acceleration due to gravity; $v_\theta$ 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, Odraard 1986 and Sarkardeh et al. 2010). Due to the complexity of the process, such conventional formulas based on regression approaches may not be good representatives for estimating $Sc$.

To estimate $Sc$, accurate empirical formulas are required. 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 $Sc$. Critical submergence is predicted using empirical equations, multi-linear regression, back propagation ANN and M5 model tree based modelling (Goel 2012) as well as classification and regression tree (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 bottom (Kocabas et al. 2008). Also, potential flow theory and dimensional analysis are applied to determine $Sc$ for intakes from both an open channel flow and still water reservoirs (Yildirim and Kocabas 1995, 1998, 2002, Yidrim et al. 2000, 2009, Yidirim and Tastan 2009).

Although these results help to understand the effect of different features of intake geometry and flow characteristics on critical submergence 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 since they do not provide quantitative information which 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 critical submergence in multiple intakes.
Another air prevention strategy is applied by preventing vortices at the intake. The available alternatives are illustrated in Gulliver et al. (1986): guiding the far field flow, reducing intake velocity or installing anti-vortex devices such as a funnel (Trivellato 2010) and horizontal perforated and solid plates at the top of intakes (Amiri et al. 2011).

2.4.2 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, as well as pipe slope and diameter, are the factors affecting flow patterns (Escarameia 2007). Rouhani and Sohal (1981) provided reviews of the two-phase flow patterns.

In theory, the following three main forces acting on an air pocket should be considered to find the criteria for air movement: buoyancy, drag, and 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 2005). However, 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 based on 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.

2.4.2.1 Sweeping

Most of the published work on air removal has been experimental, in which the study’s main 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 widely studied leading to introducing 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. Based on dimensional analysis, critical velocity is a function of Froude number, Reynolds number, surface tension and pipe slope (Bendiksen 1984, Falvey 1980 and Wisner et al. 1975). 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, and Zukoski 1966). Thus, in the literature, it is assumed that the critical velocity for a given pipe slope is proportional to \( gD \), where \( g \) is acceleration due to 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 \( V/\sqrt{gD} \), where \( V \) is the average velocity. According to the formulas, the steeper the downward slope, 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 non-dimensional air pocket size parameter, \( n \), previously used by Kent (1952), where \( n = 4V_{air}/\pi D^3 \), \( V_{air} \) 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 22.5º) 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, as well as with acceleration due to gravity. However, dependence on \( D \) is questionable due to 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 non-dimensional parameter as defined in the previous paragraph). Also, the focus of her study is on bubble to plug flow regimes, where 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.

2.4.2.2 Hydraulic jump leading to air generation and 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 due to air entrainment by the hydraulic jump. Then, these small bubbles will be transported downstream if flow velocity is more than 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, while Ervine (1998) summarized the literature on air entrainment at hydraulic jumps. Additional studies by Escarameia (2007) and Pothof et al. (2010a and 2010b) 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 (Figure 2-5). 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 due to 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 2005) and sudden air outflow (geysering) (Zhou et al. 2002b) are the common disadvantages.
Figure 2-5 (a) change in bottom slope, (b) siphon, (c) sluice gate, (d) air pocket, (e) a sketch of hydraulic jump in a sloping section with downstream pressurized flow (Hager 2010, with permission from the publisher)

The three characteristics of a hydraulic jump (Hager 2010) are the roller length (i.e., the distance from the toe of the jump to the stagnation point at the free surface), aeration length (i.e., the distance from the toe of the jump to the section where air bubbles have left the flow), and jump length (i.e., the distance from the toe of the jump to the point where the jump profile meets the system hydraulic gradeline, i.e., \( L_j \) in Figure 2-5(e)). The location of the hydraulic jump depends on the flow conditions at the upstream and downstream reaches.

Air transport through hydraulic jumps has been studied in rectangular cross sections (Rabben et al. 1983, Rajaratnam 1967, Wisner et al. 1975, and Ahmed et al. 1984) or horizontal circular pipes (Kalinske and Robertson 1943) and circular pipes with downward and upward slopes (Escarameia 2007, Falvey 1980, Pozos et al. 2010a). 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 has 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 \( Q^2/gD^5 = S_0 \), where \( Q \) is the water discharge, \( g \) is acceleration due to gravity, \( D \) is pipe diameter and \( S_0 \) is pipe slope (5° to 60°) (Pozos et al. 2010a). 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).

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 since 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 slope smaller than about 5% is negligible in rectangular ducts (Hager 1992). Hence, cross section and length of the pipe as well as flow characteristics are the factors that should be considered while accounting for air removal by hydraulic jump at the design stage.

Furthermore, an air relief system such as 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 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 air entrainment rate \( \frac{Q_{\text{air}}}{Q_{w}} \) as long as downstream pipe length is greater than the aeration length of the primary jump. Otherwise, air entrainment varies slightly independent of 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 due to 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 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 one meter. For example, to apply the available air entrainment rates to designing air control devices, pipe shapes and downstream flow conditions (Escarameia 2007) as well as water temperature (Mortensen et al. 2011) should be the same in model and prototype.

As illustrated, bubble motion as opposed to air pocket motion has received more attention in the literature. Significantly, though, published experimental works have rarely considered scale effects; such effects must be accounted for if one is to generalize and apply such empirical formula to real world problems and to provide design guidelines for hydraulically managing air in pipes. Clearly, though, the area of air pocket movement still needs further investigation.

### 2.5 Summary

Devastating consequences are sometimes associated with entrapped air during transient events or while releasing air from pressurized pipes. This reality justifies a careful review of air management strategies in order to understand the current available practice and improvements as well as the possibility of further research and development. This chapter overviews the published sources of air in both water and wastewater systems and the associated consequences, providing a critical review on the two air management strategies. Improvements in the literature are discussed and the gaps that prevent these strategies from greater feasibility and applicability to real world problems are explored.
Consequences of air pockets are categorized into the two 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 to researchers. While most of the studies deal with air release into an air medium, the study of air release into water is rarely available. 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 due to 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 on this topic mostly attempts to experimentally explore the critical submergence of intakes with different geometries in order to prevent air intrusion due to the entrance vortex. However, almost all of these studies are case-specific and do not provide general guidelines or rules of thumb. Hence, literature does still not present a clear enough of understanding scale effects and determining accurate and general practical guidelines. Obviously, the financial and time constraints for a physical model study in most projects justifies developing a set of design criteria for critical submergence especially for multiple intakes. CFD approaches are developing quickly but tend to be expensive, case specific, and still infrequently applied to routine system analysis.

Finally, the air management strategy of hydraulically removing air from the system is summarized. 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. On the other hand, to safely apply the empirical air entrainment rates by hydraulic jumps at the design stage to real world problems, further research is required to address scale effects due to pipe size and water temperature. In conclusion, establishing a general design guideline for air management in water
pipes requires physical understanding of air behaviour in water pipes through theoretical, experimental, and numerical exploration.
Chapter 3
The challenge and promise of air valves as an air management strategy: a selective critical review of the literature

This Chapter is based on Ramezani et al. (2015) with permission from ASCE.

One key alternative for removing, preventing, and managing air movement and entrapped air in water pipelines are a variety of available air valves. Despite their effective role, such valves are problematic if not well selected, designed and maintained. This chapter critically reviews current design, application, functionality, and simulation of air valves and the associated shortcomings with more focus on air vacuum valves (AVVs). It is argued that the efficient number of air valves along undulating pipelines is yet to be fully articulated. Moreover, modification to air valve simulation should consider their dynamic behaviour, the physical behaviour of air pockets forming below the air valve, and varying water surface at the air valve location. Also, the need for a comprehensive and systematic study on proper sizing and location of AVVs for transient protection of the system is discussed. Overall, the efficient application of such devices requires conducting broader research and development both in the realm of the theoretical context (i.e., their physical behaviour, and modifying their numerical simulation) and in the context of experimental or field studies (i.e., their dynamic behaviour and operational efficiency).

3.1 Introduction

The goal of controlling air in water pipes is to decrease or prevent the potentially devastating consequences of both mobile and entrapped air. Among air management strategies, the most popular is the application of air release/vacuum valves. Air release valves (ARVs) remove small-scale air present in pipes, while air vacuum valves (AVVs) generally allow for more large-scale removal/admission of air during filling/drainage or pipe break scenario. Also, AVVs may become active during transient conditions such as pump failure, admitting air into pipes under sub-atmospheric conditions and removing the admitted air once pressure increases. Combination air valves (CAVs) integrate functions of both ARVs and AVVs. However, air valves play a complex role and may potentially expose the system to extreme transients and
catastrophic failures, particularly if they fail, function improperly or are poorly selected, sized and located.

Despite the widespread application of air valves in water lines, quantitative data regarding their operational efficiency is scarce. Also, too little attention is often paid to their maintenance and operational issues. Such problems compromise the effective role of air valves in water systems. Obviously, the proper use of air valves is only possible if such concerns are understood and appropriate measures are taken to provide an efficient design criteria intended to eliminate, or at least reduce, the severity of such events. This chapter suggests that improvement in the design, operation and maintenance of air valves would greatly enhance their role in mitigating real world problems.

To provide a comprehensive perspective of current and potential research issues, this chapter reviews the published design criteria for air valves, and the readily available knowledge on air valve performance as well as their known or potential operational and maintenance problems. First, current design approaches for both air release and air vacuum valves are critically reviewed. Then, operational and maintenance problems are discussed. The review focuses on operational problems in the form of amplified overpressures due to secondary transient events. Also, suggested alternatives for preventing operational and maintenance problems of air valves are presented and examined. Finally, the real world dynamic behaviour of air valves reported in the literature is reviewed and the importance of simulating air valves based on such dynamic behaviour is emphasized.

**3.2 Current design practices of air valves**

The process of designing air valves and AVVs starts from decisions about air valve size and their positioning along the pipeline. Clearly, too few valves will inadequately protect the system and too many represents a waste of capital and operating resources. The process continues by selecting one of the marketed types of air valves. However, the choice of an appropriate size and location of an air valve is difficult and problematic, forcing one to face either implicitly or explicitly the difficulties associated with unaddressed air or poorly-performing air valves. Engineers often refer directly to manufacturers or to practical recommendations provided in AWWA M51 (American Water Works Association) for selecting the required size of air valves.
and for deciding about their location along the pipes, a guideline that seeks to provide a basic understanding of the use and application of air valves (AWWA 2001). Also, there are some guidelines in manufacturer’s catalogues which vary from one manufacturer to the other, and there is little clear justification as to why this variation in design criteria exists. However, AWWA M51 recommendations are those most often used to select the size, location, and type of air valves.

3.2.1 Sizing air release valves (ARVs)

A key design parameter of an ARV is its orifice size. According to the current AWWA design guideline, the air flow rate which determines the size of the ARV is based on two percent dissolved air in water at standard pressure and temperature (AWWA 2001). This accounts for an airflow rate of two percent of the fluid discharge in the system assuming that each ARV is to release all the air dissolved in the fluid at any one of the air valve stations. However, the actual dissolved air in water varies with pressure and temperature, and circumstances are seldom so extreme as to expect this potential amount to ever released. That is, no particular section of water pipes releases this entire amount of dissolved air due to the small pressure changes along the pipeline. This implies that if the first ARV, along a pipe, releases this amount of air, there is no air left to be released by the second ARV. Therefore, this criterion often overestimates the size and number of air valves along a pressurized main where pressure is changing. McPherson (2009) proposed considering the reduction in dissolved air volume under operating pressures in order to design smaller air valves. However, the cost effectiveness of this approach requires a broader study. On the other hand, air in the gaseous phase may enter the pipe from other sources (e.g., pumps and valves). Hence, this uncertainty and variability in the amount of air makes the design criterion for size of ARVs problematic. Considering the uncertainty in the amount of air intrusion into the system, the following questions arise: what air flow rates should be used as design criteria for sizing ARVs? Or, more clearly, what size of ARV efficiently removes small-scale air in pipes and enhances system performance?

3.2.2 Sizing air vacuum valves (AVVs) for filling and draining/pipe break

Sizing AVVs is a crucial consideration since, for a specified air flow, valve size controls the pressure differential at which the air is exhausted. A minimum valve size is established by
finding the size for filling, which is usually less than the size for drainage. In initial filling of
pipelines, air flow rate through the AVVs should be the same as pipe filling rate (i.e., 0.3 m/s).
For a draining scenario, rate of air admission should be the same as rate water is drained (i.e.,
0.3-0.6 m/s). In practice, pressure differentials of 2 and 5 psi are considered for designing filling
and draining scenarios, respectively (AWWA 2001). The 2 psi is a threshold pressure which
maintains a low air speed in the valve orifice to prevent turbulence, valve slam, and substantial
pressure rise leading to premature closure. The 5 psi differential pressure for air inflow has been
considered a safe pressure threshold to protect the pipeline and gasketed joints from damage due
to the influence of vacuum pressures. To protect the system against pipe break (AWWA 2001,
Parmakian 1950), AVVs sizes are selective based on gravity flow considerations. When sizing
of AVV for gravity flow, the slope of the pipe determines the air volume required to prevent
vacuum conditions.

Valves are rated according to maximum pressure under which they can operate as well as by
orifice size (Thomas 2003). The manufacturers provide their customers with sizing tables or
performance curves with recommended operating pressures. Figure 3-1 is a performance graph,
typical of those provided by an air valve manufacturer, for sizing AVVs based on the filling
scenario. Evidently, orifice size of air valves is designed according to the air flow rate in the
system and pressure differential across the valve. Generally, in water distribution systems, the
recommended outlet diameter of AVVs for the filling scenario is 50-200 mm while diameters of
1-5 mm are suggested for ARVs to release air under pressure during normal operating
conditions (Stephenson 1997).
Furthermore, ARVs should be sized so that they prevent destructive transient pressures (also refer to section 3.3.1). Considering air flow rate under sonic conditions, Bianchi et al. (2007) studied experimentally and theoretically the appropriate size of air valves during a filling scenario in order to avoid any transient pressures. The basic considerations for deriving these practical equations are the maximum allowable overpressure and maximum desired filling velocity. The most suitable size for air valves under the filling scenario is suggested to be the one that releases the air in a shorter time while generating allowable overpressures. For anyone who has not directly experienced it, it should be noted that the acoustic impact of a valve approaching sonic conditions can be excruciating. Hence, sound should be a consideration in air valve design.

3.2.3 Sizing AVVs for transient conditions

As illustrated in the previous section, the sizing choices of AVVs are usually driven by consideration of filling and draining/pipe break scenarios, two of which are largely controllable events (e.g., filling, draining). Obviously, filling and draining rates can usually be controlled to prevent any consequence of entrapped air in the system. Also, large inlet size of AVVs sized on the basis of pipe break can introduce contaminant flow into the pipe if not well designed and maintained. However, AVVs can have a more crucial role in protecting the system against transient events resulting in vacuum conditions. Vacuum conditions occur in pipes as a result of
sudden transient events such as power failures at pumps. There can be huge consequences to pipelines in the presence of such negative pressures. For instance, the resulting negative pressures cause flow disruption and they allow contamination to enter into water supply pipes. Hence, it is more conservative to size and locate AVVs by considering such events. In other words, the size of the inflow and outflow orifices of AVVs should be selected with care at locations where transient events create such potential consequences if vacuum conditions are to be controlled efficiently.

AVVs can protect the system against such negative pressures if well sized and located. Otherwise, they themselves induce secondary transient events as illustrated in section 3.3.1. For instance, high outflow air valves exacerbate positive transient pressures in systems with negligible amounts of entrained air (Lee 1999, Stephenson 1997). The importance of AVV characteristics on transient pressure surges is shown by a case study of a large twin pumpline by Devine and Creasy (1997). A large outlet may result in rapid expulsion of air and consequent high pressures. However, with smaller outlets, the air cavity below the air valve can cushion the deceleration of the reverse flow. This helps to control the secondary transient pressures (Lee 1999). However, if the outlet size is too small, greater air compression occurs below the AVV. It should be mentioned that air under pressure can contain a huge amount of energy and can potentially cause an explosive condition. Hence, leaving the pressurized air in the system should actually require that the system be designed according to the strict ASME codes for pressure vessels. This is seldom done. Thus, discharging air too slowly or trying to use cushioning effect of air directs us to a new set of design codes which is a complication in water pipelines. It is usually advised to properly size AVVs to prevent such explosive conditions, with the idea of designing water pipelines based on air vessel codes rejected (or simply ignored). Generally, AVVs with low outflow and high inflow capacity have been effective in suppressing peak pressures and valve slamming as well as reducing negative pressures caused by transient events (Espert et al. 2008, Lee and Leow 1999).

Properly sized and located AVVs can potentially serve as a complementary surge control device, especially in highly undulating pipelines where it is required to place a large size air vessel. In such situations, placing AVVs in the system may dramatically reduce the size of a large and expensive surge vessel. The effect of AVVs on reducing the size of main surge control devices in the system is sometimes remarkable as shown in Figure 3-2. In this example, an air
chamber, located near the pump at upstream end, is designed for sudden power failure both with and without the presence of AVV at the high point. As shown, the air chamber size without considering AVV at the high point is 200 m$^3$ while introducing AVV at the high point reduces air chamber size to 25 m$^3$. That is, the presence of AVV at the high point reduces the size of the air chamber by 87.5%, resulting in large cost saving. Even this simple consideration confirms that AVVs can be highly influential in reducing the cost of main surge protection devices in undulating pipelines.

![Figure 3-2 Effect of the presence of AVV at the high point on reducing air chamber size (reduction of 87.5% in chamber size)](image)

Furthermore, there is a crucial area ratio between air valve inlet and outlet if these valves are to play the role of a water hammer protection device (Zhu et al. 2006, Yang and Shi 2005). Of course, the magnitude of severe pressure peaks after rapid air valve closure also depends on the location of AVV, pipe configuration, and flow characteristics. For instance, when a transient event occurs upstream of the AVV, the severity of secondary transient pressure at the AVV location (Figure 3-3) depends on the intercepted wave height (i.e., $H_p$) at the high point. In this Figure, $\Delta H_1$ is the reduced transient pressure wave induced upstream of AVV. $Q_p/Q_0$ is the ratio of reduced discharge after the wave arrives at the high point. As shown, for higher elevations of the high point, the intercepted wave height is reduced, $Q_p/Q_0$ is increased and, therefore, the secondary transient pressure is higher (Ramezani and Karney 2013 and Chapter 4 of the current work). However, a systematic study of the effect of the size and location of AVVs on secondary...
transient pressures has yet to be published. That is, current studies are performed within a single system configuration and they have not explored the locations where the proper sizing of AVVs are most or least crucial in transient events.

![Diagram of AVV](image)

**Figure 3-3** Effect of intercepted wave height on secondary transient pressures at AVV location in a reservoir-pipe-reservoir system with a high point in the middle: (a) Layout of the system which is exposed to a sudden pressure drop at the upstream boundary, (b) Effect of intercepted wave height at the high point (H_p/ΔH_1) on secondary transient pressures (ΔH_{max}/ΔH_1) at AVV location. (Ramezani and Karney 2013)

### 3.2.4 Location of air valves

The second design parameter of air valves (i.e., ARVs, AVVs, or CAVs) is their location and distribution along the pipeline. AWWA recommends installing air valves at intervals along ascending, descending, and horizontal lines (i.e., intervals of 1,500 to 2,500 feet), and changes in grade as well as all the local high points along the pipe profile. However, this is at times a conservative approach and it is seldom specified how critical each location is. Elevated high points are naturally the most common places that ARVs or AVVs are recommended. Characterizing critical high points to install ARVs and AVVs or CAVs requires knowledge about the potential of air accumulation at the high point and the transient behaviour of the system, respectively. However, there is little published work regarding the influential parameters on air accumulation along pipelines or at high points in pressurized systems. Moreover, little work has been done regarding the locations along pipes where appropriate selection of AVVs is crucial for alleviating transient-induced pressures.

Placing ARVs at improper locations can be problematic. Among the improper locations of placing ARVs are the high points running under siphon conditions. Obviously, the existence of a permanent vacuum condition at the high point (e.g., with a siphon) may restrict the application
of ARVs at those locations. According to manufacturers’ catalogues, ARVs can potentially operate under vacuum conditions admitting air into the system. Hence, placing such valves at siphons where permanent vacuum condition exists may lead to flow disruption due to breaking the siphon. In such cases, the location of the high point relative to the downstream boundary affects the magnitude of the discharge reduction.

The consequence of placing ARVs at siphon locations is easily illustrated. Figure 3-4 shows a configuration in which placing an ARV at the high point, previously running under vacuum condition (i.e., a siphon), breaks the siphon flow. Obviously, siphon flow can be calculated by writing the Bernoulli equation between points 1 and 2 as well as 1 and S (Figure 3-4), resulting in Equations (3-1) and (3-2), respectively. However, at the high point, existence of an ARV which can potentially activate during vacuum conditions may introduce air into the system, increasing the pressure to atmospheric pressure and reducing the design discharge. Here, the governing equation is Equation (3-2). The reduced discharge can be calculated by considering the atmospheric pressure at the high point and solving for flow velocity by Equation (3-2). For this example, the pipe diameter (m), pipe length (m), design discharge (m³/s), friction factor, and $K_1$ are 0.5, 2000, 0.328, 0.017, 0.5, and 1, respectively. The change in relative design discharge ($Q/Q_d$) with the location of the high point is shown in Figure 3-5 in which $Q$ is the reduced discharge and $Q_d$ is the design discharge. As shown, the flow reduction is affected by the location of the high point relative to the downstream boundary. The closer the high point to the downstream boundary, the more flow reduction occurs by admitting air into the system. Such effects are more pronounced in shorter pipelines. To illustrate, Figure 3-6 is obtained by considering a constant pipe length upstream of the high point in Figure 3-4, and altering the downstream pipe length. As seen in Figure 3-6, as the downstream pipe length reduces, the discharge reduces.

$$Z_1 - Z_2 = \frac{V_2^2}{2g} + f \frac{L}{D} \frac{V_2^2}{2g} + K \frac{V_2^2}{2g}$$  \hspace{1cm} (3-1)$$

$$Z_1 - Z_S = \frac{P_S}{\gamma} + \frac{V_2^2}{2g} + f \frac{L_{s-S}}{D} \frac{V_2^2}{2g} + K_1 \frac{V_2^2}{2g}$$  \hspace{1cm} (3-2)$$
To prevent such reduction in design flow at siphons, AWWA (2001) recommends placing a vacuum check device at the outlet of the ARV. Although manufacturers claim to provide vacuum check valves, their function and practical efficiency in siphon conditions is still questionable. Even if these devices are effective in preventing the siphon break, possible malfunction of such devices may result in lowering the design discharge and the hydraulic efficiency of the pipeline. Hence, placing ARVs at such locations requires a detailed study of
such potential effects and consideration of the associated risks.

3.2.5 Type of air valves

The third design parameter is the type of air valve. After selecting the appropriate size and location of air valves, the designer must select among a variety of types of air valves marketed by manufacturers. While applying the same hydraulic and mechanical principles, these valves are different in physical properties (i.e., material, shape, float arrangement) and performance criteria with optional add-on features such as surge relief or anti-slam devices (McPherson 2009). For example, while AWWA recommends air valves made of cast iron, all manufacturers offer different material bodies such as ductile iron, stainless steel, cast steel, and cast bronze as well as polypropylene and reinforced nylon. Obviously, the capital cost of these valves differs but the maintenance cost is unknown and the relative merits are often unclear (Radulj 2007). It is seldom obvious to designers what characteristic parameter of these valves (e.g., working pressures, anti-slam features, or fewer reported failures) gives them priority over others in a specific watermain. In other words, the influence of such characteristics on system performance is not yet fully reported. Furthermore, there is a gap in the literature regarding whether such different types of air valves may affect the overall and proper number and size of air valves in a given system. Overall, the priority of one type of air valve over others is still contested.

3.3 Operating problems of AVVs during air release

The main function of AVVs is to expel excess air when the system experiences high pressures and to admit air when sub-atmospheric conditions occur (Wylie and Streeter 1999). However, analysis of the transient behaviour of systems protected with AVVs either by developing and applying numerical models (Lee and Leow 1999) or using simplified water hammer equations (Lingireddy et al. 2004; Li et al. 2009) reveals that rapid expulsion of air through air valves may cause severe transient pressures referred to as secondary transient pressures.

3.3.1 Secondary transient pressure during air release

A secondary transient event is caused by rapid air expulsion and subsequent rapid valve closure. When water strikes the closed air valve, it moves at the same rate as the exhausting air leading to severe flow deceleration and high pressure surges inside the valve. This is most common both
during filling scenarios and after suppression of vacuum conditions while the incoming air from
the AVVs is getting released from the pipe. Secondary transient pressures were experimentally
studied during filling scenarios in a simple horizontal (Zhou et al. 2002a,b, Martin and Lee
2012) or a more complex (De Martino et al. 2008) piping system. Peak pressures up to 2.7 and
15 times the upstream absolute head were observed in d/D < 0.086 and d/D = 0.2 (where d is air
valve diameter, D is pipe diameter), respectively (De Martino et al. 2008, Zhou et al. 2002a,b).
In addition, Martin and Lee (2012) observed that maximum pressures at the air valve orifice
occur at d/D = 0.18 and it is influenced by both the orifice size and the ratio of absolute
upstream reservoir pressure to the initial absolute air pressure near the valve in a simple
horizontal reservoir-pipe system. They concluded that initial air volume at the valve is less
influential on peak pressure compared to the two the aforementioned factors. Also, numerical
results of secondary transients are presented during rapid shutdown and subsequent start-up of a
pumping line for an undulating pipe containing an air valve at the high point (Lingireddy et al.
2004). A simple predictive formula is also available for calculation of the maximum pressure
based on Allievi-Joukowski results (De Martino et al. 2008). Secondary transients can lead to air
valve or other component breakage. For instance, such frequent high pressures have caused
breakage in the inlet or outlet sections of air valves in Pinellas County’s wastewater force main
(Li et al. 2009).

