QUANTIFYING THE INFLUENCE OF AIR ON THE CAPACITY OF LARGE DIAMETER WATER PIPELINES AND DEVELOPING PROVISIONAL GUIDELINES FOR EFFECTIVE DE-AERATION

Volume 2

Provisional guidelines for the effective de-aeration of large diameter water pipelines

S J van Vuuren, M van Dijk and J N Steenkamp

WRC Report No. 1177/2/03

Water Research Commission

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By

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Report to the WATER RESEARCH COMMISSION on the project:

QUANTIFYING THE INFLUENCE OF AIR ON THE CAPACITY OF LARGE DIAMETER WATER PIPELINES AND DEVELOPING PROVISIONAL GUIDELINES FOR EFFECTIVE DE-AERATION

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EXECUTIVE SUMMARY

1. Background and motivation

The extension of the design life of the aging water infrastructure requires an assessment of all the components that can negatively influence the hydraulic capacity and can endanger the pipeline. To ensure operational effectiveness of pipelines they must be effectively de-aerated.

The influence of air on the capacity of pipelines has long been a cause for concern. The quantification thereof was, however, unknown and required investigation. The investigation of air in pipelines required a review of available literature, experimental work, field investigations and the development of provisional guidelines for optimal design to limit the negative effects of air.

2. Aims of this study

The aims of this study were to:

- Provide a literature review with regard to aspects related to air in water pipelines
- Conduct experimental and field work to establish to influence of air in pipelines and
- Compile a provisional guideline for the design of effective de-aerated pipelines.

3. Implementation of the Research Findings

The Water Research Commission promotes the commercialisation and implementation of the research findings into practice. Based on the knowledge that was gained through the literature study, experimental and field investigations and the numerical modelling a Provisional Guideline has been developed that is intended for use by practitioners. Contained in the provisional guideline the following aspects are discussed:

- Intrusion of air into pipelines
- The consequences of air in pipelines
- Hydraulic transport of air
- Air valves
- Implementation of a new pipeline
- Sizing and positioning of air valves
- Typical installation details of air valves

These aspects will provide the designer assistance in the review of existing, and the design of new pipelines. The inclusion of utility software is a great advantage with regard to the analyses of pipe systems with regard to the locations and sizing of air valves.

4. User comments

It is envisaged that it might be possible that the use of the guidelines will highlight shortcomings and could lead to the implementation of other aspects to improve the provisional guidelines.

The incorporations of procedures to determine the location of air pockets, the practical experience of using the guidelines and the development of new products will create the opportunity for the upgrading and extension of the guideline. All users are requested to provide comments and feedback on the use of this guideline.

PROVISIONAL GUIDELINES FOR THE EFFECTIVE DE-AERATION OF LARGE DIAMETER WATER PIPELINES

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GLOSSARY OF TERMS

a	=	Constant (for medium sized bubble: a = 0,2178)
e	=	Coefficient of volume thermal expansion of pipe wall material (/°C)
A	=	Area of the pipe (m^2)
A_i	=	Flow area for intake orifice (m^2)
A_0	=	Flow area for outflow orifice (m^2)
A_o	=	Orifice area of the air valve (m^2)
$A_{rupture}$	=	Area of pipe rupture (m^2)
B	=	Coefficient of volume thermal expansion of liquid (/°C)
b	=	Constant (for medium sized bubble: b = 0,4007)
c	=	Celerity with no air (m/s)
c'	=	Celerity with free air (m/s)
C_D	=	Discharge coefficient for an orifice
Cd_i	=	Discharge coefficient for the inflow orifice
Cd_0	=	Discharge coefficient for the outflow orifice
C_o	=	Discharge coefficient
D	=	Inside diameter of pipe (m)
D_{outlet}	=	Inside diameter of outlet pipe (m)
E	=	Elasticity of the pipe material (MPa)
g	=	Gravitational acceleration (m/s^2)
H	=	Henry's Law constant
Δh	=	Available energy between peak and drainage point (m)
K	=	Bulk modulus of liquid (MPa)
k	=	Isentropic constant (ratio of specific heats = 1,4 for air)
k_s	=	Absolute roughness of pipe (m)
L	=	Length of pipe (m)
$\dot{m}$	=	Mass flow rate (kg/s)
m	=	Mass of free gas per unit mix (kg/m^3)
P_a	=	Partial pressure of gas
P	=	Pressure (MPa)
p	=	Absolute pressure of air in the valve (Pa)
p_a	=	Atmospheric pressure (Pa)
ΔP	=	Pressure differential across the air valve (kPa)
Q_c	=	Flow rate at which removal starts (m^3/s)