Other conditions for creating secondary transients occur when these valves do not operate well
and premature closure occurs (Lee and Leow 1999; Lingireddy et al. 2004; Li et al. 2009). For
instance, conventional air valves can prematurely close at surprisingly little pressure change
(Thomas 2003) and it is difficult to limit pipeline pressures to below-closure thresholds.

3.3.1.1 Pressure oscillation patterns during air release

Depending on the size of the air release orifice, three types of pressure oscillation patterns occur
in the entrapped air pocket during rapid filling of a pipeline (Zhou et al. 2002b). There are two
phases in each oscillation pattern: a low frequency pressure oscillation (i.e., rigid column
behaviour) followed by a sudden pressure peak (i.e., water hammer behaviour) when the water
column first reaches the orifice (De Martino 2008, Zhou et al. 2002b). The duration of the first
phase is reduced with an increase in driving head and orifice size, and increases with air pocket
size (De Martino 2008).
For small orifice sizes, the air cushioning effect is dominant and the period of pressure oscillation is long. For large orifice sizes, the air cushioning effect is negligible and the water hammer effect is dominant. In this case, there is no long period pressure oscillation pattern and just the water hammer impact pressure is present. For intermediate orifice sizes, air cushioning effect begins to reduce and water hammer pressure becomes more influential as orifice size gets larger. Therefore, there is both a long period oscillation followed by a short period oscillation pattern. Of course, experiments show that the peak pressure occurs before the final air residual is removed from the pipe due to air pocket compression (De Martino 2008, Martin and Lee 2000).

3.3.1.2 Influential parameters on secondary transient pressures

As illustrated by a simplified analytical equation by Lingireddy et al. (2004), the magnitude of secondary pressures depends on pipe and air valve characteristics and the pressure inside the valve immediately before the final air release. Also, experimental data by Zhou et al. (2002a) and De Martino et al. (2008) show that upstream driving head, air pocket volume and orifice size of air valves are the most influential factors on maximum pressure. To illustrate, the pressure peak increases with upstream driving head and outlet orifice diameter. The maximum pressure occurs at a certain ratio of orifice diameter to pipe diameter (i.e., d/D). The value ascribed to this ratio varies among researchers. Martin and Lee (2000) reported a value of d/D = 0.14, they later observed peak pressures at d/D = 0.18 (Marin and Lee 2012) while Zhou et al (2002b) reported d/D = 0.2 where maximum pressure peak occurred. This difference may be due to varying conditions under study. For example, different experimental setups such as pipe length and diameter, water column length, orifice diameter and driving head are factors that were different in each study (Zhou et al. 2002b, De Martino et al. 2008). After reaching orifice size criteria (i.e., d/D), the peak pressure decreases as the orifice size increases (Martin and Lee 2000, Zhou et al. 2002a, b, and 2004, Martin and Lee 2012).

Overall, since the d/D criteria for the occurrence of peak pressure are different in each study, these data cannot be generalized. Furthermore, this phenomenon is given little physical interpretation in the literature. For example, in the literature, it is not discussed why an air pocket’s cushioning effect is less influential at lower driving heads and smaller air release rates, although peak pressure generally decreases with air pocket volume. In addition, almost all of
these criteria are based on assuming rigid water column theory without considering friction and elastic effects. Hence, effects of water elasticity on such criteria and pressure oscillation patterns are yet to be investigated.

3.3.2 Real-time dynamic behaviour of AVVs

The dynamic behaviour of air valves influences the system’s transient response during air release from the pipe. To illustrate, the time of closing and opening of an air valve, the amount of residual air below the air valve before it closes, and the duration it takes to close, are defined as the dynamic characteristics of air valves. Such parameters are difficult to measure in the laboratory, and therefore involve some uncertainty. For instance, the discharge coefficient of air valves is determined through standard published tables (AWWA 2001), and there is considerable uncertainty in these values. Such dynamic behaviour is different for each type of air valve (i.e., its float shape, weight and size influences the closing behaviour of the valve). Pipe layout, the severity of the transient, and the type of air valve installation contribute to this as well.

Dynamic behaviour of air valves is rarely systematically studied or modified. The main reason for this lack of attention is poor understanding of dynamics of air valves due to rare large scale experimental and field data. Also, complexity in two-phase flow characterization could be a reason for the scarcity of publications on this topic. Although the effect of such dynamic behaviour is not comprehensively understood, some experimental works are available. It is noteworthy that scale effects are not explored in the experimental studies, and therefore, they cannot be generalized for all types of air valves. Yet, these explorations have important implications for the dynamic behaviour of air valves.

Recent work attempts to provide technical information and to understand the behaviour of air valves having different geometrical, mechanical, hydraulic and dynamic characteristics. Since sizing charts provided by manufacturers are rarely validated in practice, initially the characteristic curves of air valves were tested and compared with the characteristics provided by manufacturers (Lucca et al. 2010). This can lead to more realistic simulations of air valve behaviour in pipelines. For example, Bergant et al. (2012) determined the dynamic performance of float type air valves (e.g., metal ball or plastic cylinder floats) by measuring their response to flow acceleration and deceleration in a large-scale pipeline for three scenarios of pump start-up
and shut down, and pipe rupture. They presented the relationship between flow rate and pressure drop across the air valve for several float positions.

3.3.2.1 Air release through air valves considering dynamic behaviour

Generally, air release through AVVs is divided into two stages (Bergant et al. 2012). During the first stage, water and air accelerates towards the air valve until almost all air is removed from the pipe (i.e., initial event). During the second stage, residual air compresses until high pressure occurs and the water column stops and reverses (i.e., air compression event). Flow velocity at the end of the initial event is referred to as terminal velocity which is the maximum value of water velocity. However, according to real-time experiments on different models of air valves, some air valves close before air is completely exhausted from the pipe (Bergant et al. 2012), while others close only after a certain amount of water is discharged. The volume of residual air depends on the dynamic behaviour of air valves (e.g., closing times), pipe layout and severity of the transient as well as the air-water mixing process. Also, a longer closing time means less residual air. Furthermore, the higher the impacting water column, the smaller the residual air (Carlos et al. 2011).

After valve closure, the residual air continues to compress until the water column is arrested and then reverses. Maximum pressures occur at the instant of flow reversal (Bergant et al. 2012). The residual air is an influential parameter on transient pressures, especially at start-up events. Therefore, the most dangerous situations are where small uncontrolled volumes of air remain inside the pipe and cannot be removed properly through an air valve (Bergant et al. 2011, Carlos et al. 2011, Arregui et al. 2003). Results show that the smaller the residual air below the air valves, the higher the maximum pressure. Moreover, experimental data show that pressure peaks are inversely proportional to the closure time of air valves up to a certain limit after which peak pressure is not dependent on closure time (Arregui et al. 2003). However, Carlos et al. (2011) showed that in real systems, the closing time of air valves is not always a significant factor for the pressure peak magnitude. Additionally, peak pressures are inversely proportional to moving water column inertia, and directly proportional to terminal velocity (i.e., velocity of water at the time of air valve closure; Arregui et al. 2003).

Overall, the effectiveness of air valves for surge protection depends on several factors such as system configuration, the physical properties of the pipeline and fluid, and the characteristics of
the air valves as well as air distribution in the system (Lee 1999). However, the complexity in the characterization of two-phase flows and air valves has limited the associated theoretical works. Hence, the researchers have investigated the dynamic performance of air valves and their influence on transient pressures by performing large-scale experimentation (Bergant et al. 2011, Carlos et al. 2011, Arregui et al. 2003, Cabrera et al. 2003).

According to such experimental results, air valves do not respond as quickly to vacuum conditions as has traditionally been assumed (Bergant et al. 2011, Cabrera et al. 2003). That is, air valve opening occurs with a small delay (on the order of 20 milliseconds). There is also a time delay between the air valve closure and pressure rise due to cavity collapse (Bergant et al. 2012). Yet, these valves have proven to be beneficial as surge control devices if properly sized and located. Experimental results show that maximum air pressure at an air valve location depends strongly on air valve size. Both larger and smaller sizes of air valves exacerbate transient pressures. Usually, large sizes of air valves result in high pressures as a result of high velocity of adjacent water column. Smaller air valve sizes give rise to peak pressures as a result of excessive compression of air pockets below air valves (Cabrera et al. 2003). Hence, this past work confirms that the choice of an appropriate air valve size should be made if excessive pressure surges are to be avoided. In addition, experimental data implies that the discharge coefficient of air valves plays an important role in peak pressures. According to experiments simulating the expulsion of air through several commercial air valves, the smaller the discharge coefficient the smaller the impact velocity of arriving water at the air valve at the time of air valve closure and the lower the resulting peak pressure. Peak pressures are greatly influenced by the amount of residual air remaining. Small air residuals can be dangerous and burst the pipe. Friction factor and air valve outlet coefficient are other key parameters since they influence the impact velocity of water. For instance, smaller air valve outlet coefficient controls the terminal velocity of water when it reaches the closed air valve and then reduces the corresponding peak pressure (Carlos et al. 2011).

Therefore, according to the available experimental and theoretical work, the effectiveness of AVVs for surge protection depends on factors such as size and discharge coefficient of air valves. Water hammer protection of air valves is mostly dependent upon optimal value of outlet to inlet ratio. Certainly, this depends on system configuration (Zhu et al. 2006). In a case study of a water supply in Riyadh, Campbell (in Lee and Leo 1999) showed that non-return air valves
cushion the impact of slams from negative surges, allowing substantial reduction of surge vessels. However, it is not obvious how much the installation of air valves may potentially protect the system against vacuum conditions while they are installed in pipelines as main surge control devices or supplementary surge protection measures. Furthermore, the uncertainties associated with design parameters of air valves (e.g., discharge coefficient or even their basic functioning) may potentially influence the results. But such effects have not been considered in the published theoretical works.

3.3.2.2 Air valve chattering due to secondary transient pressures

While air is released through the air valve, it compresses and accelerates toward the air valve. Simultaneously, the adjacent water column is accelerating. High pressure peaks can result either due to the compression of air pockets or during air release when the accelerating water column impacts the closed air valve. The reduction of velocity in water column can produce secondary transient pressures on the order of 1 to 10 bar or even higher. Reflections of such pressure waves can potentially cause cavitation in the pipe. Such transient events can cause air valves to repeatedly open and close with high frequency, a phenomenon known as air valve chattering (Bergant et al. 2012). The water hammer pressure as well as the pressure due to air pocket compression creates high pressure peaks, and air valve failure can lead to column separation along the pipeline (Bergant et al. 2004). Obviously, the location of air valves relative to the HGL and the downstream boundary (e.g., a reservoir) affects the frequency of chattering. That is, for any vertical location of the high point (i.e., air valve location), if the total pipe length downstream of the air valve is short, the wave round trip is small. In these situations, less air enters the pipe through the air valve for preventing vacuum conditions, and less time is required to discharge the previously admitted air and to create the secondary transient. Hence, chattering occurs with more frequency at the air valve location. Such issues should be considered in the design stage of air valves.

Overall, operational problems are inevitable. Proper pipeline venting can only take place if AVVs are sized and located appropriately throughout the system, and if they resume working during transient induced pressure spikes, both of which are subjects in need of more systematic research. Since water systems are no better than their weakest component, a more rational approach for the design and selection of air valves is urgently needed.
3.4 Maintenance problems

Air valves require at least annual maintenance and inspection for damage. Certainly, due to the relative inaccessibility of most AVV locations in vaults requiring confined-space-access procedures, the valves are often left exposed to weathering, physical damage, and wear which eventually render them non-operational. Also, buried valves, located below ground, have the potential to become inaccessible due to flooding or silting of the vaults (Figure 3-7). For example, an assessment of the functionality of air valves existing over 30 years in the City of Houston water transmission main revealed that half of the air valves were not functioning (the total number of air valves was 31) and half of the buried air valves were inaccessible or had leaky gate valves and could not be tested for damage (Gregory et al. 2006).

The associated cost of flooded chambers (Figure 3-7 (a)) adds to the maintenance cost of air valves. Also, contaminated water might enter the pipes through the leaking air valves during a negative pressure event, creating health risks (Besner et al. 2010). Consequently, air valves add to the maintenance cost of the system if not well used and maintained. Figure 3-7 shows evidence of poorly maintained air valves that has led to non-operational valves.

![Evidence of poorly maintained air valves](image)

(a) Besner et al. (2010)  
(b) Escarameia (2005)

Figure 3-7 Flooded and poorly maintained air valves (Photos are used with publishers’ permission)

3.5 Avoiding operational and maintenance problems

The potential of air valves to induce secondary transient events in pipes has provoked Li et al. (2009) to theoretically investigate a modern configuration of air valves: installing an air-
throttling orifice at the air valve outlet, an anti-slam device and an air accumulator which reduces the flow velocity at the valve seat and the resulting secondary pressures. Air throttling orifices prevent all the air from expelling and, therefore, a portion is trapped in the valve chamber. The greater the air accumulation, the more the pressures are dampened. However, this raises concerns regarding pressure spikes that can be created by such trapped air pockets during sudden pump start-up. Although this method was tested under two scenarios of shutdown and the following start-up, the start-up period \( t = 300 \text{ s} \) was 60 times larger than shutdown duration \( t = 5 \text{ s} \) leading to a less severe induced transient. Obviously, care should be taken to consider sudden start-up cases, resulting in severe transients, while designing the air accumulator capacity in the valve. Although effects were theoretically investigated through a case study, the real-world practical efficiency of these valves has not yet been published.

Another approach for minimizing operational problems caused by secondary transient pressures at AVVs is the use of standpipes below the AVVs. Here, the main idea is that pipe diameter is larger than the standpipe, and consequently, water hammer wave will dampen when it reaches the main pipe. Standpipes with large volume can suppress transient pressure caused by air valve slamming. Hence, sizing standpipes should be performed with enough care. Generally, parameters affecting water hammer are length and standpipe diameter, and air valve size as well as the residual air volume in the stand pipe when the valve is closed (Stephenson 1997).

Additionally, automatic air valves, especially those applied to wastewater systems, are uncertain and not reliable since they require regular maintenance, and the possible malfunction of these valves can create high pressures which endanger pipelines (Tchobanoglous 1981). However, manufacturers claim that some of the features of modern automatic air valves allow them to function efficiently while requiring simple and effective maintenance (Zloczower 2010). Among such features are conical bodies with a large midriff which encompasses larger initial air pocket at the valve body, causing the air pocket to compress at high pressures, and result in a constant water level inside the valve, preventing the sealing mechanism from clogging and leakage. Also, outward-slanting valve walls and a funnel-shaped bottom prevent accumulation of grease by redirecting it to the force main. Furthermore, the previous complex and problematic sealing mechanism with internal levers, hinges and pins is substituted with a freely-moving float and a simple rolling seal mechanism, which provides a larger air release orifice and works even at low pressures (3 psi, 2 m). More importantly, light body, non-slam accessories, and a hydraulically-
piloted diaphragm instead of a float which can potentially eliminate local surges due to air
valves are embedded in these valves (Zloczower 2010). The dynamic behaviour of these valves
is not reported yet and their practical efficiency has not yet been published.

The most common recommendation in the literature to avoid secondary pressures is to use
smaller outflow sizes of air valves (Lingireddy et al. 2004, Zhou et al. 2002b). Such findings in
the literature emphasize that each specific system should be analyzed in order to select an
appropriate outflow size of air valve. However, there is a gap in the literature regarding the
effect of location of AVV on its sizing. In other words, rules of thumb for selecting an
appropriate outflow size of an AVV according to its location are not yet available. Also, there
are few studies concerning either the priority of each of the discussed strategies over the other,
or of the best possible or practical approach to avoid operational problems arising from
secondary transient pressures at AVVs.

Therefore, AVVs and ARVs, though designed to reduce the devastating problems created by
vacuum conditions and the presence of air pockets in pipes, also add to the operating and
maintenance problems in water systems. To designers, reducing the related operating and
maintenance problems justifies eliminating even a single air valve from the system. But how
small a number is reasonable is still a key design question. Certainly, too little attention is paid
to such a strategy in the literature, and the great concern is reduced system performance by
removing a specific air valve along a pipe. This leaves system owners wondering how effective
these air valves are in improving system performance. If an air valve in a specific location of the
pipe profile has little effect on system performance, avoiding it will have the potential to reduce
such operation and maintenance issues.

Basically, reviewing and evaluating the current design criteria of air valves (e.g., size, location)
could play an important role in highlighting the potential of any possible changes in the design
of air valves along a pipeline. Such analysis distinguishes critical locations for installing air
valves and explores how the system performance changes if an air valve, or a series of air
valves, fails to operate. Consequently, the potential to avoid installing a number of air valves
will be realized. This provides a framework for decision makers to determine the reasonable
size, type and location of air valves according to the desirable system performance. Moreover,
in order to better assess the performance of air valves and their location and sizing criteria,
supervisory control and data acquisition (SCADA) systems should monitor air valve open/close positions and differential pressures (McPherson 2009). Such monitoring may facilitate exploration of the location of the most effective air valves. Further, it helps to identify those air valves which require regular maintenance. Consequently, the aforementioned operational and maintenance problems are reduced through eliminating unnecessary air valves. Overall, if air valves are to be neglected (Figure 3-7), and if it is proven that they have little effect on system functionality, why not avoid them at the design stage?

Certainly, such an evaluation would require a clear understanding of the consequences associated with air intrusion into the system, air accumulation at high points, vacuum conditions, and the absence or malfunction of air valves as well as a subsequent consideration of system performance, all of which still require in-depth research. As an example, for evaluating current size and location criteria of ARVs, it is essential to know the amount of air accumulation at locations along the pipe and the associated consequences (i.e., headloss). According to the available experimental data, headloss created by air pockets is a function of air flow rate, pipe slope and water velocity (Pothof and Clemens 2010, Lubbers 2007, Lubbers and Clemens 2005). However, the accumulated air pocket volume and the relationship between air pocket volume and headloss are not available for pressurized lines. Also, experimental observations have indicated that air accumulation depends on air flow rate, but, the associated relationship is not yet published. Therefore, lack of such data in the literature limits the evaluation of design criteria for ARVs. Obviously, the reported results could be more effective for such an evaluation, if more experimental data (e.g., volume of accumulated air at high points, relationship between air pocket volume and headloss) were recorded. On the other hand, most of these experimental works have been performed under the operating conditions of sewer systems (i.e., low ranges of pressure: 0-3 bar). Hence, the data could be more reliably applied to water transmission systems if the experiments were performed under higher pressurized conditions and if scale effects were provided. Consequently, more research should be done on this subject if evaluation of design parameters of ARVs is desirable. Also, evaluation of design criteria for AVVs requires a systematic study of transient response of water systems in the presence of AVVs. Of course, the lack of such studies is an important gap in the literature.
3.6 Numerical modelling of air valves: a critique

Modelling the air valve boundary condition may be handled within the usual framework of the method of characteristics. Complete equations used for air valve boundary simulation are presented in Wylie and Streeter (1993). The mass flow rate of air through the valve depends on the values of atmospheric absolute pressure $p_0$ and absolute temperature $T_0$ outside the pipe, as well as the absolute temperature $T$ and pressure $p$ within the pipe. Four conditions of subsonic and sonic flow are considered for both air inflow and air outflow through the air valve. Also, four assumptions are made in the analytical equations for the air valve boundary condition (Wylie and Streeter 1993). First, isentropic flow is assumed for the air flow through the air valve. Second, the air mass within the pipe is assumed to obey the isothermal law. Third, the air admitted to the pipe is assumed to stay near the valve. Fourth, water surface elevation is assumed to remain constant, and the volume of air is considered small compared with the liquid volume of a pipeline reach.

However, in practice, the four assumptions for air valve boundary conditions cannot be universally met. For example, if an air valve is placed along a sloping pipe, the assumption the air will remain close to air valves cannot be satisfied unless a stand pipe is used and the admitted air volume is small enough to stay in the stand pipe. Otherwise, the pipe should be designed so that it contains high points (Zhu et al. 2006). If none of these situations apply, considering the air transport mechanism is essential for an accurate numerical simulation of air valves. Also, the constant water surface at the air valve location is an assumption whose influence on the transient analysis of the system and the final reverse flow should be studied.

The effect of considering a constant water surface at AVV location on the transient analysis of the system is remarkable. To illustrate, when a power failure occurs, the AVV at the high point starts to operate, admitting air into the system to prevent column separation. During deceleration of the forward flow downstream of the AVV, the water level drops at the high point. After forward flow stoppage, reverse flow accelerates towards the AVV and water level at the high point rises. If the effect of the moving boundary at the AVV location is ignored, the forward flow deceleration rate and the reverse flow acceleration rates are underestimated. That is, the computed time of cavity growth and collapse at the high point will be inaccurate.
Furthermore, for situations where the high point is higher than the downstream reservoir head (Figure 3-8), neglecting the falling water level at the high point prevents the reverse flow occurrence due to the negative reverse driving head. In the example shown in Figure 3-8, the inlet and outlet diameters of the AVV (m) and the inlet and outlet coefficients of the AVV are 0.2, 0.2, 0.6, and 0.6, respectively. Consequently, the numerical solution based on such a constant water level assumption results in a permanently growing cavity volume at the high point (Figure 3-9). Hence, in such conditions, obtaining a meaningful numerical simulation result depends on considering the moving boundary condition at the AVV location.

Overall, in the literature, less attention is paid to such shortcomings in numerical simulation of air valves. Such numerical issues and the previously discussed dynamic behaviour of air valves imply that further research and improvement are still required in the field of air valve numerical simulation. Obviously, real-world data acquisition is useful in developing the numerical model and in the validation of the numerical data and modelling results.

Figure 3-8 Layout of a pumpline containing a high point higher than the downstream reservoir head
3.7 Summary

One of the most widely published air management strategies is the application of air control devices such as air valves (i.e., air release valves and air vacuum valves). In this chapter, a critical review of the use and application of air valves is presented. The improvements in the literature are discussed and the gaps are explored. As the main focus of the chapter is on the application of AVVs, the design guidelines, and operating and maintenance issues as well as the current alternatives on preventing such problems are discussed. It is concluded that, despite the potentially effective role that air valves can play in pipeline air management, there is scant data available regarding their actual performance (e.g., frequency and efficiency of functioning). This information is necessary to better inform design practices, such as sizing and positioning, in order to promote effective and efficient application of air valves.

Although there are several case-specific studies on sizing air valves based on transient conditions, a comprehensive and systematic study on air valve sizing is yet to be published. There are still literature gaps concerning proper location, and consequently, the efficient number of air valves required along an undulating pipeline. On the other hand, the available limited experimental studies on dynamic behaviour of air valves are presented. Further, the need to modify the numerical modelling of air valves based on such dynamic behaviour is highlighted. Obviously, such consideration may influence proper selection of air valve size, number, and location.
Overall, considering the operational and maintenance problems of air valves, efficient application of such devices requires accomplishing broader research and development both in the realm of the theoretical context (i.e., understanding air valve physical behaviour, and modifying air valve numerical simulation) and in the context of experimental or field studies (i.e., understanding air valve dynamic behaviour and operational efficiency). Obviously, the experimental or field data can support the proper and more accurate simulation of air valve behaviour in water pipelines. Such knowledge gaps and recommendations for further research aimed at improving the efficiency of air valve application.
Chapter 4

Column separation and cavity collapse for pipelines with air vacuum valves: understanding the essential wave processes

Elevated high points along a pipeline profile are the most common places where air vacuum valves (AVVs) are installed. This Chapter uses basic waterhammer wave theory to analytically explore the effect of an AVV at high points in systems. In the analysis, a simple frictionless reservoir-pipe-reservoir system with an exaggerated high point at an intermediate location is first considered and, for simplicity, a sudden flow curtailment is assumed upstream. Key design parameters such as the maximum air pocket volume, the duration of air pocket growth and collapse, and the maximum magnitude of the pressure spike resulting from water column rejoinder are semi-analytically developed for high points with different horizontal and vertical distances to the associated boundaries. It is demonstrated that the magnitude of the reduced pressure wave created by the refraction at the high point, and both the high point elevation and its horizontal position are all crucial and interacting factors to be considered in the selection of AVVs in pipelines with undulating profiles. Numerical examples are presented both to show results consistent with the analytical discussion and to introduce greater realism into the discussion. Finally, the effect of friction is also introduced and results are compared with a frictionless system in order to better understand the specific role friction plays in the dynamics of an air valve under transient conditions.

4.1 Introduction

Air vacuum valves (AVVs) are designed to admit air into water pipelines whenever vacuum conditions occur as a result of transient events. The design goals of valve selection are easily stated but less easily achieved: to prevent pipe collapse while controlling or limiting both any consequent flow interruption and any adverse subsequent system dynamics. After suppressing vacuum conditions and once the pressures have risen above atmospheric, AVVs release the admitted air to avoid the problems caused by entrapped air. The primary motivation for using AVVs is that they are usually cheaper than alternative protection measures such as the effective,
but expensive, use of an air chamber or surge tank at some suitable system location. Quite clearly, however, if vacuum conditions are to be effectively controlled, AVVs must be placed and sized properly, and there is considerable ambiguity in the literature about how this should be done.

One obvious design parameter of AVVs is the orifice size of the opening. Moreover, if AVVs are not properly sized, they will tend to induce secondary transient events (Lee and Leow, 1999; Lingireddy et al., 2004; Li et al., 2009). This phenomenon can even lead to air valve breakage (Li et al., 2009). Published works address these secondary AVV-caused transient events by developing and applying numerical models (Lee and Leow, 1999) or simplified water hammer equations (Lingireddy et al., 2004; Li et al., 2009). However, AVVs can potentially be effective in transient conditions. For instance, well-chosen AVVs, typically those with low outflow and high inflow capacity, can effectively suppress peak pressures and valve slamming while reducing negative pressures caused by transient events (Espert et al., 2008; Lee and Leow, 1999). Yet, based on the manufacturer’s recommendations, AVVs are currently sized by considering filling, draining/pipe break scenarios. Therefore, they are often sized to be large enough to exhaust/admit large volumes of air when the pipeline is being filled and drained (AWWA, 2001). However, if they are activated under other transient events such as pump failure, the large outflow capacity will cause secondary transients as a result of sudden air release. In order to avoid such secondary transients and to effectively use AVVs for transient protection, their sizing should be based on transient considerations. To accomplish this, the first step is to understand the key physical regularities associated with a sudden transient event and a system protected with only an AVV.

Another key factor in AVV design is its location along the pipe. In order to prevent the accumulation of entrapped air and its associated problems (i.e., overpressure and discharge reduction) during line filling, draining/pipe break, AVVs are most commonly placed at all the local high points in the pipeline profile. This arrangement is based both on manufacturer recommendations and AWWA (2001) guidelines and results in the occurrence of a high number of AVVs in undulating pipeline profiles. However, AVVs are problematic from a practical standpoint and their number should be limited. To illustrate, the relative inaccessibility of AVV locations is a barrier to their maintenance and physical inspection for damage, and therefore, their susceptibility to weathering, physical damage, and wear can render them non-operational.
AVVs at some of the high points will also be activated under vacuum conditions such as pump failure. This implies that the design of such AVVs should be based on transient considerations, with more care taken for their maintenance. Moreover, if placing AVVs at some of the high points is ineffective in controlling vacuum conditions and they solely control infrequent events such as filling, draining/pipe break, they might sometimes be replaced with cheaper, manually-operated AVVs (i.e., pit cocks). However, in the literature, little attention is paid to the location where AVVs are most or least beneficial in transient conditions.

Despite the wealth of research detailing the effects of AVV size on secondary transient events, there is ambiguity in the literature about the physical phenomena which imposes such effects on the system. For instance, it is not physically transparent how the system’s downstream driving head and the location of AVVs affect the transient-induced pressures in pipelines. Therefore, the main objective of this Chapter is to understand how the presence of an AVV at a particular high point influences the system’s transient response.

In general, a high point is characterized by both a local geometry and its vertical and horizontal distance to various system features and boundaries (i.e., vertical distance to the downstream reservoir head and horizontal distance to the downstream reservoir in a reservoir-pipe-reservoir system). The transient response is influenced by these locational factors and by the specific characteristics of the air valve itself. Isolating these features assists the designer to improve those choices that bear on system protection and reliability. Knowledge of interactions may permit a clearer picture of AVV selection as designers understand what to pay more attention to and what not to worry about when selecting AVVs for particular applications.

### 4.2 Systems’ transient response in the presence of AVV

Exploring some of the key physical regularities associated with a sudden transient event and system protected with only an AVV helps to rank the high points in a pipeline and to understand how these size and location parameters influence transient pressures. Herein, the system has been simplified to narrowly focus on the key physical relationships in the problem. Also, the effect of friction is initially ignored, a restriction that is later relaxed.
4.2.1 Simplified exploratory system

In order to understand the physical behaviour of the system with AVV protection under transient conditions, a simple reservoir-pipe-reservoir system with an exaggerated high point is considered. Figure 4-1 depicts the configuration of the test system. The pipeline is conceived as having a single isolated high point with the system subject to a sudden depressurization associated with a sudden curtailment of the system’s inflow (mimicking a power failure event with a low-inertia pump). A check valve is imagined upstream to immediately prevent any reverse flow. When the resulting reduced pressure wave reaches the high point, a large AVV with unrestricted air inflow is assumed to instantly open. This air valve action thus creates both a reflected and refracted wave, with both waves having a “base magnitude or head” fixed by the elevation of the high point. The resulting refracted wave then continues on to the downstream reservoir, which reflects it back into the system toward the high point; the reflected wave moves back toward the original upstream position where it effectively encounters a dead-end associated with the closed check valve that is imagined at this location.

![Figure 4-1](image)

*Figure 4-1* A pipeline having a single isolated high point subjected to a sudden depressurization caused by a sudden curtailment of the system’s inflow.

4.2.2 Description of the transient event

It should be noted that in this idealized model the AVV, being assumed to be large, perfectly maintains atmospheric pressure at the high point where, without the air valve, pressures would have tended to become sub-atmospheric. Consequently, the pipe behaviour to the upstream and to the downstream of the high point becomes hydraulically independent, split by the presence of the (large) air valve at a fixed horizontal and vertical location. Hence, in order to physically understand the transient behaviour of such a system, sections upstream and downstream of the high point can be effectively analyzed separately. The complete cycle of the transient event
resulting from a sudden curtailment of inflow into the system (Figure 4-1) is discussed separately for upstream and downstream sections of the high point. Note that for clarity, the terminology of “upstream” and “downstream” is hereafter taken to refer to the original flow directions, directions which would otherwise become confused during the course of the subsequent transient events.

4.2.2.1 Upstream of the AVV

At the instant of flow curtailment, the flow into the upstream section of pipe suddenly stops and a reduced pressure wave propagates downstream. The resulting system flow and pressure is depicted in Figure 4-2(a). As the low pressure wave (-ΔH₁) moves downstream, it progressively arrests the fluid, slightly expanding it, and marginally contracting the pipe. When the wave reaches the high point (Figure 4-2(b)), all the fluid in the upstream limb of the system (A to B in Figure 4-1) is under a reduced head (H-ΔH₁) and the fluid velocity and momentum have been lost. Yet, at the high point, the presence of the AVV prevents the system from experiencing the full magnitude of low pressure; rather, air is admitted into the system and atmospheric pressure is locally established. When atmospheric pressure occurs at the high point, the upstream limb (A to B in Figure 4-1) and the downstream limb (B to C in Figure 4-1) of the system become hydraulically separated. A positive wave (ΔH₂ in Figure 4-2(c)) reflects back toward the upstream end and a (smaller) reduced wave (-ΔH₃ in Figure 4-4(a)) propagates from the high point toward the downstream reservoir. Since the behaviour of these two portions of the system is hydraulically independent, the transient cycle for each limb (i.e., pipes upstream and downstream of the high point) is now described separately.

Within the upstream limb, the positive wave created at the high point (Figure 4-2(c)), through a direct water hammer effect, causes a fluid velocity of \( v_2 = \frac{g}{a} \Delta H_2 \), where \( a \) is the wave speed. Then, this wave moves towards the upstream end bringing the increase in pressure and adjusting the fluid velocity from zero to this new reversed velocity of \( v_2 \). When this combined pressure and velocity wave arrives at the upstream reservoir, the reversed flow impacts the closed check valve and stops, thereby creating a reflected high pressure wave with another ΔH₂ rise that propagates downstream (Figure 4-2(d)). The flow near the valve is progressively compressed, brought to rest, and the pipe wall stretched. At a time of L/a later, where L is the length of this
upstream segment, when this high pressure wave reaches the high point (Figure 4-2(d)), AVV effectively establishes a constant boundary condition, quite analogous in this sense to a reservoir at the elevation of the high point. At the instant this wave reaches the high point, the pressure has increased by the second \( \Delta H_2 \) from its previous reduced value and the velocity is again zero everywhere in the system’s upstream limb. Since the pressure at the high point remains unchanged, an unbalanced condition occurs at the high point and the pressure is returned to a value of atmospheric pressure at the high point elevation (Figure 4-2(e)). Then, a forward flow towards the high point starts with velocity equal to \( V_2 \). This reduced pressure wave travels upstream at sonic velocity and again reaches the closed check valve. Since there is no water source at the closed check valve, pressure is reduced by \( \Delta H_2 \) and velocity again becomes zero. After another \( L/a \) has elapsed, this reduced pressure wave arrives at the high point and velocity is zero everywhere in the upstream system (Figure 4-2(f)). Since the effect of friction is neglected, the process described in Figure 4-2(c) to Figure 4-2(f) is endlessly repeated. In a frictionless system, the trend of change in discharge with time upstream of the high point is shown in Figure 4-2(g).
At the instant the wave arrives at the high point, AVV behaviour mimics a sudden increase in reservoir head ($\Delta H_2$) at the high point. The high point where a large AVV is placed (Figure 4-2(c)) can now be considered as a constant head reservoir with height equal to the height of
reflected wave. As illustrated, this reflected wave creates a reverse flow when it hits the closed valve. Thereafter, this upstream portion of the high point can be equivalent to a valve closure scenario as depicted in the configuration shown in Figure 4-3. Furthermore, in this section of the pipe, the air cavity grows during the resulting reverse flow (i.e., $L_1/a$ to $3L_1/a$) and shrinks during the forward flow (i.e., $3L_1/a$ to $5L_1/a$). This process continues indefinitely.

![Diagram](image)

**Figure 4-3** Equivalent system to the upstream of the AVV (i.e., sudden valve closure).

### 4.2.2.3 Downstream of the AVV

At the downstream limb of the high point (B to C in Figure 4-1), a reduced wave ($\Delta H_3 = \Delta H_1 - \Delta H_2$) propagates from the high point to the downstream reservoir reducing flow velocity from $V_0$ to $V_1 = V_0 - \Delta V^3$ (Figure 4-4(a)). There is an unbalanced condition at the downstream reservoir at the instant of arrival of the pressure wave (Figure 4-4(b)). Since the reservoir level is constant and forward flow momentum is not completely lost, flow velocity is reduced by $\Delta V'_2$ (corresponding to $\Delta H'_2$) and a high pressure wave ($\Delta H'_2$) moves at acoustic speed upstream towards the high point. This wave increases the pressure by $\Delta H'_2$ (Figure 4-4(c)). The wave arrives at the high point where pressure is atmospheric (Figure 4-4(d)). Again, a low pressure wave ($\Delta H'_2$) develops here and water velocity is reduced accordingly. This low pressure wave propagates downstream, reducing the pressure and flow velocity (Figure 4-4(e)). At the instant $L/a$ later, the wave arrives at the downstream reservoir while the pressure and flow velocity are reduced everywhere in the forward direction (Figure 4-4(f)). The process described in Figure 4-4(c) to Figure 4-4(f) is repeated until flow velocity and momentum towards the downstream reservoir becomes zero. The deceleration process will clearly cause air to progressively enter the pipe via the AVV. At the instant the forward flow stops, the maximum air volume has entered the pipe. At this moment, the unbalanced condition at the downstream reservoir forces a high pressure wave to move upstream and, therefore, flow reverses towards the high point.

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After the column stops, flow starts accelerating in the reverse direction and the air pocket starts to exit from the unrestricted outflow of the AVV. The high pressure wave ($+\Delta H_2$) propagates to the high point (Figure 4-4(g)) and a reduced pressure wave ($-\Delta H_2$) reflects back at the high point towards the downstream reservoir. Flow is accelerated by $\Delta V_2$ in each wave trip ($L/a$ second). In other words, the process in Figure 4-4(e) to Figure 4-4(f) is repeated but this time with flow in the reverse direction (from downstream reservoir to the high point). Each time the wave arrives at the high point or at the downstream reservoir where an unbalanced condition for pressure exists, pressure is changed and water flows into the pipe from the downstream reservoir acquiring a velocity increase equal to $\Delta V_2$ (Figure 4-4(g) and Figure 4-4(h)). This increase in velocity occurs every $2L/a$ s at the high point or at the downstream reservoir. Acceleration continues until all the air discharges out of the pipe through the unrestricted outflow of the AVV. At this time, water hits the closed AVV and a high pressure spike occurs depending on the velocity of water at the instant of cavity collapse. Note that the overall role of the $\Delta H_3$ wave is to progressively reduce the velocity from its original reduced value to the negative of this value. Obviously, the dissipative processes would tend to attenuate the originally formed wave.

The transient event at the downstream portion of the high point has essentially two highly significant consequences. At first, an air pocket will create and grow at the high point. After the water column stops advancing, flow reverses, the air pocket compresses, the water column rejoins, and finally, the air pocket will collapse. Obviously, these events share the same physical system but respond to different physical attributes.
Figure 4-4 Transient response downstream of the AVV

The principal task herein is to isolate these influences. Therefore, the factors affecting the time of maximum air pocket growth, time of collapse, air cavity compression, and maximum pressure resulting from water column rejoinder at the AVV location are studied. Such findings help to understand the characteristics of the high point and design factors of AVVs that cause the AVV to be effective in suppressing the transient events at a particular high point or to serve as a destructive device at another high point.
4.2.2.4 Equivalent system to downstream of AVV

To better visualize and physically illustrate the transient event occurring in the downstream limb of the system, an equivalent system is considered for the downstream section as shown in Figure 4-5. In this system, there is a reservoir at the high point with its water surface initially at the elevation of the steady hydraulic grade line of the system. Here, the transient event is induced by suddenly dropping water surface elevation at the upstream reservoir to the elevation of the high point to prevent the pressure at the high point from going below atmospheric (mimicking the behaviour of the AVV at the high point). Then, using simple wave and water hammer considerations, semi-analytical solutions are presented and physical explorations are described.

![Figure 4-5 The equivalent system to the downstream of the AVV (i.e., sudden drop in upstream reservoir water level)](image)

4.2.2.5 Flow deceleration in the equivalent system downstream of AVV

Inducing a transient event by a sudden drop in water level at the upstream reservoir in Figure 4-5, causes a wave to propagate downstream which in due course reflects back. Every time the wave arrives at the downstream reservoir or at the high point, a portion of the system’s original momentum is reduced, resulting in decreased forward flow. Based on the semi-analytical solution of (frictionless) water hammer, this incremental decrease in flow equals $\Delta Q = \frac{gA}{a} H_p$.

This process continues in discrete segments until flow stops, reverses and accelerates until reaching a reverse magnitude equal to the original steady state value of flow. Deceleration of forward flow, the time of flow reversal, acceleration of reverse flow and the time of reaching reverse flow with the same magnitude as when the transient began depend on the driving head between the downstream and upstream reservoirs. Such key parameters are compared in Figure 4-6 for $H_p/\Delta H_1 = 0.1$ and $H_p/\Delta H_1 = 0.25$, respectively. As shown, the larger the initial wave height, the larger will be the flow reduction at the instant of a transient event, the larger the deceleration of the forward flow and faster the reverse flow is achieved. The design implications
are significant: the lower the high point is below the original steady state profile, the faster forward flow stops and final reverse flow \( \frac{Q}{Q_P} = -1 \) is reached, and the concept of “faster” is measured in wave travel times in the downstream pipe segment.

Figure 4-6 Transient behaviour in the equivalent system downstream of the AVV at high point and at downstream reservoir for two ratios of \( \frac{H_P}{\Delta H_1} \)

4.3 Semi-analytical formulas

Considering the equivalent systems to the upstream and downstream portion of the AVV (Figure 4-3 and Figure 4-5), an approximate analysis of the transient event for a system with an AVV can be presented. Consequently, simple semi-analytical formulas for key parameters can be derived based on the physical reasoning and concepts illustrated previously. That is, in systems with an unrestricted inflow and outflow through the AVV at the high point, the air cavity grows at the same rate as the equivalent system’s deceleration until flow stops. Then, it
discharges through the AVV with the same rate as the reverse flow acceleration rate of the equivalent system, until the final collapse of the cavity occurs. Consequently, and helpfully, at the time of cavity collapse, the flow magnitude in the downstream leg reaches the same value as initially intercepted flow (-Q_p). Obviously, these relationships require some modification once friction is included but, as is seen later in this chapter, even this effect can be reasonably estimated.

Considering the equivalent system, at the instant the wave (∆H_1) arrives at the high point, a reduced pressure wave (H_p) develops and travels downstream. The amount of intercepted discharge by the high point can be semi-analytically calculated based on Equation (4-1). The high point flow at each time (Figure 4-6) can be semi-analytically approximated by Equation (4-2). During the transient event, an air cavity is created and grows in size until flow reverses. At the instant of flow reversal, the maximum air cavity is developed in the system. In order to determine the pipe’s maximum air cavity volume, the flow reversal time should be estimated by the average slope of the flow reduction.

The residual flow depends on how much of the original wave is intercepted by the high point:

\[
\frac{Q_p}{Q_0} = 1 - \frac{H_p}{\Delta H_1} \tag{4-1}
\]

The flow reduction relates to flow reflections and the wave travel time in the downstream pipe:

\[
\frac{Q(t)}{Q_p} = 1 - \frac{1}{Q_p} \left( \frac{a \Delta Q}{L} \right) t \quad \Delta Q = \frac{gA}{a} H_p \tag{4-2}
\]

where: Q_0 is the initial flow in the system (m^3/s); ∆H_1 (m) is the reduced wave due to initial flow curtailment; H_p (m) and Q_p (m^3/s) are the wave and flow intercepted at the high point, respectively; a is wave velocity (m/s); L is downstream pipe length (m); and t is the time from the beginning of the transient event(s).
4.3.1 Time of air cavity growth and collapse – frictionless case

As shown in Equation (4-2), the rate of change in flow at the downstream section is \( \frac{\Delta Q}{(L/a)} \).

Therefore, the number of wave round trips \( (K) \) required for the flow to completely stop can be calculated as in Equation (4-3). Obviously, the time of cavity growth can be calculated either by setting \( Q = 0 \) in Equation (4-2) or by considering that as \( K(2L/a) \). In each case, Equation (4-4) is derived for the time of air cavity growth \( (t_g) \).

\[
K = \frac{Q_0 - \Delta Q}{2\Delta Q} = \frac{Q_P}{2\Delta Q} \tag{4-3}
\]

\[
t_g = \frac{LQ_0}{gA} \frac{1}{H_P} \left( 1 - \frac{H_P}{\Delta H_1} \right) \tag{4-4}
\]

in which: \( K \) is number of wave round trips to stop the flow; \( t_g \) (s) is the time of flow reversal or maximum cavity growth; \( A \) is the cross sectional area of the pipe \( (m^2) \); and \( Q_0 \) is initial flow rate of water \( (m^3/s) \).

Assuming unrestricted inflow and outflow through the AVV, the process of air cavity growth and collapse is symmetrical. Therefore, the time of air cavity collapse (Equation 4-5) is twice the time of air cavity growth.

\[
t_c = \frac{2LQ_0}{gA} \frac{1}{H_P} \left( 1 - \frac{H_P}{\Delta H_1} \right) \tag{4-5}
\]

where \( t_c \) (s) is time of cavity collapse from the beginning of the transient event.

As seen in Equations (4-4) and (4-5), considering a given wave speed and initial flow, time of cavity growth and collapse increase with downstream pipe length \( (L) \), and decrease with the fraction of reduced wave intercepted at the high point \( (H_P/\Delta H_1) \). Therefore, the two obvious parameters that crucially determine air cavity growth and collapse are the downstream pipe length and the fraction of intercepted wave height at the high point (i.e., the high point geometry).
4.3.1.1 Effect of downstream pipe length on \( t_g \) and \( t_c \)

Considering a given wave height intercepted at the high point and applying the semi-analytical Equation (4-2), the effect of downstream pipe length (\( L_{ds} \)) on time of air cavity growth and collapse is shown in Figure 4-7. In this analysis, intercepted wave height (\( H_p/\Delta H_1 \)) is assumed to be 0.2 and three ratios of the downstream pipe length (\( L_{ds} \)) to the total pipe length (\( L \)) are considered. Obviously, \( t_g \) and \( t_c \), and consequently, air cavity volume, increase with downstream pipe length.

![Figure 4-7 Effect of downstream pipe length on time of cavity growth and collapse (\( Z/\Delta H_1 = 0.8, H_p/\Delta H_1 = 0.2 \))](image)

4.3.1.2 Effect of intercepted wave at the high point on \( t_g \) and \( t_c \)

For a given flow curtailment event, the intercepted wave height at the high point depends on the high point’s vertical location. Obviously, the acceleration or deceleration rate in the downstream pipe has a direct relationship with the magnitude of intercepted wave height at the high point. Consequently, the time of cavity growth and collapse and the maximum air cavity volume all have a reciprocal relationship with this key parameter. Again, by applying the semi-analytical Equations (4-2) and (4-4) and considering several high point elevations (i.e., several heights of the intercepted wave), such a relationship is depicted in Figures 4-8(a) and 4-8(b). It is evident in Figure 4-8(b) that the greater the intercepted wave height, the lower the intercepted discharge (\( Q_p/Q_0 \)) by the high point. Also, the air cavity’s time of growth and collapse decreases with intercepted wave height. This decrease is more pronounced for higher elevations of the high point (i.e., \( (H_p/\Delta H_1) < 0.2 \)).
4.3.2 Maximum air cavity volume

When a sudden curtailment of inflow occurs in the system in Figure 4-1, the ideal AVV activates as soon as the reduced wave arrives at the high point. Considering the continuity equation at the high point and an unrestricted inflow of air from the AVV, the rate of air entering the pipe depends only on the direction of flow both upstream and downstream of the high point. The possible cases of upstream and downstream flow direction and the associated sign for airflow into (positive sign) or out of (negative sign) the pipe are shown in Table 4-1.
Table 4-1 The sign for rate of change of air volume \( (V_{air}/\Delta t) \) at the high point according to the direction of flow in upstream \( (Q_{in}) \) and downstream \( (Q_{out}) \) section of the high point. A positive sign indicates an increase in air volume at the high point while a negative sign indicates a decrease in air volume.

<table>
<thead>
<tr>
<th>( Q_{in} ) or ( Q_{out} )</th>
<th>( Q_{in}&gt;0, Q_{out}&gt;0 )</th>
<th>( Q_{in}&lt;0, Q_{out}&lt;0 )</th>
<th>( Q_{in}&lt;0, Q_{out}&gt;0 )</th>
<th>( Q_{in}&gt;0, Q_{out}&lt;0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{in}&lt;Q_{out} )</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>( Q_{in}&gt;Q_{out} )</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>( Q_{in}=Q_{out} )</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

As described in the equivalent system upstream, over each wave round trip, flow within the upstream portion of the system is either towards or away from the high point. This implies that flow in the high point’s upstream limb has a negligible effect on maximum air cavity volume, depending on the time of maximum air cavity growth downstream of the AVV and the wave travel time at the AVV’s upstream limb. On the other hand, air enters the pipe continuously during flow deceleration in the downstream section of the high point. Therefore, the limb downstream of the high point dominates the maximum air cavity volume.

In order to derive a semi-analytical equation for the maximum air cavity size in the system depicted in Figure 4-1, upstream and downstream sections of the AVV are separated and the effect of upstream sections on air cavity growth is neglected. Also, water level (i.e., the piezometric head) at the high point is considered to be constant and the physical regularities in the equivalent system are applied. Also, in the derivation of the formula, it is assumed that the AVV, located at the high point, can allow an unrestricted amount of air into the system and there is no water inflow towards the high point \( (Q_{in}=0) \).

As discussed before, at the instant the reduced pressure wave reaches the high point, a fraction of initial flow is intercepted by the high point (i.e., \( Q_{P} \)). Then, at each \( 2L/a \) (i.e., round-trip time of pressure wave), a flow value of \( 2\Delta Q \) is reduced from the forward flow. Considering the continuity equation at the high point and the previously discussed transient process for the equivalent system downstream of the AVV (Figure 4-5), the maximum air volume admitted into the system could semi-analytically be calculated as follows:

\[
\forall Max_{air} = \sum_{k=1}^{K} \left[ Q_{0} - (2k-1)\Delta Q \right] \frac{2L}{a} = \left( KQ_{0} - K^2 \Delta Q \right) \frac{2L}{a} = K(K+1)\Delta Q \frac{2L}{a}
\]

\[(4-6a)\]
Substituting $K$ and $\Delta Q$ in the above formula, Equation (4-6a) results in:

$$\forall \text{Max}_{\text{air}} = \frac{L Q_0}{a} \left( 1 - \frac{H_p}{\Delta H_1} \right) \left[ \left( \frac{a Q_0}{2 g A H_p} \left( 1 - \frac{H_p}{\Delta H_1} \right) \right) + 1 \right]$$

(4-6b)

in which: $\forall \text{Max}_{\text{air}}$ is maximum air cavity volume ($m^3$); $Q_0$ is initial steady state discharge ($m^3/s$); $\Delta Q$ is incremental decrease in flow for each wave trip ($m^3/s$); $L$ is downstream pipe length (m); $a$ is wave velocity (m/s); and $K$ is number of round trips before flow reversal.

### 4.3.2.1 Effect of downstream pipe length and wave height on $\forall \text{Max}_{\text{air}}$

Based on Equation (4-6b), the maximum air cavity volume is primarily a function of downstream pipe length, initial pipe flow, wave speed, and the fraction of wave intercepted by the high point as well as cross-sectional area of the pipe. Assuming a given pipe diameter, wave speed, and initial pipe flow, the effect of pipe length and intercepted wave height on the amount of air volume can now be better understood. According to Equation (4-6b), air volume has a direct linear relationship with pipe length, as each wave round trip takes longer when the downstream pipe is longer, causing the AVV to allow more air into the pipe. However, the rate of change in air volume with pipe length is constant, and therefore, the ratio of air volume to pipe volume remains constant irrespective of the pipe length.