$Q_{discharge}$	=	Discharge through air valve (m^3/s)
Q_{drain}	=	Flow rate due to controlled drainage (m^3/s)
Q_{burst}	=	Flow rate due to burst (m^3/s)
R	=	Gas constant (J/kg K)
S_0	=	Slope of pipe (m/m)
t	=	Wall thickness (m)
T	=	Temperature (° Kelvin)
ΔT	=	Change in temperature (°C)
V_c	=	Clearing velocity, also called critical velocity (m/s)
V_{min}	=	Flow velocity at which point removal will start (m/s)
Vol_L	=	Permissible leakage (l)
V_2	=	Velocity in steep section (m/s)
V_1	=	Velocity in less steep section (m/s)
X_a	=	Mole fraction of the gas in the liquid phase
λ	=	Friction factor
μ	=	Poisson's ratio
ρ_a	=	Density of air at atmospheric pressure (kg/m^3)
ρ_v	=	Density of air in the air valve under line head conditions (kg/m^3)
ρ_v	=	Fluid density (kg/m^3)
θ	=	Slope of pipeline (°)

DEFINITIONS

Air valve	-	A mechanical device with which air can be removed or introduced from or into a pipeline system.
Air release valve	-	Valves which are designed to discharge air during the filling of a pipeline with fluid, for ventilating a pipeline while emptying, or for releasing air that may have accumulated in sections of a pipeline under normal working conditions (Myles K, 1994).
Atmospheric pressure	-	Atmospheric pressure is defined as the force per unit area exerted against a surface by the weight of the air above that surface.
Automatic air release valve	-	This is a valve that releases entrapped air in pressurized water/sewerage systems. It is also referred to a small orifice valve since the outlet orifice is relatively small (typically $1mm^2$).
Clearing velocity	-	The minimum velocity to clear an air pocket from a line. No distinction is made whether the air pocket is removed as a whole or by means of generation and entrainment (Wisner, Mohsen & Kouwen, 1975).
Class	-	This refers to the pressure rating usually expressed as a dimension less number.
Column separation	-	This is a phenomenon that occurs when water separates creating a vacuum.
Combination air valve	-	This is a valve that combines the function of an air release valve and a vacuum break valve.
Differential pressure	-	The difference in pressure between two points.

Discount rate	-	The interest rate used to discount future cash flow to their present values. This represents the rate of return that could have been obtained by investing in a project with risks comparable to the project being considered.
Energy head	-	The difference in height between the hydraulic gradeline and the centre line of the pipeline plus the velocity head of the fluid.
Escalation rate	-	The rate at which prices/costs increase (inflation).
Flow rate	-	The rate at which a volume of fluid is transported usually expressed as volume per time unit.
Friction head	-	The head lost by the fluid due to the intermolecular friction and the friction between the fluid and the pipeline wall.
Friction loss	-	See friction head.
Friction slope	-	The friction head per unit length of the pipeline.
Full bore	-	A valve, which has a cross sectional seat area equal to that of the inlet and outlet. In other words a valve that doesn't reduce its flow area.
Gate valve	-	A valve that closes with a gate or wedge, which is perpendicular to the flow of the fluid.
Head	-	The height of the free surface of fluid above any point in a system.
Head loss	-	The decrease in energy between two points due to friction and other obstructions (secondary losses)
High point	-	A point on the pipeline where the slope changes from positive to negative.

Hydraulic gradeline	-	A hydraulic profile of the piezometric level of water at all points along a pipeline.
Hydraulic gradient	-	The hydraulic gradeline slope or the rate of change in pressure head.
Isolation valve	-	A shut-off valve used to isolate a section of pipeline. Can be a gate valve, butterfly valve etc.
Kinetic air vacuum valve	-	This is a valve used to discharge or admit a large volume of air at a high rate. This is required when a pipeline is filled or emptied. Also referred to a vacuum breaker or large orifice valve.
Laminar flow	-	The region in which the relative roughness has no influence on the friction factor (Chadwick & Morfett, 1994).
Large orifice valve	-	See kinetic air vacuum valve.
Negative pressure	-	A pressure which is less than the atmospheric pressure at a given point (also referred to as vacuum pressure)
Net Present Value (NPV)	-	The present value of the future net revenues of an investment less the investment's current and future cost. An investment is profitable if the NPV of the net revenues it generates in the future exceeds its costs, in other words if the NPV is positive.
Non-return valve	-	A valve that is used in a pipeline to prevent a fluid from flowing back i.e. only allows flow in one direction. Also called a check valve or a reflux valve.
Operating pressure	-	The pressure under which the pipeline and components normally operate.
Pipe collapsing pressure	-	The maximum internal negative pressure a pipe can withstand before it will collapse on itself.

Pipeline profile	-	A longitudinal view of a pipeline indicating elevation and length.
Pressure	-	The force exerted by a fluid on the surfaces containing it (Val-Matic.1996)
Pumping head	-	The total head delivered by a pump at a given flow rate (usually static head and friction head).
Secondary losses	-	The energy loss at a specific point due to obstructions in the fluid path such as bends, valves, reducers etc. Losses are due to eddy formation generated in the fluid at the obstruction.
Slope	-	The angle of the pipeline expressed as change in elevation divided by length. A positive slope is where the change in elevation is positive.
Small orifice valve	-	See Automatic air release valve.
Surge	-	Unsteady conditions due to the change in operating conditions i.e. closure of isolating valve or pump trip (Chadwick & Morfett, 1994).
Vacuum breaker	-	See kinetic air vacuum valve.
Vacuum pressure	-	It is a space in which the pressure is far below the atmospheric pressure. The definition of vacuum is used to describe any pressure below one standard atmosphere. See also negative pressure.
Vacuum valve	-	This is a valve used to admit a large volume of air at a high rate to prevent a vacuum from forming. This is required when a pipeline is emptied. See also kinetic air vacuum valve.
Valve	-	A device, which controls fluid flow.

Water column	-	This term is used as a measure of head or pressure in a closed pipe.
Water hammer	-	The phenomenon of oscillations in the pressure of water about its normal pressure in a closed conduit, flowing full, which results from a too-rapid acceleration or retardation of flow (Val-Matic, 1996)
Working pressure.	-	See operating pressure.

QUANTIFYING THE INFLUENCE OF AIR ON THE CAPACITY OF LARGE DIAMETER WATER PIPELINES AND DEVELOPING PROVISIONAL GUIDELINES FOR EFFECTIVE DE-AERATION

1. INTRODUCTION

1.1 Aim of the study

The Water Research Commission (WRC) has funded the research on the quantification of air on large diameter pipelines and the development of provisional guidelines for the effective de-aeration of such systems

The aim of the study was:

- To quantify the influence of air on the capacity of large diameter water pipelines, and
- To develop provisional guidelines for effective de-aeration.

The research findings are contained in two Volumes, Volume 1 contains details of the literature study, experimental work, field work and numerical modeling while Volume 2 consists of a number of chapters that comprises the provisional guideline for the effective de-aeration of pipelines.