For a given pipe diameter, initial discharge and wave speed, the effect of the intercepted wave height at the high point on the maximum air cavity is investigated. Since the relative amount of air volume ($V_{\text{air}}/V_{\text{pipe}}$) in the pipe remains constant (as noted above), the effect of the intercepted wave height on relative air volume is depicted in Figure 4-9. As shown, there is a reciprocal relationship between the relative air volume in the pipe and intercepted wave height at the high point. According to the previous discussion, when the amount of the intercepted wave at the high point is smaller, a greater fraction of flow is intercepted at the high point (i.e., $Q_p$ is larger and $\Delta Q$ is smaller). Hence, it takes longer for the downstream water column to reverse and there is more opportunity for air cavity to grow in size.
In summary, when the high point is farther upstream (i.e., a longer downstream pipe) and its elevation is higher (smaller intercepted wave height), it takes longer for the forward flow to subside. Therefore, the system will experience reduced pressure for a longer duration and there will be more opportunity for the air cavity to grow in size. By contrast, a high point located closer to the downstream reservoir and lower in height, provides a reduced opportunity for the air cavity to grow, resulting in smaller air exchanges and cavities.

4.3.3 Column rejoinder event – frictionless case

After the maximum air pocket enters the pipe, flow starts reversing and accelerating towards the high point. Flow accelerates until all the air in the pipe discharges out of the system through the AVV. At the instant of air cavity collapse, the two water columns upstream and downstream of the AVV rejoin. In order to provide a physical illustration of this phenomenon, unrestricted air inflow and outflow are initially assumed.

4.3.3.1 Unrestricted air inflow and outflow

After reverse flow occurs and as water is accelerating towards the high point, air is discharged through the AVV. Considering an unrestricted airflow, air discharge occurs at the same rate as the water flow behind it. Since there is (in this initial analysis) no restriction, the air cavity does not compress and the pressure at the high point remains atmospheric until all the air is expelled. When all the air is removed from the pipe, the AVV closes. At the instant of air cavity collapse,
a pressure spike occurs due to the waterhammer event associated with the colliding water columns and the resulting high pressure wave travels both upstream and downstream from the AVV location. The magnitude of the resulting pressure spike can be shown to be half of the value arising from the Joukowsky equation (Equation (4-7a)) (it is half because the wave propagates both upstream and downstream of the high point; Wylie and Streeter 1993).

\[
\Delta H_{\text{max}} = \frac{a}{2g} \left( V_{\text{up}} - V_{ds} \right)
\]  

(4-7a)

where: \( \Delta H_{\text{max}} \) is the pressure spike as a result of column rejoinder event (m); \( a \) is wave speed (m/s); \( g \) is acceleration due to gravity (m/s\(^2\)); \( V_{\text{up}} \) is flow upstream of the AVV (m/s); and \( V_{ds} \) is flow downstream of the AVV (m/s).

As is seen in Equation (4-7a), the magnitude of the pressure rise depends on the amount of flow both upstream and downstream of the high point at the time of air cavity collapse. Turning back to the initial problem (Figure 4-1), the downstream velocity (i.e., \( Q_{P}/A \)) at the time of air cavity collapse can be estimated from Equation (4-3). It should be mentioned that the worst case scenario for maximum pressure spike at the instance of air cavity collapse occurs when the upstream water column has stopped. Under such conditions, the resulting pressure spike may become even more severe when superimposed onto the source transient wave traveling within the upstream pipe section (\( \pm \Delta H_2 \) in Figure 4-2(d) and 4-2(f)). To illustrate, the source transient pressure at the high point can be \( \pm \Delta H_2 \) depending on the time of air cavity collapse. Therefore, the maximum pressure spike at the instance of cavity collapse can be calculated by Equation (4-7b).

\[
\Delta H_{\text{max},\text{min}} = 2KH_P \pm \Delta H_2
\]  

(4-7b)

The trend of change of \( KH_P/\Delta H \), maximum and minimum pressure spike (\( \Delta H_{\text{max}}/\Delta H \) and \( \Delta H_{\text{min}}/\Delta H \)) at the instance of air cavity collapse with respect to different high point elevations is shown in Figure 4-10. At lower high point elevations (i.e., higher \( H_P \)), since reverse flow at the high point (\( Q_P \)) is smaller, less severe pressure spikes occur. These pressure spikes have a reciprocal relationship with the magnitude of intercepted wave height and a direct relationship with reverse flow velocity. Furthermore, the resulting pressure spike gets more severe when it is
superimposed onto the source transient wave ($\Delta H_2$) traveling through the upstream side of the AVV.

![Figure 4-10 Pressure spikes at AVV location at the instance of cavity collapse](image)

4.4 Comparing Semi-analytical results with numerical solution

A numerical solution and program was developed to verify the analytical discussion. This model uses the method of characteristics (MOC) to solve the 1-D water hammer governing equations. These equations and the AVV boundary condition are presented in the classic text by Wylie and Streeter (1993).

4.4.1 A numerical example

A sudden upstream valve closure is induced to the frictionless system in Figure 4-1 in which the initial discharge is $Q_0 = 0.196$ m$^3$/s. The length of each pipe (m), the pipe diameter (m), the static head of the system (m), and the wave speed (m/s) are 1000, 0.5, 100, and 1000, respectively. Two ratios of $H_p/\Delta H_1$ equal to 0.05 and 0.1 are considered in the analysis. The numerical results in Figure 4-11 are in excellent agreement with the semi-analytical results in Figures 4-9 and 4-10 for maximum volume of air and maximum pressure spike at cavity collapse for $H_p/\Delta H_1$ equal to 0.05 and 0.1, respectively. It should be noted that the very tiny discrepancy between the amount of air volume calculated in the semi-analytical and numerical solutions justifies ignoring the effect of the portion of the system upstream of the AVV’s in the semi-analytical solution.
The results obtained for semi-analytical formulas and numerical analyses are compared for different intercepted wave heights in Figures 11(b) to 11(c). As shown, semi-analytical data obtained for time of growth and collapse of air cavity and maximum air cavity volume are in good agreement with the numerical results. Also, at higher elevations of high point, maximum pressure spikes are in good agreement with the numerical results. However, at lower elevations of high point, the difference between numerical and semi-analytical data is more emphasized. This is due to the assumptions made in estimating the flow downstream of the AVV. Of course, the trends for both numerical and semi-analytical results are the same. And, this is the focus of the paper.
Figure 4-11 Effect of wave height on maximum air volume, time of cavity growth and collapse and column rejoinder pressure (a numerical example in a frictionless system with unrestricted air flow into and out of the pipe)
4.5 Moving boundary condition at the AVV

The analysis of the AVV boundary condition conventionally assumes that the water level at the high point remains constant and is equal to the high point elevation. However, the water level clearly must drop at least a little at the high point while flow is decelerating towards the downstream reservoir and rises when it is accelerating toward the AVV. This consideration may alter the results of transient simulation and the final steady state solution. Also, semi-analytical analysis of such behaviour may become more complicated since $H_p$ and, consequently, deceleration and acceleration rates are no longer constant but now become a function of time. A full exploration of the effect of moving boundary condition at AVV location needs to be considered in further work.

4.6 Considering the effect of friction

Considering the effect of friction introduces more realism into the discussion while resulting in a much more time consuming numerical computation of the transient event. Since the purpose of this Chapter is to introduce a clear physical understanding of the phenomenon and in order to compare the results from frictional effects with those semi-analytical results obtained in a frictionless system, a semi-analytical procedure is developed by applying the Joukowski formulation in combination with friction losses.

4.6.1 Transient event upstream of the AVV in systems with friction

Introducing friction into the problem causes the transient wave to attenuate with each wave trip as illustrated by Figure 4-12(a) to Figure 4-12(f) and, therefore, results in attenuating the discharge upstream of the AVV. The phenomenon described in Figure 4-12(c) to 4-12(f) continues until the downstream and upstream columns rejoin. Here, the process is the same as before, except that the transient wave attenuates with each wave trip resulting in the reduction of upstream discharge with time. Since the upstream discharge is attenuating, the effect of the upstream limb of the high point on the pressure spike at the time of cavity collapse may be negligible.
4.6.1.1 A step function representing transient event upstream of AVV considering friction

The following step function represents the transient event with friction upstream of the AVV as shown in Figure 4-13. Obviously, a frictionless system is a particular case of such a step function.

\[
Q_n = \begin{cases} 
Q_Q = -\frac{gA}{a} \Delta H_2 & \text{for } n = 0 \\
\frac{gA}{a} \left( \Delta H_2 - h_f(Q_i) \right) & \text{for } n \geq 1 
\end{cases}
\]

\[
t_n = n \frac{2L_1}{a}, \; n=0,1,2,\ldots
\]
Figure 4-13 Trend of change of discharge upstream of the AVV (\(H_p/\Delta H_1 = 0.1\))

4.6.2 Transient event downstream of the AVV in systems with friction

As described in Figure 4-14(a) to Figure 4-14(h), the process of discharge reduction is different from the frictionless system in that the transient wave attenuates with each wave trip due to the effect of friction. This causes the forward flow to take more time to stop and, therefore, more air enters the pipe through the AVV. The process in Figure 4-14(a) to Figure 4-14(f) continues until forward flow stops, and then, backward flow begins (Figure 4-14(h)). Here, as opposed to frictionless systems, the magnitude of change in discharge is a function of time (\(\Delta Q'(t)\) in Figure 4-15).
Figure 4-14 Transient responses downstream of the AVV (considering friction)

Figure 4-15 Trend of change in discharge at the high point in frictional systems relative to frictionless systems

\[
\frac{\Delta Q'(t)}{\Delta Q} = H_p/DH_1 = 0.1
\]
4.6.2.1 A step function representing transient event downstream of AVV

The formula describing this event can be shown as a step function with variable \( \Delta Q' \). Discharge at each wave trip and the amount of air volume entering the pipe can be computed by the procedure below. Accordingly, the time of air cavity growth can be calculated by considering the time at which the maximum air cavity enters the pipe, and the time of air cavity collapse is the time at which all the air discharges out of the pipe.

\[
\begin{align*}
    t_n &= \frac{t_1}{a} + n \frac{L_2}{a} \quad n = 1,2,3,4,... \\
    Q_n &= Q_p - \sum_{i=1}^{n} \Delta Q'_i \\
    \Delta Q'_n &= \frac{gA}{a} (H_p - h_f(Q_0) + h_f(Q_{n-1})) \quad \text{if} \quad Q_{n-1} > 0, \quad h_f(Q_{n-1}) = f \frac{L_2}{D} \frac{Q_{n-1}^2}{2gA^2} \\
    \Delta Q'_n &= \frac{gA}{a} (H_p - h_f(Q_0) - h_f(Q_{n-1})) \quad \text{if} \quad Q_{n-1} \leq 0 \\
    \nu_{air} &= 2 \frac{L_2}{a} \sum_{i=1}^{n} (Q_i) \quad i = 0,2,4,... \quad \begin{cases} @ Max \nu_{air}^n & t_n = t_g \\ @ \nu_{air} = 0 & t_n = t_c \end{cases}
\]

Where: \( t_n \) is time (s); \( Q_n \) is discharge (m\(^3\)/s); \( \Delta Q' \) is the incremental change in discharge (m\(^3\)/s); \( h_f(Q_n) \) is the headloss associated with \( Q_n \); and \( \nu_{air} \) is air volume (m\(^3\)).

4.7 Comparing transient behaviour upstream and downstream of AVV in frictional systems

Figure 4-16 depicts transient behaviour upstream and downstream of the AVV in both frictionless and real (frictional) systems. As shown, upstream discharge is attenuating with time. Also, on the downstream limb, the discharge increment is smaller for friction systems. This results in less final reverse flow at the time of air cavity collapse. The reduced discharge upstream and the smaller final reverse flow downstream account for the less severe pressure spike when considering friction effects. In the majority of cases, friction will tend to reduce the pressure rise that would occur in an otherwise frictionless system.
**Figure 4-16** Discharge variation upstream (a) and downstream (b) of AVV and secondary transient pressures (b) in frictionless systems and systems with friction by application of the step function \( H_p/\Delta H_1 = 0.1 \)

### 4.7.1.1 Effect of downstream pipe length on \( t_g \) and \( t_c \) considering frictional effects

Considering the step function for the downstream section, the effect of the downstream pipe length \( L_{ds} \) on the trend of variation in discharge, time of air cavity growth and collapse, and the final reverse flow at the time of collapse is examined. Figure 4-17 shows such a trend for two ratios of intercepted wave height \( H_p/\Delta H_1 = 0.2 \) and 0.5) at the high point and three fractions of downstream pipe length \( L_{ds} \) to total pipe length \( L \).
Figure 4-17 Comparing systems with and without friction: effect of downstream pipe length on discharge pattern downstream of AVV (a: \( \frac{H_p}{\Delta H_1} = 0.2 \), b: \( \frac{H_p}{\Delta H_1} = 0.5 \))

Since friction is directly proportional to pipe length, for each \( \frac{H_p}{\Delta H_1} \) ratio when downstream length increases, friction is also increased. Also, \( \Delta Q' \) is decreased resulting in larger \( Q \) with each round trip. Both larger pipe length and larger \( Q \) account for a larger amount of friction losses. Therefore, the total number of wave round trips for stoppage of forward flow to occur is increased. Consequently, for longer downstream pipes lengths, the differences in \( t_g \) and \( t_c \) of frictional systems as opposed to frictionless systems are higher. However, for shorter downstream pipe lengths, since friction loss is reduced and the magnitude of \( \Delta Q \) and \( \Delta Q' \) are getting closer, the difference in \( t_g \) and \( t_c \) between the two systems is less pronounced.
Also, when $H_p/\Delta H_1$ decreases, the total number of round trips to reach to final reverse flow increases. Also, discharge is higher with each wave trip and, therefore, friction is higher. Therefore, frictional effects are more pronounced at lower $H_p/\Delta H_1$ because of the direct relation of headloss to both $Q$ at each wave trip and $L$. That is, $H_p/\Delta H_1$ decreases, $\Delta Q'$ decreases, $Q$ is more with each wave trip, and $L$ is also more, therefore, $h_f$ increases.

However, the difference between systems with and without friction is much less for higher ratios of $H_p/\Delta H_1$. Since number of round trips is lower and friction has less opportunity to affect the system (Figure 4-17(b)).

4.7.1.2 Effect of intercepted wave height on $t_g$ and $t_c$ considering friction effects

By application of the step function, the difference in the trends of change in discharge downstream of the AVV at different elevations of high points are shown and compared with frictionless systems. For smaller ratios of $H_p/\Delta H_1$, the differences between $t_g$ and $t_c$ for systems with and without friction is greater. However, as the ratio of $H_p/\Delta H_1$ increases, the total number of round trips required to achieve to final reverse flow decreases and frictional effects are less pronounced. Hence, the trend of discharge is similar for both systems. However, there are situations where the final reverse flow gets higher values than $Q_p$. This is mainly due to the high $\Delta Q$’s at higher ratios of $H_p/\Delta H_1$. Eventually, during the reverse flow, there are situations when the reverse flow has approached $Q_p$ but there is still a small amount of remaining air in the system ($H_p/\Delta H_1 = 0.5$). In such conditions, the transient resumes adding a high $\Delta Q'$ to the previous discharge and, therefore, the final reverse flow at the time of air cavity collapse gets a higher value than expected. Obviously, this results in higher pressure spikes at the time of cavity collapse.
4.8 Semi-analytical formula extended to consider friction

Approximate analytical formulas for computing time of cavity growth and collapse, maximum air cavity entering the pipe, and the secondary transient pressures occurring at the time of cavity collapse are developed herein. This is based on the physical reasoning of the transient behaviour in real systems with AVVs. Such approximate formulas allow comparisons of the transient behaviour in systems with an AVV and with different geometries of the high point (i.e., horizontal and vertical distances to the associated boundaries). They can serve as rules of thumb for evaluating the systems requiring careful design of the AVV.

4.8.1 Upstream section of AVV - considering friction

With the assumption of a constant rate of discharge reduction with each wave round trip, a decay function can describe the upstream discharge attenuation. Here, it is assumed that the rate of change in discharge is equal to the rate of change in discharge at the first round trip (N = 1).
4.8.1.1 Rate of reduction in upstream discharge at each round trip (2L₁/a) - considering friction

When friction is introduced into the analysis, the upstream discharge reduces with a variable rate. To analytically approximate the amount of flow with time, a constant rate of flow reduction is considered in Equation (4-8).

\[ H_U = \Delta H_1 - H_p \]
\[ Q_U = \frac{gA}{a} H_U \]
\[ Q_{N=1} = \frac{gA}{a} H_{N=1} = \frac{gA}{a} (\Delta H_1 - H_p - h_f(Q_U)) \]

\[ r = \frac{Q_{N=1} - Q_U}{Q_U} \quad r = -\frac{fL_1g}{2Da^2} (H_U) \]  

(4-8)

in which \( Q_U \) is the initial backward flow at the time the wave arrives at the high point, \( N \) is the number of round trips (2L₁/a) that have passed after initial wave arrives at the high point and initial reverse flow occurs in the upstream section, \( L_1 \) is upstream pipe length and \( f \) is the friction factor.

4.8.1.2 Upstream Discharge Decay Function - considering friction

To estimate the upstream flow at each time step, a decay function is introduced. Substituting the approximate rate of discharge reduction in the following decay function, the approximate analytical formula for the upstream discharge is expressed in Equation (4-9).

\[ Q_{N(2L_1/a)} = Q_U e^{-Nr} \]

\[ \frac{Q_N}{Q_U} = \exp \left( -N \frac{fL_1g}{2Da^2} (H_U) \right) \cos((N + 1)\pi) \quad \text{for } N = 0,1,2,3,\ldots \]  

(4-9)

in which \( Q_N \) is the discharge at the \( N^{th} \) round trip after initial reverse flow has occurred at the high point (m³/s).
4.8.1.3 Upstream Head Decay Function - considering friction

It should be noted that friction dissipates the upstream head with each wave trip. To estimate the reduced upstream head, Equation (4-9) is written in terms of head at the high point, resulting in the following approximate analytical equation.

\[
\frac{H_N}{H_U} = \exp \left( -\frac{N}{2DA^2} g (H_U) \right) \cos \left( (N + 1)\pi \right) \quad \text{for } N = 0, 1, 2, 3, \ldots
\]

\( H_N \) is the head at the \( N^{th} \) round trip after initial reverse flow has occurred at the high point (m).

4.8.1.4 Number of round trips at upstream end at the time of air cavity collapse \((N_C)\) - considering friction

In order to estimate the upstream head and discharge at the time of air cavity collapse, it is worthwhile to estimate the number of round trips required before the air cavity collapses, as follows:

\[
N_C = \frac{t_c}{2L/a} = \frac{aL^2Q_b}{2LagA} \frac{1}{H_U \left( 1 - \frac{H_p}{\Delta H} \right)} \left( 1 + \frac{h_f(Q_b)}{H_p} \left[ 0.5 \left( 1 - \frac{H_p}{\Delta H} \right)^2 - 1 \right] + \frac{h_f(Q_b)}{H_p} \left[ 0.5 \left( 1 - \frac{H_p}{\Delta H} \right)^2 + 1 \right] \right)
\]

(4-11)

4.8.1.5 Upstream head at the time of cavity collapse - considering friction

The upstream head at the time of cavity collapse is required to estimate the associated pressure spike. By substituting \( N_C \) in Equation (4-10), the upstream head at the time of cavity collapse is computed as follows:

\[
H_{N_C} = H_U \exp \left( -N_C \frac{fLg}{2Da^2} (H_U) \right) \cos \left( (N_C + 1)\pi \right)
\]

(4-12)

Where \( N_C \) is the number of round trips \((2L/a)\) that have passed at time of air cavity collapse.
4.8.2 Downstream section of the AVV - considering friction

As previously discussed, the rate of discharge increments in transient events in such systems with friction is a function of time. Therefore, two assumptions are made: mean $\Delta Q$’s are assumed for both forward and backward flows. Also, it is assumed that final backward flow reaches $-Q_p$ at the time of cavity collapse regardless of the magnitude of the intercepted wave height. Then, the same concept as previously discussed in frictionless systems is considered and the formulas below are derived.

4.8.2.1 Forward flow - considering friction

As discussed previously, the incremental rate of discharge reduction in the downstream section of the pipe is varied due to the dissipating nature of friction. That is, friction reduces the magnitude of the wave height and the associated discharge increment with each wave trip. In order to be able to roughly estimate the effect of friction, a mean value is assumed for the incremental rate of flow reduction in Equation (4-13).

$$
\Delta Q_{Max} = \frac{gA}{a} \left( H_p - h_f(Q_0) + h_f(Q_p) \right) \\
\Delta Q_{Min} = \frac{gA}{a} \left( H_p - h_f(Q_0) + h_f(Q = 0) \right) \\
\Delta Q_1 = \Delta Q_{Mean} = \frac{gA}{a} \left( H_p - h_f(Q_0) + 0.5h_f(Q_p) \right)
$$

(4-13)

The mean value for $\Delta Q_1$ is substituted in Equation (4-1) resulting in the following formula.

$$
\frac{Q(t)}{Q_p} = 1 - \frac{1}{Q_p} \left( \frac{a\Delta Q_1}{L} \right)_f
$$

(4-14)

4.8.2.2 Time of air cavity growth - considering friction

As discussed previously, $t_g$ occurs when $Q(t) = 0$. Substituting this value in Equation (4-14) will result in Equation (4-15). The nondimensional form of the equation is written as in Equation (4-16).

$$
t_g = \frac{LQ_0}{gA} \left[ \frac{1}{H_p + \frac{fLQ_0^2}{2gDA^2}} \right] \left[ 0.5 \left( \frac{H_p}{\Delta H_1} \right)^2 - 1 \right] \left( 1 - \frac{H_p}{\Delta H_1} \right)
$$

(4-15)
\[
\frac{t_g}{L/a} = \frac{aQ_0}{gA H_P} \frac{1}{1 + \frac{h_f(Q_0)}{H_P}} \left[ 1 + 0.5 \left( 1 - \frac{H_P}{\Delta H_1} \right)^2 - 1 \right] \left( 1 - \frac{H_P}{\Delta H_1} \right) \tag{4-16}
\]

### 4.8.2.3 Backward flow - considering friction

The incremental rate of increase in reverse flow is also varied due to the dissipating nature of friction. That is, friction reduces the magnitude of the wave height and the associated discharge increment at each wave trip. In order to be able to roughly estimate the effect of friction, a mean value is assumed for the incremental rate of flow increase in the following equation.

\[
\Delta Q_{\text{Max}} = \frac{gA}{a} (H_P - h_f(Q_0) - h_f(Q = 0))
\]
\[
\Delta Q_{\text{Min}} = \frac{gA}{a} (H_P - h_f(Q_0) - h_f(Q_P))
\]
\[
\Delta Q_2 = \Delta Q_{\text{Mean}} = \frac{gA}{a} (H_P - h_f(Q_0) - 0.5h_f(Q_P))
\]

The mean value for \(\Delta Q_1\) is substituted in Equation (4-1) resulting in the following formula.

\[
\frac{Q(t)}{Q_P} = - \frac{1}{Q_P} \left( \frac{a \Delta Q_2}{L} \right) (t - t_g) \tag{4-17}
\]

### 4.8.2.4 Time of air cavity collapse - considering friction

As discussed previously, \(t_c\) occurs when \(Q(t) = Q_p\). Substituting this value in Equation (4-17) will result in Equation (4-18). The nondimensional form of the equation is written as in Equation (4-19).

\[
t_c = t_g + \frac{L Q_0}{gA} \frac{1}{H_P - \frac{fL Q_0^2}{2 g A^2}} \left[ 1 + 0.5 \left( 1 - \frac{H_P}{\Delta H_1} \right)^2 + 1 \right] \left( 1 - \frac{H_P}{\Delta H_1} \right) \tag{4-18}
\]
\[
\frac{t_c}{L/a} = \frac{t_g}{L/a} + \frac{aQ_0}{gA H_P} \left[ 1 - \frac{h_f(Q_0)}{H_P} \right] \left[ 1 + 0.5 \left( 1 - \frac{H_P}{\Delta H_1} \right)^2 + 1 \right] \left( 1 - \frac{H_P}{\Delta H_1} \right) \tag{4-19}
\]
By applying Equations (4-16) and (4-19), the trend of change in the growth and collapse time of the air cavity is compared in systems with and without friction (Figure 4-19). As shown, the effect of friction is greater with lower intercepted wave heights. Although the difference in $t_g$ for the two systems is small, the difference in $t_c$ becomes larger when frictional effects are high. This is due to the lower rate of discharge increments in the reverse flow due to the effect of friction.

![Figure 4-19 Comparing time of growth and collapse of air cavity with intercepted wave height in systems with friction and frictionless systems](image)

### 4.8.2.5 Maximum air cavity volume - considering friction

Maximum air cavity volume occurs as soon as forward flow stops. In other words, the area under Equation (4-14) is defined as the maximum air volume entering the pipe. This assumption results in Equation (4-20) with Equation (4-21) being its nondimensional form.

\[
\frac{\gamma_{\text{air}}}{\gamma_{\text{max}}} = \frac{LQ_0^2}{2gA} \left( H_P + \frac{\beta Q_0^2}{2gDA^2} \right) \left[ 0.5 \left( 1 - \frac{H_P}{\Delta H_1} \right)^2 - 1 \right] \left( 1 - \frac{H_P}{\Delta H_1} \right)^2
\]  

(4-20)

\[
\frac{\gamma_{\text{air}}}{\gamma_{\text{Pipe}}} = \frac{Q_0^2}{2gA^2} \frac{1}{H_P} \left[ 0.5 \left( 1 - \frac{H_P}{\Delta H_1} \right)^2 - 1 \right] \left( 1 - \frac{H_P}{\Delta H_1} \right)^2
\]  

(4-21)
By applying Equation (4-21), the trend of change in the maximum air cavity size with intercepted wave height is compared in systems with and without friction (Figure 4-20). As shown, the effect of friction is greater with lower intercepted wave heights. Consequently, the difference in maximum air volume between the two systems is higher at lower intercepted wave heights. This is due to the lower rate of discharge increments in the backward flow due to the effect of friction.

![Figure 4-20 Effect of friction on trend of maximum air volume with relative to wave height](image)

4.8.3 Column rejoinder event - considering friction

Considering unrestricted air flow into and out of the AVV, a semi-analytical formula is developed for maximum and minimum transient pressure at the time of cavity collapse. It is assumed that discharge in the downstream limb has reached \( Q_p \). Also, the worst case scenario is when \( Q \) in the upstream section is zero. Therefore, \( \Delta H_{\text{max, min}} \) can be computed from Equation (4-22).

\[
\Delta H_{\text{max, min}} = 2K\left(H_P - h_f(Q_0) - 0.5h_f(Q_p)\right)\pm H_{Nc}
\]  

(4-22)

By applying Equation (4-22), the effect of friction on pressure spikes at the time of cavity collapse is shown in Figures (4-21) to (4-23) for three different ratios of downstream pipe length to upstream pipe length (\( L_2/ L_1 = 5,10,15 \)). Figures 4-21 to 4-23 show that the effect of friction
is higher at lower intercepted wave heights. Hence, it takes more time for the reverse flow to reach $Q_P$. During this time, the upstream discharge has more time to attenuate. Therefore, at lower intercepted wave heights, $\Delta H_{\text{max}}$ is lower and $\Delta H_{\text{min}}$ is higher. With regard to the ratio of $h_f(Q_0)/H_P$, maximum $H_{\text{max}}$ occurs at the Knee in the $h_f(Q_0)/H_P$ curve. Since friction loss is directly proportional to pipe length, this knee alters as the length of the downstream pipe is increased. Therefore, depending on the distance of the high point to the downstream boundary, maximum $H_{\text{max}}$ occurs at a specific ratio of $H_P/\Delta H_1$. For instance, maximum $H_{\text{max}}$ for $L_2/L_1 = 5$, 10, and 15 occur when $H_P/\Delta H_1 = 0.1, 0.15,$ and 0.2, respectively. Such a trend is shown in Figure 4-24.

![Figure 4-21](image_url)  
**Figure 4-21** Effect of friction on pressure spikes at AVV location at the instance of cavity collapse ($L_2/L_1 = 5$)
Figure 4-22 Effect of friction on pressure spikes at AVV location at the instance of cavity collapse ($L_2/L_1 = 10$)

Figure 4-23 Effect of friction on pressure spikes at AVV location at the instance of cavity collapse ($L_2/L_1 = 15$)
4.8.4 Comparing semi-analytical results with numerical solution—considering frictional effects

Herein, the results obtained for semi-analytical formulas and numerical analyses for different intercepted wave heights in systems with friction are compared. Results are presented in Figures 11(b) to 11(c). As shown, semi-analytical data obtained for time of growth and collapse of air cavity and maximum air cavity volume are in good agreement with the numerical results. Also, at higher elevations of high point, maximum pressure spikes are in good agreement with the numerical results. However, at lower elevations of high point, the difference between numerical and semi-analytical data is more emphasized. As illustrated in frictionless systems, this difference can be due to the assumptions made in estimating the flow downstream of the AVV. Of course, both numerical and semi-analytical results show the same trend. And, this justifies the discussions made in the paper.
Figure 4-25 Comparing semi-analytical and numerical results in systems with friction

4.9 Conclusion

Transient behaviour in a pipeline containing a high point in the middle and protected with an AVV is physically illustrated through a variety of semi-analytical formulas in frictionless systems and systems with friction. In order to simplify the problem, the upstream and downstream part of the high point is divided into two sub-problems, with each part analytically discussed. Consequently, it is understood that the downstream limb plays a more important role in the air volume entering the system and the resulting pressure spike at the instant of air cavity
collapse. Therefore, considering the downstream limb, key parameters such as air volume, time of growth and collapse of the air cavity, and the water velocity are calculated for both systems.

To understand the effect of wave height and length of downstream pipe on air volume and the resulting pressure spikes, the horizontal and vertical distance of the high point to the associated boundaries are altered. Both semi-analytical and numerical results show that maximum air volume is directly proportional to the length of downstream pipe. However, it has a reciprocal relationship with the reduced wave height intercepted at the high point. To illustrate, as the high point elevation increases, more time is required for forward flow to stop, allowing more air to enter the pipe.

Furthermore, the column rejoinder event is analytically and numerically discussed considering unrestricted air inflow and outflow. Results show that the maximum pressure spike ($H_{\text{max}}$) at the instance of air cavity collapse increases with the elevation of the high point. This is due to the fact that final reverse flow at higher elevations is larger. Consequently, water velocity at the time of column rejoinder is higher, thereby, creating more severe pressure spikes. However, in systems with friction, the maximum $H_{\text{max}}$ occurs at an intercepted wave height at which a turning point occurs in the relative friction curve. Therefore, depending on the length of the downstream pipe and the magnitude of friction, $H_{\text{max}}$ occurs at a specific intercepted wave height. To verify the semi-analytical results, numerical examples are presented whose results are in good agreement with the semi-analytical discussion and the physical illustration.
Chapter 5 Understanding Sensitivity of Transient Response of Undulating Pipelines to Design Parameters of Air Vacuum Valves (AVVs)

This chapter studies the sensitivity of the transient response of undulating pipelines, containing air vacuum valves (AVV) at the high point, to the input parameters of the water hammer governing equations and to the design parameters of the AVV (i.e., particularly its inlet and outlet orifice sizes and related discharge coefficients). This is performed by application of three methods of sensitivity analysis, namely Monte Carlo Filtering, the visual benefits of scatter plots and Sobol’s method. The influential parameters and their main and interaction effects are explored. It is obvious from the results of the previous chapter that the transient response of the system depends on the horizontal and vertical position of the AVV relative to the upstream and downstream boundaries; this chapter quantitatively explores system sensitivity to key parameters. Results highlight the importance of designing AVVs based on the transient response of the system at specific locations. In particular, the results illustrate the importance of properly sizing of AVVs based on transient considerations and that this sizing may differ depending on the location of the AVV at the high point relative to the downstream boundary. Of course, few systems are as simple as a single uniform pipe with a well-defined high point subject to a sudden upstream stoppage of flow. Nevertheless, the sensitivity studies illustrate the kind of dependencies that are almost certainly to continue to be crucial in more realistic pipeline systems.

5.1 Introduction

The main function of large orifice air vacuum valves (AVVs) is to discharge a significant volume of air from the pipe while being filled in order to prevent entrapped air and the associated consequences, or to admit significant volumes of air into the pipe during draining operations or pipe breaks in order to prevent pipe collapse. However, they are occasionally activated under other transient-induced pressures such as pump failure. Transient activation of such valves can potentially produce destructive secondary transient pressures leading to AVV
breakage (Li et al., 2009). Obviously, the size of AVVs which are activated under transient conditions should be selected with considerable care. It is semi-analytically shown in Chapter 4 that the severity of secondary transients induced by AVVs depends on key locational factors. This was done by applying some simplifying assumptions and by the application of the Joukowsky’s water hammer equation. This chapter numerically studies the sensitivity of the transient response of undulating pipelines to the size and location of AVVs and water hammer input parameters.

Sensitivity analysis studies how the variation in the output of a numerical or analytical model can be apportioned to variations in input parameters (Saltelli et al. 2004). Through such analysis, the most influential and/or insignificant factors on the model output are identified. Also, the parameters or group of parameters that interact with each other can be realized. This can be performed by exploring the model’s response to varying inputs. Furthermore, sensitivity analysis can be applied to decision making. For instance, it can identify which design variables have an important influence upon system response and which are less important (Hall et al. 2009).

Herein, the sensitivity of transient responses of hypothetical undulating pipelines to different input parameters of the water hammer governing equations (i.e., discharge, wave velocity, friction factor) and design parameters of AVVs (i.e., inflow and outflow orifice sizes) as well as the characteristics of the high point where the AVV is located (i.e., vertical and horizontal distance of the high point to the associated boundaries) is performed. This will facilitate identification of key parameters to be considered in preliminary decision making for AVV size and location. Three methods of sensitivity analysis are implemented: Monte Carlo Filtering, scatter plots, and Sobol’s variance-based method.

First, a numerical model is developed to solve water hammer in conjunction with the air valve governing equations by applying the method of characteristics (MOC). Then, the numerical model is coupled to a Monte Carlo simulator. Indices for evaluating the transient response of the system are selected and the sensitivity analysis is performed. The Monte Carlo Filtering is applied to explore which AVV design parameters are most influential for system safety and to prevent vacuum conditions. Scatter plots are presented for a visualization of the effect of each parameter. The variance-based method is applied to ascertain the main and interaction effects of
each hydraulic variable of the water hammer governing equations and AVVs parameters on the transient response. Finally, the most influential input parameters are identified. Specifically, the sensitivity of the transient response to inlet and outlet sizes of AVVs and variables such as wave speed, friction factor, and system discharge is explored. Also, it is realized how this sensitivity changes with AVV location. Overall, the importance of properly designed AVVs based on transient considerations is explored at different locations.

5.2 Developing the transient model

The method of characteristics (MOC) is the most popular procedure for solving the one dimensional water hammer governing equations. Among its most frequently mentioned advantages are its simplicity in coding and treating boundary conditions as well as its accuracy and efficiency (Ghidaoui et al. 2005). Herein, a computer code is developed to analyze the transient event (i.e., pump shutdown) using the MOC. The governing equations as solved in this work are as follows:

\[
\frac{dV}{dt} - g \frac{dH}{dt} + \frac{f}{2D}V|V| = 0 \quad \text{where} \quad \frac{dx}{dt} = +a \quad \text{C}^+ \text{ characteristics} \quad (5-1)
\]

\[
\frac{dV}{dt} - g \frac{dH}{dt} + \frac{f}{2D}V|V| = 0 \quad \text{where} \quad \frac{dx}{dt} = -a \quad \text{C}^- \text{ characteristics} \quad (5-2)
\]

where \(V, H, g, f, D\) and \(a\) are water velocity (m/s), pressure head (m), acceleration due to gravity (m/s\(^2\)), friction factor, pipe diameter (m), and wave velocity (m/s), respectively. As is commonly done, slope and advective terms are neglected here as this is not only justified but often leads to better numerical results.

The characteristics equations are solved using first-order finite difference approximation. The resulting program is capable of modeling water hammer of pipes in series. Common boundary conditions such as those imposed by an upstream pump, downstream reservoir, and air valve have been included in the model. The associated governing equations for these boundaries are presented in Wylie and Streeter (1993). Since the emphasis of this thesis is on air valves, the air valve governing equations, the associated assumptions, and how air valve boundary is implemented in the model is presented next.
5.2.1 Air valve governing equations

The boundary condition for these valves is handled within the usual framework of the characteristics method. The following assumptions are made in modeling the AVV (Wylie and Streeter 1993):

1) Air flows under isentropic flow conditions.
2) The air mass within the pipe follows the isothermal law in that the mass is generally small and large areas of pipe and liquid surface provides heat capacity to hold the temperature close to the liquid temperature.
3) The air admitted to the pipe stays near the valve, where it can be expelled.
4) The elevation of the liquid surface remains substantially constant, and the volume of air is small compared with the liquid volume of a pipeline reach.
5) The mass rate of flow of air through the valve depends on the values of atmospheric absolute pressure \( p_0 \) and absolute temperature \( T_0 \) outside the pipe, as well as the absolute temperature \( T \) and pressure \( p \) within the pipe. There are four cases that are considered:

**Subsonic airflow in**

\[
\dot{m} = C_{in} A_{in} \sqrt{\frac{\alpha R T}{\rho_0}} \left[ \left( \frac{p}{p_0} \right)^{1.4286} - \left( \frac{p}{p_0} \right)^{1.714} \right] \geq p \geq 0.53 p_0
\]  

(5-3)

in which, \( \dot{m} \) is mass rate of inflow of air, \( C_{in} \) is valve discharge coefficient, \( A_{in} \) is area of valve opening, \( \rho_0 \) is mass density of atmospheric air, \( R \) is gas constant, and \( P \) is pressure inside the pipe.

**Critical flow in**

\[
\dot{m} = C_{in} A_{in} \frac{0.686}{\sqrt{RT_0}} p_0, \quad p \leq 0.53 p_0
\]  

(5-4)

**Subsonic airflow out**

\[
\dot{m} = -C_{out} A_{out} \sqrt{\frac{\alpha R T}{\rho_0}} \left[ \left( \frac{p_0}{p} \right)^{1.4286} - \left( \frac{p_0}{p} \right)^{1.714} \right] \geq p \geq 0.53 p_0
\]  

(5-5)
in which, $A_{out}$ is the area of valve opening and $C_{out}$ is its discharge coefficient

**Critical flow out**

\[
\dot{m} = -C_{out}A_{out} \frac{0.686}{\sqrt[3]{RT}} p, \ p \geq \frac{p_0}{0.53} \tag{5-6}
\]

At the junction of two reaches, the boundary condition is treated like the usual internal section when no air is present in the pipe and the head is greater than atmospheric head. Air valve opens as soon as the head drops below pipe elevation and flow enters. At the end of each time increment of the calculation the general gas law for constant internal temperature is to be satisfied until the air is expelled.

\[
PV = mRT \tag{5-7}
\]

From Figure (5-1):

\[
p[V_i + \Delta t(Q_i - Q_{U_i} - Q'_{U_i} + Q'_i)] = [m_0 + \Delta t(m_0 + \dot{m})]RT \tag{5-8}
\]

in which, $V$ is volume of cavity $2\Delta t$ earlier, $Q_i$ is initial outflow from cavity $2\Delta t$ earlier, $Q'_i$ is final outflow from cavity (at current time), $Q_{ui}$ is initial inflow to cavity, $Q'_{ui}$ is final inflow in cavity, $m_0$ is initial mass of air in cavity, $m_0$ is initial rate of air mass flow into or out of cavity, $m$ is final rate of air mass flow into or out of cavity, and $RT$ is product of gas constant $R$ and absolute temperature.

![Figure 5-1 Air-inlet valve flow notation (Wylie and Streeter 1993)](image-url)
Then the $C^+$ and $C^-$ equations, in short form, are

$$
\begin{align*}
C^+ : H'_i &= C_P - B_P Q'_{ui} &
C^- : H'_i &= C_M + B_M Q'_{ii}
\end{align*}
$$

(5-9)

And the relation between $H'$ and $p$ is

$$
p = \gamma \left( H' - z + \overline{H} \right)
$$

(5-10)

Where, $H'$ is the barometric head, $\gamma$ is the specific weight of liquid, and $z$ is the elevation of the air valve above datum for $H'$. Equations (5-8) to (5-10) and one of Equations (5-3) to (5-6), depending on the type of flow, provide the relations to solve for the variables $H'_i$, $p$, $m' Q'_{ui}$, and $Q'_{ii}$. It should be indicated that the coding is done in Visual Fortran.

### 5.2.2 Indices for evaluating transient response of the system

The damage induced by pressure surges can be a function of the amount of deviation of positive and negative pressures from the allowable maximum and minimum pressures and the time during which pipe experiences these pressures. Therefore, the likelihood of a damaging transient event can be measured by a parameter called the surge damage potential factor or SDPF (Jung and Karney 2011). Positive/negative surge damage factors will be the integration of the transient pressures that are higher/lower than the rating pressure/minimum allowable pressure ($H_{\max}/H_{\min}$) of the pipe. The indices used in this study to evaluate the transient response of the system are formulated as follows (Jung and Karney 2011):

$$
SDPF^+ = \sum_{i=1}^{nodes} \int H_i dt \quad \text{where} \quad H_i < H_{\max}
$$

(5-11)

$$
SDPF^- = \sum_{i=1}^{nodes} \int H_i dt \quad \text{where} \quad H_i > H_{\min}
$$

(5-12)

### 5.2.3 The system under study

The problem under study is a hypothetical pipeline containing an AVV at the high point (Figure 5-2). Table 5-1 shows the hydraulic characteristics of the system (i.e., initial discharge $Q$, wave speed $a$, and friction factor $f$), the range of variations of AVV design parameters (i.e., inlet
diameter of AVV $D_{in}$, outlet diameter of AVV $D_{out}$, inlet coefficient of AVV $cd_{in}$, outlet coefficient of AVV $cd_{out}$) and the range of variation of the high point characteristics (i.e., its elevation, $Z_0/H_s$, and its distance along the pipeline from the upstream boundary, $X/L$). For each characteristic of the high point, the importance of each AVV parameter and parameters in water hammer governing equations in deriving the model target behaviour (SDPF- = 0) is analyzed by applying MCF and KS tests. The number of Monte Carlo Simulation (MCS) runs used is 4000. This is determined by monitoring the convergence of the variance and mean of the targeted output. That is, if the mean and variance of the distribution of SDPF do not change, this means that the number of simulations is enough. In this study, the number of sufficient Monte Carlo Simulations is 4000 and this results in calculation of 4000 SDPF- values.

![Figure 5-2 The pipe configuration under study](image)

<table>
<thead>
<tr>
<th>$L_1+L_2+L_3+L_4$ (m)</th>
<th>$L_2$ (m)</th>
<th>$L_3$ (m)</th>
<th>$D$ (m)</th>
<th>$Q$ (m$^3$/s)</th>
<th>$H_i$ (m)</th>
<th>$H_e$ (m)</th>
<th>$D_{in}$ (m)</th>
<th>$D_{out}$ (m)</th>
<th>$cd_{in}$</th>
<th>$cd_{out}$</th>
<th>$X/L$</th>
<th>$H_e/\Delta H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>200</td>
<td>150</td>
<td>0.914</td>
<td>0.881</td>
<td>178.49</td>
<td>176.9</td>
<td>0.01-0.2</td>
<td>0.001-0.02</td>
<td>0.6-0.7</td>
<td>0.6-0.7</td>
<td>0.2, 0.4, 0.6</td>
<td>0.2-0.9</td>
</tr>
</tbody>
</table>
5.3 Monte Carlo Filtering (MCF)

AVVs are installed to prevent vacuum conditions along the pipe or, in other words, they are responsible for eliminating low pressure problems (SDPF- equal to zero). Hence, the first step in the sensitivity analysis is to understand which AVV design factor is most responsible for producing a desirable SDPF- of 0 and how this sensitivity changes with AVV location. Before performing the sensitivity analysis, a setting should be selected depending on the purpose of the sensitivity analysis. In such situations where a specific portion of the model output is studied (i.e., SDPF- = 0), factor mapping (i.e., specific portions of the model output are mapped backwards onto the space of the input factors, here this specific portion is SDPF- = 0) is selected as the sensitivity analysis setting. Since Monte Carlo Filtering (MCF) as a Regional Sensitivity Analysis (RSA) provides such a tool, it is implemented in this section. Here, the purpose is to realize which of the AVV design parameters are most responsible for producing SDPF- = 0.

5.4 Applying Monte Carlo Filtering

In the method of MCF, a set of Monte Carlo Simulations (MCS) should be performed. The procedure applied in this thesis for performing Monte Carlo experiments is depicted in Figure 5-3. A uniform probability distribution is first assigned to input variables, and random sampling is then used to select the values of the contributing parameters from their corresponding distributions. Then, transient simulations are performed. In each run, positive and negative surge damage potential factors are calculated. At the end of the simulation, good and bad realizations are separated and the KS test is performed for each parameter under study.
5.4.1 Accuracy of Monte Carlo Simulation

In this method, Monte Carlo experiments are run to produce the outputs of interest (SDPF-). The accuracy of the Monte Carlo Simulation statistics and probability distributions of the output of interest is a function of the number of runs, the quality of each simulation and the assumption about input distributions. This is determined by monitoring the convergence of the variance and mean of the targeted output. That is, if the mean and variance of the distribution of SDPF do not change, this means that the number of simulations is enough. In this study, a sufficient number of Monte Carlo Simulations was found to be around 4000 and this results in calculation of 4000 SDPF- values.

5.4.2 Separation of MCS Output Values

MCF requires that the output values from the MCS be separated as good and bad realizations. In this study, the outputs of MCS (i.e., 4000 SDPF- values) are separated into two groups of “good” (i.e., SDPF- = 0) and “bad” (i.e., SDPF->0) realizations. The elements of the SDPF- that fall within the ‘good’ realizations (i.e., SDPF- = 0) are reported as ‘Behavioural’ while the
remaining ones (i.e., SDPF->0) are considered as ‘Non-Behavioural’. Those parameter values (e.g., $D_{in}$, $D_{out}$, $cd_{in}$, $cd_{out}$, $Q$, $a$, $f$), which caused the behavioural system output (i.e., SDPF = 0), are separated from those that caused non-behavioural results (i.e., SDPF->0). Finally, the Cumulative Distribution Functions (CDFs) of Behavioural (B) and Non-Behavioural (NB) outputs for each parameter of interest are compared.

5.4.3 Performing KS Test

The Cumulative Distribution Functions (CDFs) of Behavioural and Non-Behavioural outputs (i.e., SDPF = 0, SDPF->0) for each parameter (e.g., $D_{in}$, $D_{out}$, $cd_{in}$, $cd_{out}$, $Q$, $a$, $f$) are compared by application of Kolmogrov-Smirnov (KS) test which is a non-parametric test. This test does not make any assumption about the data distribution. Here, the null hypothesis is that both sets of data are sampled from populations with identical distributions. And it tests for any violation from that null hypothesis at a 5% significance level.

The KS test reports a K value which is the maximum difference between the two CDFs of the parameters resulting in Behavioral and Non-behavioral outputs and calculates a P value from that. The P value is the probability that the KS test value will be as large as what is observed if the two samples were randomly sampled from identical distributions. If the P value is small it is concluded that the two groups are sampled from populations with different distributions. Therefore, if the two Cumulative Distribution Functions (i.e., CDFs of B and NB) are significantly different for a given parameter, then that parameter is a key factor in driving the model’s target behaviour. Further, one can distinguish the identifiable subsets of values in their predefined ranges that are more likely to fall under behavioural than under non-behavioural categories (Saltelli et al. 2008).

5.5 Results and discussion: MCF analysis

After 4000 Monte Carlo were runs for each elevation of the high point at X/L = 0.2, 0.4, and 0.6, respectively, the KS tests were performed to understand the importance of the input parameter by exploring the difference between the behavioural (SDPF = 0) and non-behavioural (SDPF->0) cumulative distribution functions for each parameter under study (i.e., $D_{in}$, $D_{out}$, $Cd_{in}$, $Cd_{out}$, $Q$, $a$, and $f$). Such an analysis is performed for each of the horizontal and vertical distances of the high point.
5.5.1 KS test values and the associated P values

After applying the KS test, a KS test value, a P value and a plot showing the CDFs of both behavioural and non-behavioural model output are reported. The KS Test value is the maximum difference between the two CDFs of the parameters resulting in Behavioral and Non-behavioral outputs. The higher this value is the more effective that parameter is in deriving the model output behaviour. The P value is the probability that the KS test value will be as large as what is observed if the two samples were randomly sampled from identical distributions. If the P value is small it is concluded that the two groups are sampled from populations with different distributions. Therefore, if the two Cumulative Distribution Functions (i.e., CDFs of B and NB) are significantly different for a given parameter, then that parameter is a key factor in driving the model’s target behaviour.

The KS test and the associated P values for the problem under study are shown in Tables 5-2, 5-3 for X/L = 0.2. According to these Tables, $D_{in}$, $D_{out}$, $Q$ are showing high KS test values and small P values, while $cd_{in}$, $cd_{out}$, $a$ and $f$ are showing small KS test values and high P values. Hence, the importance of $D_{in}$, $D_{out}$, and $Q$ in deriving the desired behaviour of the model (SDPF- = 0) at each location of the high point is inferred. The same conclusion is drawn by considering Tables A-1 to A-4 in Appendix A for X/L = 0.4 and 0.6, respectively.