1.2 Methodology

The approach that was used for the compilation of the provisional guidelines was based on the knowledge gained during the experimental and field investigations and the addition of current pipeline design and installation practice. The layout of the Volume 2 has been structured in such a way to assist the designer to be able to evaluate a pipeline and to provide results with regard to the de-aeration of pipelines.

Results from the experimental work and field measurements were used to develop provisional guidelines with regard to the effective de-aeration of pipelines. The provisional guidelines also include utility design software for the sizing and location of air valves. This software is freely available from air valve manufacturers.

1.3 Layout of the reports

This Research report was divided into two volumes, each consisting of a number of chapters and where applicable, supporting Appendices containing data captured during the research. The Provisional Guideline for effective de-aeration of pipelines (Volume 2) was compiled in such a way that it can be read as a stand-alone document. The following two volumes, reflect the findings of this research:

Volume 1: Quantifying the influence of air on the capacity of large diameter water pipelines
Volume 2: Provisional guidelines for the effective de-aeration of large diameter water pipelines

The contents of Volume 1 comprises:

- Introduction
- Influence of air on pipelines
- Field investigations
- Experimental work
- Numerical modeling of air release from pipelines (CFD)
- Effective de-aeration of pipelines
- Further developments.

Volume 2, titled **“**Provisional guidelines for the effective de-aeration of large diameter water pipelines” **(This report – Provisional Guidelines)** includes the following sections:

- Introduction
- Intrusion of air into pipelines
- The consequences of air in pipelines
- Hydraulic transport of air
- Air valves
- Implementation of a new pipeline
- Sizing and positioning of air valves
- Typical installation details of air valves
- User comments

2. INTRUSION OF AIR INTO PIPELINES

2.1 Introduction

Air in pipelines is nearly unavoidable. The manner in which air gets into a pipeline, which is, supposed to transport water, can be divided into two categories.

Category A – Implementation: Initial air in pipeline that was not completely removed during the filling process.

Category B – Operational: Air that enters into the system at intakes, vents etc. and air that is freed from solution during normal operation.

These two categories are now discussed in more detail.

2.2 Category A – Implementation of a new pipeline or the refilling of an existing pipeline

- **Filling of pipelines**

  During the initial filling of a pipeline, or at any other stage when the pipeline is emptied for regular maintenance or to fix a pipe burst and needs to be refilled, large quantities of air can be trapped if sufficient air release mechanisms are not incorporated in the design. **Figure 2.1** reflects this condition, which is referred to as an air lock, which represents the inability to transport water through the pipe due to the limited energy head, $H_{shuttoff}$, which is less than the summation of the heads reflected in **Figure 2.1** as A, B and C.