The effectiveness of $D_{in}$ and $Q$ in producing SDPF- = 0 is obvious, and the importance of $D_{out}$ in producing SDPF- = 0 is justified by considering the induced secondary transient pressures as a result of a large AVV outlet orifice. However, it cannot be concluded from the resulting KS test values which factor is more important in producing the desired model output.
Table 5-2 KS test values for different intercepted wave heights at the high point at X/L = 0.2

<table>
<thead>
<tr>
<th>X/L=0.2</th>
<th>KS Test Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hp/ΔH</td>
<td>Din</td>
</tr>
<tr>
<td>0.20</td>
<td>0.41</td>
</tr>
<tr>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>0.30</td>
<td>0.29</td>
</tr>
<tr>
<td>0.40</td>
<td>0.25</td>
</tr>
<tr>
<td>0.50</td>
<td>0.20</td>
</tr>
<tr>
<td>0.60</td>
<td>0.25</td>
</tr>
<tr>
<td>0.70</td>
<td>0.17</td>
</tr>
<tr>
<td>0.80</td>
<td>0.08</td>
</tr>
<tr>
<td>0.90</td>
<td>0.05</td>
</tr>
<tr>
<td>0.95</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 5-3 P values for different intercepted wave heights at the high point at X/L = 0.2

<table>
<thead>
<tr>
<th>X/L=0.2</th>
<th>P Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hp/ΔH</td>
<td>D_in</td>
</tr>
<tr>
<td>0.20</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.25</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.40</td>
<td>2.6E-09</td>
</tr>
<tr>
<td>0.50</td>
<td>1.5E-03</td>
</tr>
<tr>
<td>0.60</td>
<td>5.0E-03</td>
</tr>
<tr>
<td>0.70</td>
<td>6.0E-04</td>
</tr>
<tr>
<td>0.80</td>
<td>5.0E-04</td>
</tr>
<tr>
<td>0.90</td>
<td>3.0E-02</td>
</tr>
<tr>
<td>0.95</td>
<td>3.0E-02</td>
</tr>
</tbody>
</table>
5.5.2 Cumulative distribution functions and associated information

Result of the KS test are reported as a comparison between cumulative distribution functions of behavioural and non-behavioural model output. The maximum vertical difference between these two distributions is reported as KS test value. The higher this value is the more effective that parameter is in deriving the model output behaviour.

The resulting cumulative distribution functions (CDFs) of behavioural and non-behavioural output for each of the important parameters (i.e., $D_{in}$, $D_{out}$, and $Q$) are plotted; they are shown for different intercepted wave heights in Figures 5-4 to 5-6 for $X/L = 0.2$. In each Figure a KS Test value and a P value is reported at the top of the Figure. The P value is the probability that the same magnitude of the KS test value will be observed if the two samples were randomly sampled from identical distributions. A small P value means that there is a small probability that the same results can be inferred if the two distributions are identical. In other words, it is less probable that the importance of the parameter under study is wrongly obtained. Furthermore, the range of parameter which is more likely to fall within behavioural than non-behavioural model output can be inferred from these Figures. The following discussion helps to better interpret these Figures.

In Figure 5-4a, the CDF of the parameter values which caused $\text{SDPF}^- = 0$ is shown with solid lines and that of $\text{SDPF}^- > 0$ is shown with dashed lines. After comparing the two CDFs of behavioural and non-behavioural model outputs by application of the KS test, the resulting KS test value is 0.41 and this implies that the parameter (e.g., $D_{in}/D_P$) is a key parameter in deriving the model output (i.e., $\text{SDPF}^-$). Moreover, the P value is less than 0.0001 and this implies that this difference is not calculated by chance or the probability that a KS test value with such a magnitude be obtained if the two samples are randomly sampled from the identical distributions is very small. In other words, there is definitely a difference between these two distributions, and therefore, the parameter (e.g., $D_{in}/D_P$) has a substantial impact on the model output (i.e., $\text{SDPF}^-$).

Furthermore, the CDF plots show the probability that the parameter value (e.g., $D_{in}/D_P$) less than or equal to which value or ranges of values results in behavioral or non-behavioral model output. In other words, the ranges of each parameter which are effective or not effective in producing the desired model output ($\text{SDPF}^- = 0$) is shown in these Figures. For example, in
Figure 5-4a, $D_{in}/D_p$ less than 0.075 does not result in the desired model output (SDPF- = 0). If the $0.075 < D_{in}/D_p < 0.14$, it is more likely to fall within non-behavioural model output (SDPF- > 0) than behavioural model output (SDPF- = 0). And finally, if the $D_{in}/D_p > 0.14$, it is more likely to obtain SDPF- = 0 than SDPF- > 0. Such information can be useful for selecting the initial size for AVVs at early stages of design. This prevents the blind search procedure currently practiced by designers for selecting a size for AVVs effective for transient events. Thus, it can be a good justification for performing such a sensitivity analysis.

5.5.3 Variation in sensitivity of SDPF- to $D_{in}$ at vertical locations of the high point

Figure 5-4 presents the CDF plots and the results obtained from the KS test for several elevations of the high point at $X/L = 0.2$ for $D_{in}$. As is shown, at higher elevations of the high point (lower $H_p/\Delta H$), the minimum limit for $D_{in}$ that produces SDPF- = 0 is larger. And, this implies that at higher elevations of high point larger inlet diameter of AVV is required to suppress the transient-induced pressures. This is due to the higher magnitude of negative pressures experienced by the high point at higher elevations. Results obtained for $X/L = 0.4$ and $X/L = 0.6$ are presented in Figures A-1 to A-2 in Appendix A. These Figures also confirm such a conclusion.

5.5.4 Variation in sensitivity of SDPF- to $D_{in}$ at horizontal locations of the high point

As shown in Figure 5-4 for $D_{in}$ at $X/L = 0.2$ and in Figures A-1 to A-2 for $X/L = 0.4$ and 0.6, at each elevation of the high point, the farther the horizontal distance of the high point from the downstream reservoir, the larger the minimum limit for $D_{in}$ for producing behavioural model output becomes. This is because, in the pumping line, the magnitude and duration of negative pressure affecting the high point increases as the high point moves upstream. Therefore, a larger $D_{in}$ is required to produce SDPF- = 0 at locations closer to the pump.
(a) $H_p/\Delta H = 0.2$

(b) $H_p/\Delta H = 0.3$

(c) $H_p/\Delta H = 0.4$

(d) $H_p/\Delta H = 0.5$
(e) $H_p/\Delta H = 0.6$

(f) $H_p/\Delta H = 0.7$

(g) $H_p/\Delta H = 0.8$

(h) $H_p/\Delta H = 0.9$

**Figure 5-4** Cumulative distributions curves for $D_{in}/D_p$ at $X/L = 0.2$ for several elevations of high point ($H_p/\Delta H$)
5.5.5 Sensitivity of SDPF- to $D_{out}$ at vertical locations of the high point

The cumulative distribution functions (CDFs) for $D_{out}$ are presented. As seen in Figure 5-5 for $X/L = 0.2$ and Figures A-3 and A-4 in Appendix A for $X/L = 0.4$ and 0.6, respectively, when the elevation of the high point gets lower, the outlet diameter of the AVV gets more important. The highest difference between behavioural and non-behavioural CDFs are at $H_P/\Delta H = 0.4$ to 0.6 for $X/L = 0.2$ and 0.4. Such high differences occur at $H_P/\Delta H = 0.5$-0.65 for $X/L = 0.6$. At high point elevations where $h_t/H_P$ is high, the effect of friction is introduced through decreasing the backward driving force and, consequently, reducing the secondary transients. However, there is a high point elevation where $h_t/H_P$ can be neglected and the secondary transient is experiencing its maximum magnitude. After that point, as the high point is lowered below the above-mentioned limits at each $X/L$, since the intercepted wave height becomes higher, the reverse flow at the time of cavity collapse is small and the associated secondary transient is less severe compared to higher elevations of the high point. This is the reason for the lower sensitivity of the transient response to $D_{out}$ at lower limits of $H_P/\Delta H$ at each $X/L$. These results imply that in order to prevent such destructive events, the size of the AVV outlet diameter should be smaller at higher elevations of the high point.
Kstest = 0.23, P < 0.0001

Kstest = 0.64, P < 0.0001

Kstest = 0.72, P < 0.0001

Kstest = 0.73, P < 0.0001

(a) $H_p/\Delta H = 0.2$

(b) $H_p/\Delta H = 0.3$

(c) $H_p/\Delta H = 0.4$

(d) $H_p/\Delta H = 0.5$
Figure 5-5 Cumulative distributions curves for $D_{out}/D_P$ at $X/L = 0.2$ for several elevations of high point ($H_p/\Delta H$)
5.5.6 Sensitivity of SDPF- to $Q$

Figure 5-6 and Figures A-5 and A-6 show the results obtained from the KS test for the sensitivity of the transient response of the system (SDPF-) to $Q$ for three horizontal locations (i.e., $X/L = 0.2$, $0.4$, $0.6$, respectively) and several high point elevations at each horizontal location. As is seen, the sensitivity of SDPF- to $Q$ increases as the high point elevation is lowered. At lower elevations of high point the sensitivity of the SDPF- to inlet and outlet diameter of AVV decreases and the only parameter that impacts the transient response of the system is $Q$. Therefore, depending on the magnitude of discharge ($Q$) in the system, the sensitivity of the transient response to this parameter varies. And, at higher water flows ($Q$), it is more likely to fall within the non-behavioural model output (i.e., SDPF- > 0).

Although the importance of each variable can be understood by MCF by applying the KS test, it should be noted that the KS test is sufficient to ascertain whether a factor under analysis is important. However, it does not provide the necessary condition for importance. Moreover, the interaction structures among the variables are not detected by KS test values (Saltelli et al. 2008).

Overall, the results obtained from the MCF application ensure us that the three parameters (i.e., $D_{in}$, $D_{out}$, and $Q$) are the important parameters mostly responsible for deriving the model output behaviour. However, these results don’t confirm the priority of each parameter over the other in producing the behavioural model output. Of course, these Figures presented in this section confirm that the AVV inlet and outlet orifice diameters, and pipe discharge are crucial factors that can affect the model output.
(a) $H_p/\Delta H = 0.2$

(b) $H_p/\Delta H = 0.3$

(c) $H_p/\Delta H = 0.4$

(d) $H_p/\Delta H = 0.5$
Figure 5-6 Cumulative distributions curves for $Q$ at $X/L = 0.2$ for several elevations of high point ($H_p/\Delta H$)
5.6 Scatter plots

The effect of the AVV design parameters and the parameters in the water hammer governing equations on SDPF- can also be visually assessed by a graphical sensitivity method using scatter plots. The Monte Carlo simulation performed on the model produces a series of input values and corresponding output values. Such simulated pairs can be graphically presented as scatter plots.

In order to visually assess the results of MCF method, scatter plots are drawn for the first 4000 Monte Carlo simulations performed in the previous section at the previously mentioned X/L (i.e., 0.2, 0.4, and 0.6) ratios for each H_p/ΔH. Representative results for X/L = 0.6 and H_p/ΔH = 0.5 are depicted in Figure 5-7. The Relative SDPF- shown in the Y axis is the ratio of SDPF- in the system under study with the presence of an AVV to SDPF- in the system without the presence of an AVV at a mean discharge.

These scatter plots show how the magnitude of SDPF- changes with changing D_in, D_out and inlet and outlet coefficients of AVVs, as well as Q and a. Also, the ranges of these parameters that produce both behavioural and non-behavioural model output are shown. As is shown in Figure 5-7, the SDPF- has a nonlinear relationship with D_in. There is also a correlation between SDPF- and D_out and Q. But, SDPF- has a very small correlation with cd_in, cd_out, and a. Such a trend has been observed for other horizontal and vertical locations of the high point. The results confirm the MCF results.
As is shown in Figure 5-7, SDPF- is more sensitive to $D_{in}$ and $Q$. The scatter plots for these two parameters are shown for $X/L = 0.4$ and different elevations of the high point in Figures 5-8 and 5-9 for $D_{in}$ and $Q$, respectively, to visualize any spatial variability of sensitivity of these parameters.
5.6.1 Sensitivity of SDPF- to $D_{in}$ at different elevations of the high point

Scatter plots for $D_{in}$ at different elevations of the high point are shown in Figure 5-8 for $X/L = 0.4$. As is shown, as the high point elevation lowers ($H_p/H$ increases), the correlation between $D_{in}$ and SDPF- is reduced. This implies that at low elevations, the sensitivity of SDPF- to the size of $D_{in}$ is low. This also confirms the results from the MCF analysis.

5.6.2 Sensitivity of SDPF- to $Q$ at different elevations of the high point

Scatter plots for $Q$ at different elevations of the high point are shown in Figure 5-9 for $X/L = 0.4$. As is shown, as the high point elevation lowers ($H_p/H$ increases), the correlation between $Q$ and SDPF- is increased. And at the lowest elevation the nonlinear relationship to SDPF- is completely visible. This confirms that at the lowest elevations, the SDPF- is solely correlated with $Q$ and other parameters have less of an effect.

Overall, the possible dependencies between the input and the corresponding output can be inferred by scatter plots. Scatter plots identify potentially complex dependencies and the nature of such dependencies. This helps for proper selection of the sensitivity analysis method to apply. However, scatter plots are mostly interpreted qualitatively. It cannot be inferred from scatter plots that the sensitivities of two inputs differ significantly from each other.

The method selected for sensitivity analysis should be able to diagnose the effect of input factors acting individually or in combination in order to identify the effect of interactions between variables. Hence, in order to figure out the main effect contribution of each input factor to the variance of the SDPF-, and to understand how much that parameter is involved in interactions, another method should be applied. Therefore, the next step in performing the sensitivity analysis is to understand the main and total effect contribution of each parameter by applying a variance-based method (Saltelli et al. 2008).
Figure 5-8 Scatter plots for $D_{in}/D_P$ at $X/L = 0.4$ and several elevations of the high point ($H_p/\Delta H$)
Figure 5-9 Scatter plots for $Q$ at $X/L = 0.4$ and several elevations of the high point ($H_p/\Delta H$)
5.7 Variance-based method

The variance-based sensitivity analysis (e.g., Sobol’s method) is based on the decomposition of the variance of the model output to its sources of variation (Equation 5-13). In Sobol’s method, the variance of the output is decomposed into components resulting from each input parameter as illustrated in Equation (5-13).

\[ V = \sum_i V_i + \sum_{i<j} V_{ij} + \ldots + V_{1,2,3,\ldots,n} \]  

The first order terms \( V_i \) show the partial variance in the model output due to the individual effect of a random variable \( X_i \), and the higher order terms incorporates the interaction effects between two or more random variables.

5.7.1 Main and total effect sensitivity indices

Decomposition of the output variance introduces the two important indices known as the main effect (i.e., \( S_i \)) and the total effect (i.e., \( ST \)). Main effect refers to the effect of a specific random variable. And, the total effect incorporates both the individual effect of a random variable and its interaction with other random variables. The main effect index of a random variable \( V_i \) is obtained by normalizing the main effect variance over the total variance of the output (Equation (5-14)). The sensitivity index for the interactions between two random variables, \( V_i \) and \( V_j \) is given in Equation (5-15). Equation (5-16) represents a general sensitivity index.

\[ S_i = \frac{V_i}{V}, \quad 1 \leq i \leq m. \]  

\[ S_{ij} = \frac{V_{ij}}{V}, \quad 1 \leq i(j \leq m. \]  

\[ S_{i,j+1,\ldots,m} = \frac{V_{i,j+1,\ldots,m}}{V}, \]  

When a significant interaction exists among random variables, computing only the main effects of the input parameters is not enough in order to understand its importance in producing the model output. Therefore, the total effect of a random variable \( X_i \), which includes its main effect and all the interaction effects involving \( X_i \), is required. The total effect is computed by
partitioning the whole set of variables into a subset of interest and its complementary (i.e., \(X_i\) and \(X_{-i}\), where the latter is the subset of all variables excluding \(X_i\)),: 
\[ S_{Ti} = 1 - S_{~i} \]
where, \(S_{~i} = S_{1,...,i-1,i+1,...,m}\) is the index for the combined effect of all random variables except \(X_i\).

### 5.7.2 Computing main and total effect sensitivity indices

The above sensitivity indices can be calculated by several approaches. The impact of a random input can be evaluated by reducing the variance of a response \((Y)\) by fixing the associated random variable. The ratio \(\frac{V_i}{V} = \frac{V[E(Y/X_i)]}{V}\) is known as the correlation ratio or called importance measures. Generally, the sensitivity of each input parameter of a model is evaluated by understanding its contribution to the total variance of the model output distribution.

The variances can be calculated using Monte Carlo numerical integrations. It requires \(n(m+2)\) runs to compute the first and the total sensitivity indices, where \(n\) is the number of simulations for calculation of the sensitivity indices for each parameter and \(m\) is the number of parameters. The convergence of the Monte Carlo integrations used in Sobol’s method is affected by the sampling scheme selected. The Monte Carlo integration error decreases by \(\frac{1}{\sqrt{n}}\), considering uniform random samples at \(n\) points in the \(m\)-dimensional space (Tang et al. 2007).

### 5.7.3 Sobol’ indices

Sobol’ (1993) proposed a more practical approach which uses an unique decomposition of a function with increasing dimensions as follows:

\[
f(X) = f_0 + \sum_{i=1}^{m} f_i(x_i) + \sum_{i=1}^{m} \sum_{j=i+1}^{m} f_{ij}(x_i, x_j) + \ldots + f_{1,...,m}(x_1,\ldots,x_m)
\]

where \(x\) is a vector of \(m\) variables, \(f_0\) is a constant, \(f_i\) is a function of \(X_i\) only, \(f_{ij}\) is a function of \(x_i\) and \(x_j\) only, and so on. Then the variance and partial variance terms in Equation (5-13) becomes:

\[
V = \int f^2(x)P(x)dx - f_0^2
\]

\[
V_{i,...,m} = \int f^2_{i,...,m}(x_i,\ldots,x_m)P(x_1,\ldots,x_m)dx_1\ldots dx_m,
\]
where \( p(x_1, \ldots, x_m) \) is the joint PDF of random variables \( x_i \) to \( x_m \), inclusive. Equation (5-18) and (5-19) can be evaluated by Monte Carlo methods to obtain the main effects and total effects defined in Equations ((5-14)-(5-16)). However, calculating the interaction effects requires a multidimensional integration.

### 5.7.4 Computing Sobol’s sensitivity indices

For estimating the total effects, Sobol’ developed a Monte Carlo based procedure, which requires the same computational expense as for computing the main effects. For the analysis, uniform probability distributions are assigned to the input parameters within their range of variation. And, the following sensitivity indices are computed (Saltelli et al. 2008): The first order sensitivity index which represents the main effect of each input factor to the variance of the output; and the total effect sensitivity index which accounts for the total contribution to the output variation due to the factor \( x_i \) (i.e., its first-order effect plus all higher-order effects due to interactions). The procedure for the analysis, as illustrated in Saltelli et al. (2008), is as follows:

- Generate a \((N, 2k)\) matrix of random numbers \((k \text{ is the number of input factors})\) and define two matrices of data \((A \text{ and } B)\), each containing half of the sample.
- Define a matrix \( C_i \) formed by all columns of \( B \) except the \( i^{th} \) column, which is taken from \( A \).
- Compute the model output for all the input values in the sample matrices \( A, B \) and \( C_i \), obtaining three vectors of model outputs of dimension \( N \times 1: y_A = f(A), \ y_B = f(B), \text{ and } y_{C_i} = f(C_i). \) These vectors are used to compute the first- and total-effect indices, \( S_i \) and \( ST_i \), for a given factor, \( X_i \), according to Equations (5-20 to 5-22).

\[
S_i = \frac{V[E(Y/X_i)]}{V(Y)} = \frac{y_A y_{C_i} - f_0^2}{y_A y_A - f_0^2} = \frac{(1/N) \sum_{j=1}^{N} y_A^{(j)} y_{C_i}^{(j)} - f_0^2}{(1/N) \sum_{j=1}^{N} (y_A^{(j)})^2 (y_{C_i}^{(j)})^2 - f_0^2} \tag{5-20}
\]

\[
f_0^2 = \left( \frac{1}{N} \sum_{j=1}^{N} y_A^{(j)} \right)^2 \tag{5-21}
\]

\[
ST_i = 1 - \frac{V[E(Y/X_i)]}{V(Y)} = 1 - \frac{y_B y_{C_i} - f_0^2}{y_A y_A - f_0^2} = 1 - \frac{(1/N) \sum_{j=1}^{N} y_B^{(j)} y_{C_i}^{(j)} - f_0^2}{(1/N) \sum_{j=1}^{N} (y_A^{(j)})^2 (y_{C_i}^{(j)})^2 - f_0^2} \tag{5-22}
\]
The cost of this approach is \( N(k+2) \) runs of the model. In this study, \( N = 2000 \) and \( k = 7 \) (inlet and outlet diameter of AVV: \( D_{in} \) and \( D_{out} \); inlet and outlet coefficient of AVV: \( Cd_{in} \) and \( Cd_{out} \); wave velocity: \( a \); steady state discharge: \( Q \); friction factor: \( f \)), and therefore, the total number of MCS runs is 18000.

5.7.5 Model application

The variance-based method is applied to the problem introduced in Figure 5-2. The variance-based sensitivity analysis (i.e., Sobol’ method) is performed for each elevation of high point at \( X/L = 0.6, 0.4, \) and \( 0.2 \), respectively. \( N \) is 2000 and the 7 parameters under study are \( D_{in}, D_{out}, cd_{in}, cd_{out}, a, Q \) and \( f \). The total number of Monte Carlo Simulations (MCSs) for each sensitivity analysis is 18000.

Uniform probability distributions are assigned to each input variable. A 20 percent variation is assigned to \( Q, a \) and \( f \). The range of variation of the design parameters of the AVVs is shown in Table 5-1. The procedure proposed by Saltelli et al. (2008) is applied to calculate the first order and total effect sensitivity indices using Equations ((5-20) to (5-22)). The uncertainty range of the sensitivity indices are calculated by application of the bootstrap confidence intervals. Finally, the importance of each parameter in deriving the outputs of interest (i.e., SDPF- and SDPF+) and the ranking of each important parameter are identified.

5.7.6 Bootstrap confidence intervals

The next step after calculating the sensitivity indices is to determine the uncertainty of the computed sensitivity indices. To estimate the uncertainty range of the calculated sensitivity indices, a bootstrap simulation (Effron and Tibshirani 1993) is performed based on resampling of the output values. At each bootstrap simulation, 10000 bootstrap samples each with a size of 2000 were drawn from replacement of the previously obtained MCS output values (i.e., 2000 SDPF+ values and 2000 SDPF- values) for each location of the high point. At each bootstrap simulation, main and total effect sensitivity indices are calculated based on Equations (5-20) to (5-22). Therefore, 10000 main effects and 10000 interaction effects for each input are estimated at each location of the high point. A bias corrected and accelerated percentile method was applied to calculate the 95% confidence intervals (i.e., CI).
Finally, the uncertainty ranges for sensitivity of SDPF- and SDPF+ to the parameters under study are reported. Parameters with positive bootstrap confidence intervals are considered as important parameters in deriving the model target behaviour (i.e., SDPF- and SDPF+).

5.7.6.1 Sensitivity of SDPF- to the parameters under study

An uncertainty range for main and total effect sensitivity indices is reported for each parameter in Table 5-4 to Table 5-7 for SDPF- at X/L = 0.6 and 0.4, respectively, for each location of the high point. Factors with a negative lower range are considered as unimportant inputs. Therefore, according to the results in these tables, $D_m$ and $Q$ show the positive uncertainty ranges for sensitivity indices. And therefore, they are considered as the two most important variables contributing to the variance of SDPF- at each elevation of the high point. These results confirm that if $D_m$ is not selected properly (e.g., low values of $D_m$), AVV is not capable of preventing the system from negative pressures. Also, at higher flow rates, sudden stoppage of flow can cause high negative pressures where the sole use of AVV might not be sufficient for protecting the system against negative pressures.
### Table 5-4 Confidence intervals for first order (S₁) sensitivity to SDPF- at X/L = 0.6

<table>
<thead>
<tr>
<th>SDPF- at X/L=0.6</th>
<th>Dₙ</th>
<th>Dₙₓ</th>
<th>cdₙ</th>
<th>cdₙₓ</th>
<th>a</th>
<th>Q</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP/DH</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
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<td>Si</td>
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<td>0.865</td>
<td>0.05</td>
<td>-0.075</td>
<td>0.123</td>
<td>0.05</td>
<td>-0.114</td>
</tr>
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<td>-0.034</td>
<td>0.172</td>
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<td>-0.103</td>
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<td>0.120</td>
<td>0.04</td>
<td>-0.100</td>
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<td>0.090</td>
<td>0.03</td>
<td>-0.070</td>
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### Table 5-5 Confidence intervals for Total effect (S₁) sensitivity to SDPF- at X/L = 0.6

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<th>Dₙ</th>
<th>Dₙₓ</th>
<th>cdₙ</th>
<th>cdₙₓ</th>
<th>a</th>
<th>Q</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP/DH</td>
<td>ST</td>
<td>std</td>
<td>ST</td>
<td>std</td>
<td>ST</td>
<td>std</td>
<td>ST</td>
</tr>
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<td>0.06</td>
<td>-0.357</td>
<td>0.430</td>
<td>0.20</td>
<td>-0.400</td>
</tr>
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<td>0.412</td>
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<td>0.634</td>
<td>0.942</td>
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<td>-0.388</td>
<td>0.396</td>
<td>0.20</td>
<td>-0.489</td>
</tr>
<tr>
<td>0.65</td>
<td>0.343</td>
<td>0.683</td>
<td>0.09</td>
<td>-0.120</td>
<td>0.450</td>
<td>0.15</td>
<td>-0.200</td>
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<tr>
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<td>0.127</td>
<td>0.472</td>
<td>0.08</td>
<td>-0.090</td>
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Table 5-6 Confidence intervals for first order ($S_i$) sensitivity to SDPF- at X/L = 0.4

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<th>Din</th>
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<th>Dout</th>
<th>cdin</th>
<th>std</th>
<th>cdout</th>
<th>std</th>
<th>a</th>
<th>std</th>
<th>Q</th>
<th>std</th>
<th>f</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP/DH</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
</tr>
<tr>
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<td>0.02</td>
<td>-0.050</td>
<td>0.040</td>
<td>0.02</td>
<td>-0.040</td>
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<td>0.02</td>
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<td>0.058</td>
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<td>-0.042</td>
<td>0.052</td>
<td>0.02</td>
<td>-0.040</td>
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<td>0.030</td>
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<td>0.020</td>
<td>0.02</td>
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<td>0.02</td>
<td>-0.070</td>
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<td>0.114</td>
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<td>-0.077</td>
<td>0.037</td>
<td>0.03</td>
<td>-0.075</td>
<td>0.040</td>
<td>0.03</td>
<td>-0.080</td>
</tr>
<tr>
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<td>-0.030</td>
<td>0.125</td>
<td>0.04</td>
<td>-0.014</td>
<td>0.114</td>
<td>0.03</td>
<td>-0.070</td>
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<tr>
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<td>0.060</td>
<td>0.03</td>
<td>-0.040</td>
<td>0.070</td>
<td>0.03</td>
<td>-0.050</td>
<td>0.060</td>
<td>0.03</td>
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<td>0.060</td>
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139
Table 5-7 Confidence intervals for Total effect (S_T) sensitivity to SDPF- at X/L = 0.4

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<th>SDPF- at X/L=0.4</th>
<th>Din</th>
<th>Dout</th>
<th>cdin</th>
<th>cdout</th>
<th>a</th>
<th>Q</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP/DH</td>
<td>ST</td>
<td>std</td>
<td>ST</td>
<td>std</td>
<td>ST</td>
<td>std</td>
<td>ST</td>
</tr>
<tr>
<td>0.2</td>
<td>0.935</td>
<td>1.040</td>
<td>0.03</td>
<td>-0.338</td>
<td>0.322</td>
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<td>-0.377</td>
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<td>0.905</td>
<td>0.987</td>
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<td>0.390</td>
<td>0.17</td>
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<td>0.869</td>
<td>1.010</td>
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<td>0.458</td>
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<td>0.10</td>
<td>-0.070</td>
<td>0.316</td>
<td>0.09</td>
<td>-0.126</td>
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</tbody>
</table>

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5.7.6.2 Sensitivity of SDPF+ to the parameters under study

As illustrated previously, by applying the bootstrap confidence intervals, the uncertainty ranges are obtained for the sensitivity of SDPF+ to the input parameters. Results for uncertainty ranges for main and total effect sensitivity indices at \( X/L = 0.6 \) and \( 0.4 \) for SDPF+ are shown in Table 5-8 to Table 5-11. Inputs with positive bootstrap confidence intervals are considered as important parameters in producing SDPF+. And, inputs with negative lower limits of confidence intervals are considered as unimportant variables in producing SDPF+.

As shown in these Tables, the uncertainty range of the sensitivity indices for \( D_{out} \) and \( Q \) are positive and this implies that these two parameters are the most important parameters with highest contribution to the variance of SDPF+. That is, if \( D_{out} \) is improperly selected (i.e., either too large or too small), it can cause the system to undergo high positive transient pressures. For instance, if \( D_{out} \) is too large, the secondary transient pressure at the instance of cavity collapse will result in higher SDPF+ and if \( D_{out} \) is too small the high pressure due to the compression of the air pocket below the air valve will affect the magnitude of SDPF+. And finally, it is obvious that the larger the magnitude of \( Q \) in the system, the higher the magnitude of transient pressures as the flow stops.
### Table 5-8 Confidence intervals for first order (Si) sensitivity to SDPF+ at X/L = 0.6

<table>
<thead>
<tr>
<th>SDPF+ at X/L=0.6</th>
<th>Din</th>
<th>Dout</th>
<th>cdin</th>
<th>cdout</th>
<th>a</th>
<th>Q</th>
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<tbody>
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<td></td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
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<td>0.315</td>
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<td>0.05</td>
<td>-0.060</td>
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<tr>
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<td>0.423</td>
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<td>0.223</td>
<td>0.445</td>
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<td>-0.141</td>
<td>0.166</td>
<td>0.08</td>
<td>-0.120</td>
</tr>
<tr>
<td>0.8</td>
<td>-0.162</td>
<td>0.104</td>
<td>0.07</td>
<td>-0.151</td>
<td>0.113</td>
<td>0.07</td>
<td>-0.163</td>
</tr>
<tr>
<td>0.9</td>
<td>-0.133</td>
<td>0.080</td>
<td>0.05</td>
<td>-0.130</td>
<td>0.090</td>
<td>0.05</td>
<td>-0.128</td>
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### Table 5-9 Confidence intervals for Total effect (Si) sensitivity to SDPF+ at X/L = 0.6

<table>
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<th>SDPF+ at X/L=0.6</th>
<th>Din</th>
<th>Dout</th>
<th>cdin</th>
<th>cdout</th>
<th>a</th>
<th>Q</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
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<td>ST</td>
<td>std</td>
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<td>std</td>
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Table 5-10 Confidence intervals for first order (Si) sensitivity to SDPF+ at X/L = 0.4

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<th>std</th>
<th>cdin</th>
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<th>a</th>
<th>std</th>
<th>Q</th>
<th>std</th>
<th>f</th>
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<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
<td>Si</td>
<td>std</td>
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<td>std</td>
<td>Si</td>
<td>std</td>
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<td>0.090</td>
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<td>-0.142</td>
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Table 5-11 Confidence intervals for Total effect (S_T) sensitivity to SDPF+ at X/L = 0.4

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<th>cdout</th>
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<td>ST</td>
<td>std</td>
<td>ST</td>
<td>std</td>
</tr>
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<td></td>
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</tr>
<tr>
<td>0.2</td>
<td>0.472</td>
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<td>0.368</td>
<td>0.19</td>
<td>-0.490</td>
</tr>
<tr>
<td>0.3</td>
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<td>0.305</td>
<td>0.13</td>
<td>0.303</td>
<td>0.677</td>
<td>0.09</td>
<td>-0.432</td>
</tr>
<tr>
<td>0.4</td>
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<td>0.254</td>
<td>0.14</td>
<td>0.500</td>
<td>0.810</td>
<td>0.08</td>
<td>-0.412</td>
</tr>
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<td>0.5</td>
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<td>0.381</td>
<td>0.14</td>
<td>0.367</td>
<td>0.740</td>
<td>0.09</td>
<td>-0.235</td>
</tr>
<tr>
<td>0.6</td>
<td>-0.143</td>
<td>0.484</td>
<td>0.16</td>
<td>0.343</td>
<td>0.822</td>
<td>0.12</td>
<td>-0.296</td>
</tr>
<tr>
<td>0.7</td>
<td>-0.297</td>
<td>0.452</td>
<td>0.19</td>
<td>-0.040</td>
<td>0.626</td>
<td>0.17</td>
<td>-0.449</td>
</tr>
<tr>
<td>0.8</td>
<td>-0.139</td>
<td>0.390</td>
<td>0.14</td>
<td>-0.110</td>
<td>0.417</td>
<td>0.13</td>
<td>-0.171</td>
</tr>
<tr>
<td>0.9</td>
<td>-0.132</td>
<td>0.327</td>
<td>0.12</td>
<td>-0.134</td>
<td>0.323</td>
<td>0.12</td>
<td>-0.149</td>
</tr>
</tbody>
</table>
5.7.7 Spatial variability of sensitivity indices

The magnitude of the calculated sensitivity indices confirms that sensitivity of SDPF- and SDPF+ to input parameters show a spatial dependence. That is, the sensitivity changes with the location of the AVV. Here, a mean value of $S_i$ and $S_T$ in their bootstrap confidence intervals is used to show the trend of change of the sensitivity indices at each AVV location.

5.7.7.1 Variability of sensitivity of SDPF- with high point elevation

Results for the mean main and total effect sensitivity of SDPF- to the parameters under study are summarized in Figure 5-10 at $X/L = 0.6$ for different elevations of the high point. A comparison between sensitivity trends reveals that the most important parameter at higher elevations of high point is $D_{in}$. However, the importance of $D_{in}$ is waned as the elevation of high point is decreased ($H_p/\Delta H$ is increased). As the sensitivity of SDPF- to $D_{in}$ reduces, the sensitivity to $Q$ emerges and at lower elevations, SDPF- is solely dependent on $Q$. These two inputs account for most of the output variance. Thus, the other variables are of less importance on an individual basis. Of course, at lower elevations of the high point, the SDPF- experienced by the system is smaller compared to higher elevations of the high point. Thus, the relatively high sensitivity of SDPF- to $Q$ at lower elevations of the high point may be of little practical significance.

5.7.7.2 Spatial variability of sensitivity of SDPF- to $D_{in}$

Figure 5-11 shows the trend of change in main and total effect sensitivity indices of SDPF- to $D_{in}$ at different elevations of high point for $X/L = 0.6$, 0.4, and 0.2. As shown, at each $X/L$, as the elevation of the high point decreases, the effect of $D_{in}$ on SDPF- is reduced. As the elevation of the high point decreases, $H_p$ increases, and $Q_p$ decreases, therefore, less time is required for the forward flow to stop in the downstream limb of the AVV, and therefore, the maximum air cavity is reduced and the sensitivity to the size of inlet diameter of AVV is reduced since less air is required to enter the pipe.
Figure 5-10 Sensitivity of parameters to SDPF- at X/L = 0.6 at different intercepted wave heights (i.e., $H_P/\Delta H$) (Note: $S_i$ is first order index and $S_T$ is total effect index)

Figure 5-11 Sensitivity of SDPF- to $D_{in}$ at different intercepted wave heights at different X/L ($S_i$ is first order and $S_T$ is total effect index.)

5.7.7.3 Variability of sensitivity of SDPF+ with high point elevation

The spatial variability of sensitivity of SDPF+ to input parameters is also investigated. Mean value bootstrap sensitivity indices for different parameters at all elevations of high point are shown in Figure 5-12 for X/L = 0.6. Comparing these figures, it is realized that SDPF+ is sensitive to both $D_{out}$ and $Q$. Although the sensitivity indices for $D_{out}$ are increasing up to a certain elevation, it experiences a decreasing trend afterwards. That is, there is a local maximum sensitivity to $D_{out}$. This maximum sensitivity occurs at a specific elevation at each of the horizontal distances under study. Of course, at lower elevations of the high point, SDPF+ shows only a significant sensitivity to $Q$. This is due to the fact that, at lower elevations of high point,
the final reverse flow at the time of cavity collapse is small. And therefore, the secondary transient pressure resulting from the large-sized $D_{out}$ is negligible. And, $Q$ is the only parameter affecting the magnitude of SDPF+ at lower elevations of the high point.

![Figure 5-12](image)

**Figure 5-12** Sensitivity to SDPF+ at X/L = 0.6 at different intercepted wave heights (i.e., $H_P/\Delta H$) (Note: $S$ is first order index and $ST$ is total effect index)

### 5.7.7.4 Spatial variability of sensitivity of SDPF+ to $D_{out}$

Figure 5-13 shows the trend of change in main and total effects of $D_{out}$ on SDPF+ at different elevations of high point for X/L = 0.6, 0.4, and 0.2. As the elevation of the high point decreases, the main and total effects of $D_{out}$ on SDPF+ increase up to a certain elevation. Afterwards, the sensitivity is reduced. Hence, there is a local maximum sensitivity of SDPF+ to $D_{out}$ in each X/L. Obviously, the effect of friction causes the sensitivity to $D_{out}$ to decrease below this elevation. That is, at high point elevations where $h_f/H_P$ is high (Figure 5-14), the effect of friction decreases the backward driving force and, consequently, reduces the secondary transient pressure at the instance of the cavity collapse. However, there is a high point elevation where $h_f/H_P$ is negligible ($H_P/\Delta H = 0.3-0.4$ in Figure 5-14) and the secondary transient is at its maximum value. As the high point elevation gets lower than the above mentioned limits for each X/L, since the intercepted wave height gets larger, the reverse flow at the time of cavity collapse is small and the associated secondary transient becomes less severe. This can be the reason why the lower sensitivity of the transient response to $D_{out}$ occurs at lower limits of $H_P/\Delta H$.
at each X/L, such findings suggest smaller sizes of AVV outlet diameter at higher elevations of the high point.

Figure 5-13 Sensitivity of SDPF+ to $D_{out}$ at different intercepted wave heights at different X/L (S_i is first order and S_T is total effect index.)

Figure 5-14 Trend of change in $h_f/H_P$ at each intercepted wave height for X/L = 0.6, 0.4, and 0.2

5.7.8 Ranking input variables

Variance-based approaches can introduce an importance ranking for all random variables. In engineering projects, prior to beginning the design phases, such rankings can help designers identify those random variables with little potential impact on the variance of the model output. Thereafter, such variables can be fixed at a given value and the dimension of the probabilistic design space is reduced. Obviously, such understandings help to reduce the computational cost. Furthermore, these rankings are important for the post-design analysis. They provide valuable information on where to spend additional resources to further control the source of variations.
Ranking the input parameters should be based on one of the main or total effect sensitivity indices. As mentioned before, total effect sensitivity indices consider both main effects and interaction effects of the inputs. For nonlinear models, since the model response is more influenced by interactions, the total effect would be a preferred measure of sensitivity (Saltelli 2002). Therefore, inputs can be ranked based on the magnitude of mean total effect on SDPF- and SDPF+ as shown in Table 5-12 to Table 5-17 for each elevation of high point at X/L = 0.6, 0.4, and 0.2, respectively. Each of the mean values presented in these tables represents the arithmetic average of the 10000 bootstrap estimates for sensitivity indices.

A ranking represents the order of importance of each input. Here, the input with the highest sensitivity index is ranked 1 while the least important input is ranked 7. As can be seen, the two highest ranking variables are $D_{in}$ and $Q$ for SDPF- and $D_{out}$ and $Q$ for SDPF+ at different elevations of the high point. Ranking of inputs for different locations of high point confirms that the importance of an input has a spatial dependence. Some inputs have different ranks at different elevations of the high point.
### Table 5-12 Mean values of sensitivity indices to SDPF- at X/L = 0.6

<table>
<thead>
<tr>
<th>SDPF- at X/L=0.6</th>
<th>H/ΔH</th>
<th>0.2</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.8</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{in}$</td>
<td>Si</td>
<td>0.767</td>
<td>0.751</td>
<td>0.664</td>
<td>0.232</td>
<td>0.077</td>
<td>0.057</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.947(1)</td>
<td>0.916(1)</td>
<td>0.798(1)</td>
<td>0.521(2)</td>
<td>0.302(2)</td>
<td>0.300(2)</td>
</tr>
<tr>
<td>$D_{out}$</td>
<td>Si</td>
<td>0.016</td>
<td>0.065</td>
<td>0.040</td>
<td>0.035</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.081(3)</td>
<td>0.075(3)</td>
<td>0.055(3)</td>
<td>0.056(7)</td>
<td>0.040(7)</td>
<td>0.035(7)</td>
</tr>
<tr>
<td>$Cd_{in}$</td>
<td>Si</td>
<td>0.004</td>
<td>0.007</td>
<td>0.005</td>
<td>0.004</td>
<td>0.010</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.020(6)</td>
<td>0.012(5)</td>
<td>0.045(5)</td>
<td>0.106(6)</td>
<td>0.081(6)</td>
<td>0.127(6)</td>
</tr>
<tr>
<td>$cd_{out}$</td>
<td>Si</td>
<td>0.002</td>
<td>0.003</td>
<td>0.004</td>
<td>0.002</td>
<td>0.009</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.019(7)</td>
<td>0.013(6)</td>
<td>0.045(5)</td>
<td>0.111(5)</td>
<td>0.088(5)</td>
<td>0.129(5)</td>
</tr>
<tr>
<td>$a$</td>
<td>Si</td>
<td>0.002</td>
<td>0.005</td>
<td>0.031</td>
<td>0.000</td>
<td>0.004</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.040(4)</td>
<td>0.005(7)</td>
<td>0.048(4)</td>
<td>0.140(3)</td>
<td>0.152(3)</td>
<td>0.292(3)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Si</td>
<td>0.041</td>
<td>0.075</td>
<td>0.158</td>
<td>0.440</td>
<td>0.669</td>
<td>0.569</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.097(2)</td>
<td>0.089(2)</td>
<td>0.164(2)</td>
<td>0.690(1)</td>
<td>0.879(1)</td>
<td>0.871(1)</td>
</tr>
<tr>
<td>$f$</td>
<td>Si</td>
<td>0.004</td>
<td>0.006</td>
<td>0.006</td>
<td>0.005</td>
<td>0.009</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.025(5)</td>
<td>0.014(4)</td>
<td>0.048(4)</td>
<td>0.118(4)</td>
<td>0.093(4)</td>
<td>0.132(4)</td>
</tr>
</tbody>
</table>

### Table 5-13 Mean values of sensitivity indices to SDPF- at X/L = 0.4

<table>
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<tr>
<th>SDPF- at X/L=0.4</th>
<th>HP/ΔH</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{in}$</td>
<td>Si</td>
<td>0.908</td>
<td>0.853</td>
<td>0.731</td>
<td>0.507</td>
<td>0.313</td>
<td>0.208</td>
<td>0.037</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>1.002(1)</td>
<td>0.987(1)</td>
<td>0.954(1)</td>
<td>0.762(1)</td>
<td>0.635(1)</td>
<td>0.588(2)</td>
<td>0.226(2)</td>
<td>0.134(4)</td>
</tr>
<tr>
<td>$D_{out}$</td>
<td>Si</td>
<td>0.008</td>
<td>0.004</td>
<td>0.025</td>
<td>0.056</td>
<td>0.054</td>
<td>0.050</td>
<td>0.047</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.045(2)</td>
<td>0.105(2)</td>
<td>0.178(2)</td>
<td>0.304(3)</td>
<td>0.355(3)</td>
<td>0.302(3)</td>
<td>0.177(3)</td>
<td>0.136(3)</td>
</tr>
<tr>
<td>$Cd_{in}$</td>
<td>Si</td>
<td>0.007</td>
<td>0.006</td>
<td>0.002</td>
<td>0.022</td>
<td>0.004</td>
<td>0.024</td>
<td>0.010</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.011(7)</td>
<td>0.023(6)</td>
<td>0.044(7)</td>
<td>0.081(7)</td>
<td>0.107(6)</td>
<td>0.135(6)</td>
<td>0.037(7)</td>
<td>0.089(6)</td>
</tr>
<tr>
<td>$cd_{out}$</td>
<td>Si</td>
<td>0.006</td>
<td>0.007</td>
<td>0.012</td>
<td>0.024</td>
<td>0.004</td>
<td>0.002</td>
<td>0.011</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.011(6)</td>
<td>0.033(4)</td>
<td>0.054(5)</td>
<td>0.088(5)</td>
<td>0.107(6)</td>
<td>0.133(7)</td>
<td>0.040(5)</td>
<td>0.088(7)</td>
</tr>
<tr>
<td>$a$</td>
<td>Si</td>
<td>0.010</td>
<td>0.005</td>
<td>0.016</td>
<td>0.033</td>
<td>0.016</td>
<td>0.029</td>
<td>0.016</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.013(5)</td>
<td>0.017(7)</td>
<td>0.072(4)</td>
<td>0.147(4)</td>
<td>0.230(4)</td>
<td>0.222(4)</td>
<td>0.141(4)</td>
<td>0.146(2)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Si</td>
<td>0.006</td>
<td>0.000</td>
<td>0.003</td>
<td>0.072</td>
<td>0.130</td>
<td>0.236</td>
<td>0.655</td>
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<tr>
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<td>0.028(3)</td>
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<td>0.174(3)</td>
<td>0.391(2)</td>
<td>0.491(2)</td>
<td>0.718(1)</td>
<td>0.935(1)</td>
<td>0.985(1)</td>
</tr>
<tr>
<td>$f$</td>
<td>Si</td>
<td>0.005</td>
<td>0.007</td>
<td>0.022</td>
<td>0.031</td>
<td>0.042</td>
<td>0.021</td>
<td>0.009</td>
<td>-0.003</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.018(4)</td>
<td>0.025(5)</td>
<td>0.048(6)</td>
<td>0.083(6)</td>
<td>0.111(5)</td>
<td>0.146(5)</td>
<td>0.038(6)</td>
<td>0.093(5)</td>
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</table>
Mean values of sensitivity indices to SDPF\(^-\) at X/L = 0.2

<table>
<thead>
<tr>
<th>SDPF(^-) at X/L=0.2</th>
<th>HP/(\Delta H)</th>
<th>0.2</th>
<th>0.26</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Din</td>
<td>Si</td>
<td>0.888</td>
<td>0.863</td>
<td>0.707</td>
<td>0.494</td>
<td>0.319</td>
<td>0.107</td>
<td>0.059</td>
<td>0.0</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>1.001 (1)</td>
<td>0.983 (1)</td>
<td>0.904 (1)</td>
<td>0.773 (1)</td>
<td>0.556 (1)</td>
<td>0.450 (3)</td>
<td>0.324 (4)</td>
<td>0.2</td>
<td>0.146 (4)</td>
</tr>
<tr>
<td>Dout</td>
<td>Si</td>
<td>0.002</td>
<td>0.002</td>
<td>0.044</td>
<td>0.111</td>
<td>0.105</td>
<td>0.094</td>
<td>0.093</td>
<td>0.0</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.002 (5)</td>
<td>0.118 (2)</td>
<td>0.193 (2)</td>
<td>0.340 (3)</td>
<td>0.306 (3)</td>
<td>0.478 (2)</td>
<td>0.398 (2)</td>
<td>0.2</td>
<td>0.209 (3)</td>
</tr>
<tr>
<td>cdin</td>
<td>Si</td>
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<td>0.006</td>
<td>0.002</td>
<td>0.022</td>
<td>0.003</td>
<td>0.059</td>
<td>0.055</td>
<td>0.0</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.005 (3)</td>
<td>0.008 (5)</td>
<td>0.008 (7)</td>
<td>0.141 (7)</td>
<td>0.022 (7)</td>
<td>0.178 (7)</td>
<td>0.133 (6)</td>
<td>0.0</td>
<td>0.075 (6)</td>
</tr>
<tr>
<td>cdout</td>
<td>Si</td>
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<td>0.005</td>
<td>0.002</td>
<td>0.029</td>
<td>0.003</td>
<td>0.069</td>
<td>0.053</td>
<td>0.0</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.004 (4)</td>
<td>0.008 (5)</td>
<td>0.018 (5)</td>
<td>0.161 (5)</td>
<td>0.035 (5)</td>
<td>0.205 (5)</td>
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<td>a</td>
<td>Si</td>
<td>0.006</td>
<td>0.003</td>
<td>0.002</td>
<td>0.017</td>
<td>0.015</td>
<td>0.080</td>
<td>0.019</td>
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<td>0.009</td>
</tr>
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<td></td>
<td>ST</td>
<td>0.008 (2)</td>
<td>0.004 (6)</td>
<td>0.023 (4)</td>
<td>0.171 (4)</td>
<td>0.181 (4)</td>
<td>0.458 (4)</td>
<td>0.327 (3)</td>
<td>0.2</td>
<td>0.236 (2)</td>
</tr>
<tr>
<td>Q</td>
<td>Si</td>
<td>0.005</td>
<td>0.011</td>
<td>0.010</td>
<td>0.074</td>
<td>0.247</td>
<td>0.325</td>
<td>0.413</td>
<td>0.4</td>
<td>0.651</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.008 (2)</td>
<td>0.015 (3)</td>
<td>0.113 (3)</td>
<td>0.358 (2)</td>
<td>0.539 (2)</td>
<td>0.747 (1)</td>
<td>0.728 (1)</td>
<td>0.8</td>
<td>0.966 (1)</td>
</tr>
<tr>
<td>f</td>
<td>Si</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
<td>0.023</td>
<td>0.003</td>
<td>0.067</td>
<td>0.056</td>
<td>0.0</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>ST</td>
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<td>0.009 (4)</td>
<td>0.017 (6)</td>
<td>0.143 (6)</td>
<td>0.028 (6)</td>
<td>0.156 (6)</td>
<td>0.140 (5)</td>
<td>0.0</td>
<td>0.084 (5)</td>
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Mean values of sensitivity indices to SDPF\(^+\) at X/L = 0.6

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<th>SDPF(^+) at X/L=0.6</th>
<th>HP/(\Delta H)</th>
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<th>0.9</th>
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<td>Din</td>
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<td>0.097</td>
<td>0.027</td>
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<td>0.015</td>
<td>0.011</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>0.168 (3)</td>
<td>0.062 (3)</td>
<td>0.044 (6)</td>
<td>0.024 (7)</td>
<td>0.116 (4)</td>
<td>0.079 (5)</td>
</tr>
<tr>
<td>Dout</td>
<td>Si</td>
<td>0.304</td>
<td>0.408</td>
<td>0.333</td>
<td>0.010</td>
<td>0.013</td>
<td>0.020</td>
</tr>
<tr>
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<td>0.390 (2)</td>
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<td>0.082 (4)</td>
</tr>
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<td>0.033</td>
<td>0.029</td>
<td>0.015</td>
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<td>0.030 (6)</td>
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<td>0.055 (5)</td>
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<td>0.026</td>
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<td>0.030 (6)</td>
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<td>0.057 (4)</td>
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<td>0.074 (6)</td>
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<td>0.050</td>
</tr>
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<td>0.050 (4)</td>
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<td>0.081 (3)</td>
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<td>0.206 (2)</td>
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<td>0.387</td>
<td>0.420</td>
<td>0.454</td>
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<td>0.398 (2)</td>
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<td>0.026</td>
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<td>0.030</td>
<td>0.010</td>
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### Table 5-16 Mean values of sensitivity indices to SDPF+ at X/L = 0.4

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<th>0.7</th>
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<tbody>
<tr>
<td><strong>Din</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td></td>
<td>0.609</td>
<td>0.061</td>
<td>0.014</td>
<td>0.015</td>
<td>0.042</td>
<td>0.014</td>
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<td>0.114 (4)</td>
<td>0.181 (4)</td>
<td>0.086 (4)</td>
<td>0.122 (5)</td>
<td>0.099 (4)</td>
<td></td>
</tr>
<tr>
<td><strong>Dout</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
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<td>0.640</td>
<td>0.407</td>
<td>0.490</td>
<td>0.308</td>
<td>0.296</td>
<td>0.160</td>
<td>0.033</td>
<td>0.017</td>
</tr>
<tr>
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<td>0.499 (1)</td>
<td>0.664 (1)</td>
<td>0.565 (2)</td>
<td>0.586 (2)</td>
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<td>0.147 (4)</td>
<td>0.090 (5)</td>
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</tr>
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<td><strong>cdin</strong></td>
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</tr>
<tr>
<td>Si</td>
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<td>0.010</td>
<td>0.002</td>
<td>0.022</td>
<td>0.001</td>
<td>0.031</td>
<td>0.026</td>
</tr>
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<td>0.061 (7)</td>
<td>0.056 (7)</td>
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<td>0.097 (7)</td>
<td>0.090 (5)</td>
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</tr>
<tr>
<td><strong>cdout</strong></td>
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<td>0.025</td>
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<td>0.068 (6)</td>
<td>0.023 (6)</td>
<td>0.099 (6)</td>
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<tr>
<td><strong>a</strong></td>
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<td>0.060 (4)</td>
<td>0.187 (3)</td>
<td>0.247 (3)</td>
<td>0.175 (3)</td>
<td>0.216 (2)</td>
<td>0.205 (2)</td>
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<td><strong>Q</strong></td>
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<td>0.667 (1)</td>
<td>0.684 (1)</td>
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<td><strong>f</strong></td>
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### Table 5-17 Mean values of sensitivity indices to SDPF+ at X/L = 0.2

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<th>0.3</th>
<th>0.4</th>
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<td>0.101 (4)</td>
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<td>0.658</td>
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<td><strong>Q</strong></td>
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<td>0.018</td>
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</tr>
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</table>
5.8 Conclusions

This chapter numerically explores the importance of sizing AVVs on the basis of transient conditions at high points with different geometries. This is performed by studying the sensitivity of the transient response of undulating pipelines, containing air vacuum valves (AVVs) at the high point to the input parameters of the water hammer governing equations and to the design parameters of the AVV (i.e., particularly its inlet and outlet orifice sizes and related discharge coefficients). The three methods of the sensitivity analysis applied are as follows: Monte Carlo Filtering, scatter plots, and the Sobol’s method.

The MCF results generally confirm our understanding about the sensitivity of the transient response of the system to $D_{in}$, $D_{out}$, and $Q$ at each high point location. The importance of each variable is clarified through the KS test. While the KS test can ascertain whether a factor under analysis is important, the test is fairly weak and it does not provide the necessary condition for importance. Also, the interaction structures among the variables are not detected by KS test values. Therefore, one cannot identify parameters to which the system is more sensitive.

Scatter plots identified the potentially complex dependencies and the nature of such dependencies between the parameters under study and the corresponding output (SDPF- and SDPF+). The scatter plots are mostly interpreted qualitatively and they assist in the proper selection of the sensitivity analysis method. That is, the importance of each parameter cannot be inferred from scatter plots.

Ideally, the chosen method for sensitivity analysis should be able to diagnose the effect of input factors acting individually or in combination in order to identify the effect of interactions between variables. Hence, in order to figure out the main effect contribution of each input factor to the variance of the SDPF- and SDPF+, and to understand how much that parameter is involved in interactions, Sobol’s method is applied.

The global sensitivity analysis (i.e., Sobol’s method) reveals the influential parameters and their main and interaction effects. The magnitude of the calculated sensitivity indices confirms that sensitivity of SDPF- and SDPF+ to input parameters show a spatial dependence. That is, the transient response of the system depends on the horizontal and vertical position of the AVV relative to the downstream boundary. For instance, the sensitivity of SDPF- to $D_{in}$ is greater at
higher elevations of high point and at distances close to the upstream boundary (pump). While such a finding seems to be intuitive, it should assist designers to identify the sensitive points where properly selection of $D_{in}$ is most important, an outcome that can be understood by applying the current methodology to the case-specific study. Furthermore, the sensitivity of SDPF+ to $D_{out}$ is shown to have a local maximum at each high point location. Such a finding from this numerical investigation is exactly what has been previously explored by the simple semi-analytical formulas derived in Chapter 4. Hence, the results from this Chapter are primarily a confirmation of the contents in Chapter 4. They can serve as the answer to the puzzling question as why sizing AVV matters at some locations and does not matter at others. That is, results show that properly sizing $D_{out}$ is more crucial at specific vertical location of the high point.

Also, the results of Sobol’s method imply that special care should be paid to the maintenance of AVVs at locations sensitive to the transient response of the system. Neglecting the installation of AVVs at such sensitive locations risks catastrophic consequences due to the secondary transient events. These results clearly support the conclusions of Chapter 4: that is, the current results show that the importance of properly sizing of AVVs on the basis of the transient response of the system varies with the AVV location relative to hydraulic gradeline and the downstream boundary.

Moreover, an importance ranking is assigned to each input variable by the Sobol’s method. In engineering projects, prior to beginning the design phases, low-ranking input parameters with little potential impact on the variance of SDPF- and SDPF+ can be identified. And, such variables can be fixed at a given value to reduce the dimension of the probabilistic design space and, consequently, to cut the computational cost. Also, during the post-design process, such rankings provide valuable information on sensitive locations where regular maintenance of AVVs is more important to further control the source of variations.

Certainly, water pipelines are more complex than the current simple configuration under study assuming to be subject to a sudden upstream flow curtailment. But, the results obtained from this case-specific sensitivity analysis can serve as general warnings that continue to exist in real-world projects. Obviously, applying the proposed methodology in this chapter to specific and proposed cases is required to turn these warnings into practical advice.
Air vacuum valves (AVVs) often play a crucial role in pipeline system design and performance and can provide transient protection if well specified, sized and located. Yet an extensive survey of the existing literature confirms that there is an ambiguity regarding the locations along a pipeline where the properly sizing and maintaining of AVVs is most crucial to system safety. This thesis focuses on this sizing and locating issue and seeks to clarify the key considerations through its two main studies. First, a physical understanding of the transient response of systems with AVVs is undertaken to develop relatively simple semi-analytical formulas in an idealized undulating pipeline containing an AVV. Then, the importance of properly sizing AVVs based on the transient response of the system and the importance of frequent maintenance of AVVs is explored using three methods of sensitivity analysis.

This thesis paves the way for a better understanding of AVV behaviour under transient conditions and their different role in transient protection of the system, rather than to facilitate line filling/draining or protecting the system against pipe break, with consideration of their size and location to the system boundaries (i.e., vertical and horizontal location relative to the downstream reservoir). This can help designers in the preliminary evaluation of the size and location of AVVs for transient protection and encourages them in preparing and enforcing strict protocols for the maintenance of such AVVs.

### 6.1. Main contributions

This thesis provides a much more systematic understanding than is currently available of the various effects of AVV choices on the generation of secondary transient pressures, an understanding intended to help designers to make better choices, and to prevent possible system failures that might be induced by improper selection of AVVs. Here, new tools are developed to assess the transient performance of the system and its sensitivity to AVV size and location characteristics. Both the physical and numerical results introduce a clear picture of AVV selection and the influential factors for preventing system failures due to AVVs. Engineers can
use the proposed semi-analytical formulas for a quick estimation of key AVV parameters. Overall, the results provide an explanation of the puzzling question as why AVV sizing, locating and maintaining matter in some configurations and does not matter in others. The key results are summarized as follows:

1) Elevated high points along a pipeline profile are the most common and natural places where air vacuum valves (AVVs) are installed. Basic waterhammer wave theory and derived semi-analytical formulas show that the magnitude of the reduced pressure wave created by the refraction at the high point, and both the high point elevation and its horizontal position, are crucial and interacting factors in the selection of AVV in pipelines with undulating profiles. Proper selection of AVVs can prevent potentially highly destructive consequences due to the resulting pressure spikes at the time of air cavity collapse.

2) The importance of sizing AVVs based on the transient response of the system, and therefore, the importance of frequent maintenance of AVVs at high points with different characteristics are numerically investigated. This is performed by studying the sensitivity of the transient response of hypothetical undulating pipelines, containing air vacuum valves (AVVs) at the high point, to input parameters of water hammer governing equations and design parameters of AVVs (i.e., inlet and outlet sizes and discharge coefficients), and particularly, to the horizontal or vertical distance of the AVV relative to its upstream and downstream boundaries. MCF, scatter plots and Sobol’s method are applied. While it cannot be inferred from the results from MCF and scatter plots, which input parameter is most responsible for producing SDPF- or SDPF+, they can serve as tools to understand the important parameters in producing the output of interest.

Sobol’s method highlights the importance of properly sizing and maintaining of AVVs based on the transient response of the system at specific locations. It is illustrated that the importance of properly sizing of AVVs based on transient considerations and the importance of maintenance of AVVs may differ depending on the location of the AVV at the high point relative to both the hydraulic grade line and the distance to the downstream boundary. Finally, it is illustrated how the location of AVVs change the influence or effectiveness of each parameter on the transient response of the system.
It is specifically shown SDPF- at which locations are more sensitive to $D_{in}$ (i.e., at higher high points and at horizontal distances closer to the upstream pump). This finding may help designers to identify the sensitive points where properly selection of $D_{in}$ is crucial to system safety. And this can be understood by applying the current methodology to the case-specific study. Furthermore, the sensitivity of SDPF+ to $D_{out}$ is shown to have a local maximum at each high point location. Such a finding confirms the results from the simple semi-analytical formulas derived in Chapter 4. That is, results show that properly sizing $D_{out}$ is more crucial at specific vertical location of the high point.

3) AVVs are still often placed in pipelines according to the recommendations in AWWA M51 manual of practice (AWWA 2001). According to this manual, AVVs should be placed at the following locations: at abrupt increases in downslope and abrupt decreases in upslope, at intervals of 400 m to 800 m along ascending and descending sections as well as horizontal sections of pipelines, and at the beginning and end of long horizontal sections. Furthermore, it is recommended that they be placed at all the high points in the pipeline for the exclusive goal of removing air during pipe filling or admitting air during pipe draining/pipe break while it doesn’t consider transient events. In this manual, a high point is defined as “the upper end of any pipe segment that slopes up to the hydraulic gradient or runs parallel to it”. However, it is shown that blind use of these rules can be problematic: AWWA M51 (AWWA 2001) doesn’t make distinction of whether a high point is high or low relative to the downstream reservoir and whether the importance of placing and maintaining of AVVs at high points with different characteristics (i.e., its vertical distance to the hydraulic grade line of the system or its horizontal distance to the downstream boundary) is different by considering the transient events. If transient events are not considered, the AVVs located for the exclusive goal of filling scenario will be neglected after the pipeline is filled, and as is currently the case, attention is not made to their frequent maintenance. The outcome of this thesis confirms that depending on whether a high point is low or high relative to the downstream boundary, the importance of placing and maintaining AVVs at that high point would be different due to the induced secondary transient pressure. That is, this importance depends on the pipe length downstream of the AVV and on the vertical distance of the AVV location to the hydraulic gradeline. Both Chapter 4 (the semi-analytical formula) and Chapter 5 (the sensitivity analysis) contribute to such a conclusion. AWWA M51 manual of practice (AWWA 2001) lacks such considerations and the rules should be revisited in order that AVVs be effective in transient protection of the system.
4) The AWWA M51 manual of practice sizes AVVs based on filling and draining/pipe break scenarios, without explicitly considering transient events. For the filling scenario, it recommends that AVVs be sized so that air be vented to the atmosphere at a typical differential pressure of 2 psi (13.8 kPa) through ordinary AVVs and at a differential pressure of 5 psi (34.5 kPa) through AVVs equipped with anti-slam or slow closing devices. For this purpose, a compressible adiabatic flow equation through a short nozzle is applied, and it is assumed that there is no heat transfer to the air. For draining, M51 recommends that an AVV be placed at the high point adjacent to the draining location, and this valve should be sized to admit air at the same volumetric rate as the recommended rate of pipeline draining (i.e., 0.3-0.6 m/s). Sizing according to filling and draining/pipe break scenarios results in large capacity AVVs that can be ineffective and even destructive when activated during transient events. However, thesis results show that these rules can be simplistic: that sizing on the basis of transient events should also be considered. And the importance of sizing AVVs on the basis of transient events and maintaining them is different and depends on the location of the high point. Such conclusions are drawn from both Chapter 4 (the semi-analytical formula) and Chapter 5 (the sensitivity analysis).

5) If a numerical code is applied to select a proper size for an AVV at a particular high point, an effectively blind search procedure should ideally be performed. Yet if the engineer doesn’t have a good sense of how to characterize the high points and how close he/she is to the points that are most sensitive to AVV parameters, poor choices may result. The results obtained from this thesis are really just warnings but they can turn into advice if one runs a specific case. That is, the methodology can be used again. The methodology in Chapters 4 and 5 can be applied in practice to understand the importance of sizing AVVs on the basis of transient event at a particular high point in the system. For instance, this can easily be performed by the semi-analytical formulas derived in Chapter 4 through providing some system inputs (e.g., pipe diameter and length, hydraulic head, friction factor, wave speed, water discharge, and other factors) in a design module in an Excel spreadsheet. And, the maximum secondary transient pressure due to improperly sizing of AVV can be calculated. This can serve as an expert advice of whether sizing of an AVV at a particular high point is crucial. Furthermore, the methodology applied in Chapter 5 can be applied in practice to understand the sensitive points where careful sizing of AVVs on the basis of transient events should be performed. The long period for study phases of engineering projects justifies application of the Monte Carlo-based methodology presented in Chapter 5.
6) While designing engineering projects, reality is simplified and monotonic responses are assumed. For example, it is assumed that the higher the high point the worst the transient response due to improper sizing of the AVV is. And, the less friction the worst the secondary transient is. However, the results obtained from Chapter 5 show that nothing is monotonic.

Chapters 2 and 3 provide a critical appraisal of the published knowledge concerning air and air management in pipelines. Specifically the chapters review both the current application of air valves and the possible problems associated with their malfunction (i.e., the presence of air in water pipes). Overall, the chapters make clear that further knowledge is required to better use and apply air valves. The key findings are as follows:

7) Chapter 2 provides a critical appraisal on the two air management strategies, preventing air from entering the system and hydraulically removing air with the gaps in the current strategies being explored. Air pockets which both accumulate air at most susceptible locations along pipelines (i.e., high points) and reduce pipe capacity in pressurized watermains are particularly noted. The need to establish a general design guideline for air management in water pipes based on the physical understanding of air behaviour in water pipes is highlighted.

8) In chapter 3, a critical review on the use and application of air valves is presented. The improvements in the literature are discussed and the gaps are explored. Furthermore, the design guidelines, and operating and maintenance issues as well as the current alternatives on preventing such problems are discussed. Overall, considering the operational and maintenance problems associated with air valves, efficient application of such devices requires conducting broader research and development both in the realm of the theoretical context (i.e., understanding air valve physical behaviour, and modifying air valve numerical simulation) and in the context of experimental or field studies (i.e., understanding air valve dynamic behaviour and operational efficiency). Obviously, the experimental or field data can support the proper and more accurate simulation of air valve behaviour in water pipelines. Such knowledge gaps and recommendations for further research are discussed, aiming for the more efficient application of air valves.

6.2. Future work

This methodology developed in this work is applied to a simple undulating pipeline containing an AVV at the high point. Yet, it is immediately obvious that the effect of AVVs may be
different in more complex pipelines, particularly those containing several, possibly interacting, AVVs. It is proposed that future work consider this methodology in a more complex undulating pipeline with the presence of several AVVs at different high points. This can be performed to understand the interactions of AVVs on each other and the associated effect on secondary transient pressures.

Furthermore, it has up until now been assumed that AVVs act as a main surge control device in the system. There are systems in which AVVs are placed as a complementary surge control device. It is recommended that future works be performed to understand the effectiveness of AVVs on the transient response in such systems. For instance, the effect of sizing and locating AVVs in systems with the presence of an air chamber or a surge tank can be investigated by applying the methodology presented in this thesis.

There are still knowledge gaps in the field of air valves which can be explored in future work. Some of these gaps are illustrated through a critical appraisal of the current literature presented in Chapters 2 and 3. These two chapters could possibly serve as the provisional foundation for a risk analysis of a system containing an air release or air vacuum valve. For this purpose, the associated problems with malfunction or improper selection of air valves are required to be understood. However, there is little knowledge in the literature to quantify such problems created by air valves. For example, in case of the malfunction of an AVV or an air release valve, a specific amount of air may be trapped underneath these valves. But, it is not obvious how much air can accumulate at the high points beneath an air valve. Also, the ability of this air volume to reduce the pipe capacity in pressurized pipelines is still unknown. Such data can be obtained through numerical and physical investigation of the ability of air pockets to accumulate at high points with different geometries (i.e., angle, descending pipe length). Future laboratory or numerical work may help to understand the risk of improper selection or malfunction of air valves in pressurized water pipelines.
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Appendix A

A.1 MCF Results

The following Tables and Figures represent the MCF results for X/L=0.4 and X/L=0.6 and different elevations of high point at each of these horizontal locations.

Table A-1 KS test values for different intercepted wave heights at the high point at X/L = 0.4

<table>
<thead>
<tr>
<th>H/ΔH</th>
<th>Din</th>
<th>Dout</th>
<th>cd_in</th>
<th>cd_out</th>
<th>a</th>
<th>Q</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.40</td>
<td>0.30</td>
<td>0.03</td>
<td>0.02</td>
<td>0.08</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>0.30</td>
<td>0.31</td>
<td>0.48</td>
<td>0.02</td>
<td>0.03</td>
<td>0.09</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>0.40</td>
<td>0.26</td>
<td>0.63</td>
<td>0.03</td>
<td>0.02</td>
<td>0.10</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>0.50</td>
<td>0.20</td>
<td>0.63</td>
<td>0.03</td>
<td>0.05</td>
<td>0.10</td>
<td>0.13</td>
<td>0.03</td>
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<td>0.60</td>
<td>0.15</td>
<td>0.57</td>
<td>0.05</td>
<td>0.05</td>
<td>0.10</td>
<td>0.25</td>
<td>0.04</td>
</tr>
<tr>
<td>0.70</td>
<td>0.17</td>
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<td>0.03</td>
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<tr>
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<td>0.08</td>
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<td>0.78</td>
<td>0.01</td>
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<td>0.04</td>
<td>0.09</td>
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<td>0.02</td>
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</table>

Table A-2 P values for different intercepted wave heights at the high point at X/L = 0.4

<table>
<thead>
<tr>
<th>H/ΔH</th>
<th>Din</th>
<th>Dout</th>
<th>cd_in</th>
<th>cd_out</th>
<th>a</th>
<th>Q</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>5.9E-01</td>
<td>8.3E-01</td>
<td>4.5E-05</td>
<td>5.0E-08</td>
<td>9.0E-01</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>8.3E-01</td>
<td>5.7E-01</td>
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<td>7.1E-07</td>
<td>9.8E-01</td>
</tr>
<tr>
<td>0.40</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>8.5E-01</td>
<td>8.4E-01</td>
<td>9.5E-06</td>
<td>5.0E-03</td>
<td>1.0E+00</td>
</tr>
<tr>
<td>0.50</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>8.8E-01</td>
<td>3.3E-01</td>
<td>2.0E-04</td>
<td>3.0E-06</td>
<td>8.3E-01</td>
</tr>
<tr>
<td>0.60</td>
<td>2.1E-07</td>
<td>0.0E+00</td>
<td>3.0E-01</td>
<td>1.9E-01</td>
<td>3.0E-03</td>
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<td>5.8E-01</td>
</tr>
<tr>
<td>0.70</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>5.3E-01</td>
<td>7.6E-01</td>
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<td>0.0E+00</td>
<td>1.1E-01</td>
</tr>
<tr>
<td>0.80</td>
<td>0.0E+00</td>
<td>3.5E-05</td>
<td>5.8E-01</td>
<td>1.1E-01</td>
<td>8.9E-07</td>
<td>0.0E+00</td>
<td>9.9E-01</td>
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<td>0.0E+00</td>
<td>1.9E-07</td>
<td>1.2E-01</td>
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<td>4.5E-07</td>
<td>0.0E+00</td>
<td>7.6E-01</td>
</tr>
</tbody>
</table>
Table A-3  KS test values for different intercepted wave heights at the high point at X/L = 0.6

<table>
<thead>
<tr>
<th>H_p/ΔH</th>
<th>Din</th>
<th>Dout</th>
<th>cd_in</th>
<th>cd_out</th>
<th>a</th>
<th>Q</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.93</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.05</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>0.40</td>
<td>0.91</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.13</td>
<td>0.02</td>
</tr>
<tr>
<td>0.50</td>
<td>0.49</td>
<td>0.31</td>
<td>0.03</td>
<td>0.02</td>
<td>0.08</td>
<td>0.32</td>
<td>0.03</td>
</tr>
<tr>
<td>0.65</td>
<td>0.27</td>
<td>0.33</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
<td>0.60</td>
<td>0.02</td>
</tr>
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<td>0.55</td>
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</tr>
<tr>
<td>0.90</td>
<td>0.64</td>
<td>0.06</td>
<td>0.03</td>
<td>0.06</td>
<td>0.28</td>
<td>0.52</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table A-4  P values for different intercepted wave heights at the high point at X/L = 0.6

<table>
<thead>
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<th>P Values</th>
</tr>
</thead>
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<td></td>
<td>Din</td>
</tr>
<tr>
<td>0.25</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.40</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.50</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.65</td>
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</tr>
<tr>
<td>0.80</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.90</td>
<td>0.0E+00</td>
</tr>
</tbody>
</table>
Kstest = 0.4, P < 0.0001

(a) $\frac{H_p}{\Delta H} = 0.2$

(b) $\frac{H_p}{\Delta H} = 0.3$

Kstest = 0.31, P < 0.0001

(c) $\frac{H_p}{\Delta H} = 0.4$

(d) $\frac{H_p}{\Delta H} = 0.5$
Figure A-1 Cumulative distributions curves for $D_m/D_p$ at $X/L = 0.4$ for several elevations of high point ($H_p/\Delta H$)
Kstest = 0.93 , P < 0.0001

(a) $H_P/\Delta H = 0.25$

Kstest = 0.9 , P < 0.0001

(b) $H_P/\Delta H = 0.4$

Kstest = 0.49 , P < 0.0001

(c) $H_P/\Delta H = 0.5$

Kstest = 0.28 , P < 0.0001

(d) $H_P/\Delta H = 0.65$
Figure A-2 Cumulative distributions curves for $D_m/D_p$ at $X/L = 0.6$ for several elevations of high point ($H_p/\Delta H$)

(e) $H_p/\Delta H = 0.8$

(f) $H_p/\Delta H = 0.9$
(a) $H_{p}/\Delta H = 0.2$

(b) $H_{p}/\Delta H = 0.3$

(c) $H_{p}/\Delta H = 0.4$

(d) $H_{p}/\Delta H = 0.5$
Figure A-3 Cumulative distributions curves for $D_{out}/D_P$ at $X/L = 0.4$ for several elevations of high point $(H_p/\Delta H)$.
Kstest = 0.03, P < 0.0001

Kstest = 0.04, P < 0.0001

Kstest = 0.31, P < 0.0001

Kstest = 0.34, P < 0.0001

(a) \( \frac{H_p}{\Delta H} = 0.25 \)

(b) \( \frac{H_p}{\Delta H} = 0.4 \)

(c) \( \frac{H_p}{\Delta H} = 0.5 \)

(d) \( \frac{H_p}{\Delta H} = 0.65 \)
Kstest = 0.16, P < 0.0001

Kstest = 0.06, P < 0.0001

(e) $H_P/\Delta H = 0.8$

(f) $H_P/\Delta H = 0.9$

Figure A-4 Cumulative distributions curves for $D_{out}/D_P$ at $X/L = 0.6$ for several elevations of high point ($H_P/\Delta H$)
Kstest = 0.1, P < 0.0001

(a) $H_p/\Delta H = 0.2$

Kstest = 0.09, P < 0.0001

(b) $H_p/\Delta H = 0.3$

Kstest = 0.07, P < 0.0001

(c) $H_p/\Delta H = 0.4$

Kstest = 0.12, P < 0.0001

(d) $H_p/\Delta H = 0.5$
Figure A-5 Cumulative distributions curves for $Q$ at $X/L = 0.4$ for several elevations of high point ($H_p/\Delta H$)
(a) $H_p/\Delta H = 0.25$

(b) $H_p/\Delta H = 0.4$

(c) $H_p/\Delta H = 0.5$

(d) $H_p/\Delta H = 0.65$
Figure A-6 Cumulative distributions curves for $Q$ at $X/L = 0.6$ for several elevations of high point ($H_P/\Delta H$)