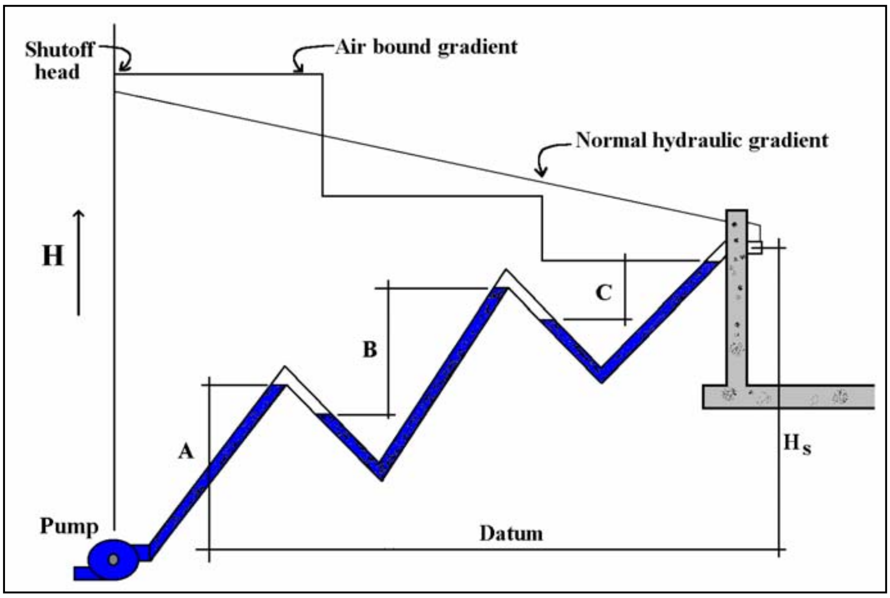


Figure 2.1: Schematic definition of the concept of an air lock

2.3 Category B – Operational conditions

- **Air production at low pressure along rising main (Air from solution)**

Water contains dissolved air, which comes out of solution in the form of very small bubbles when the water pressure is sufficiently reduced. In a pipeline, this usually occurs in sections, which are topographically close to the hydraulic grade line or at siphons. The quantity of air, which comes out of solution at these lower pressure zones, is given by Henry's Law - "The weight of gas dissolved in a given mass of liquid, at constant temperature is directly proportional to the partial pressure exerted upon the gas." (Wisner, 1982a), Equation 2.1.

$$H = \frac{P_a}{X_a} \quad \text{...} (2.1)$$

Where:

H = Henry's Law constant

P_a = Partial pressure of gas

X_a = Mole fraction of the gas in the liquid phase

Low pressures can also be caused, by changing operational conditions such as when negative surge pressures are generated by power failure, air can be released from solution if sufficient vacuum break facilities have not been provided.

- **Air separation at restrictions**

Air may also be released when there is a drop in pressure due to an increase in velocity at a restriction such as a partially closed valve (Stephenson, 1981). Water at atmospheric conditions contains approximately 2% per volume of dissolved air, which can be released from solution if the pressure drops, or if there is a rise in temperature (Van Vuuren, 1991). Once air is released from solution, it does not easily dissolve and free air thus remains in the pipeline.

- **Pumps and pump sumps**

Low pressure at pump intakes may be the source of air introduction (Wisner, 1982a), especially when the suction pressure is negative. If at any point from the water source to the pump the suction pipe is not air tight, air will intrude. Air may also be drawn in at pump glands where pressure is sub-atmospheric.

On start-up, well pumps can add into the supply pipe a considerable quantity of air that was trapped in the riser pipe, if no provision has been made to release the air before the check valve opens.

Inlet sumps are a major source of air in pumping lines (Stephenson, 1981). In a sump the water has a free surface that will absorb air depending on the temperature, pressure and degree of saturation of the water. The correct design of pump sumps to prevent air being drawn into the system was investigated by Denny and Young (1957) as well as Prosser (1977). Favourable design conditions/criteria such as sufficient submergence, bell mouthed entrance-floating grids or cover plates are some options that will limit free air vortex formation and air intrusion.

- **Intakes**
  Free surface vortices might result from characteristics such as unfavourable flow conditions, inlet geometry and insufficient submergence.

- **Vents**
  Vents, such as standpipes, are placed at apex points, in order to prevent the system against high pressures and to prevent the formation of vacuums under which conditions air will flow into the pipeline. Excessive air can be detrimental to the system if it cannot be released in a controlled manner.

3. THE CONSEQUENCE OF AIR IN PIPELINES

3.1 Introduction

"It has been said that if a pipeline is properly de-aerated, you can't guarantee against a line break. However if you *don't* properly de-aerate a pipeline, you should be prepared for one."(Val-Matic, 1993)

The free air in pipelines should be removed for two important reasons: Firstly to maintain the efficiency of the pipeline system and secondly to protect the pipeline against high induced pressures. These reasons are discussed in more detail below.

3.2 Reduction of capacity

Pipelines, which are not effectively de-aerated, can experience a substantial loss of hydraulic capacity. When an air pocket is present in a pipeline the flow is restricted and an additional head loss occurs. This head loss is directly proportional to the size of the air pocket (Wisner, 1982a) and can be so high that the capacity reduces with up to 16%.

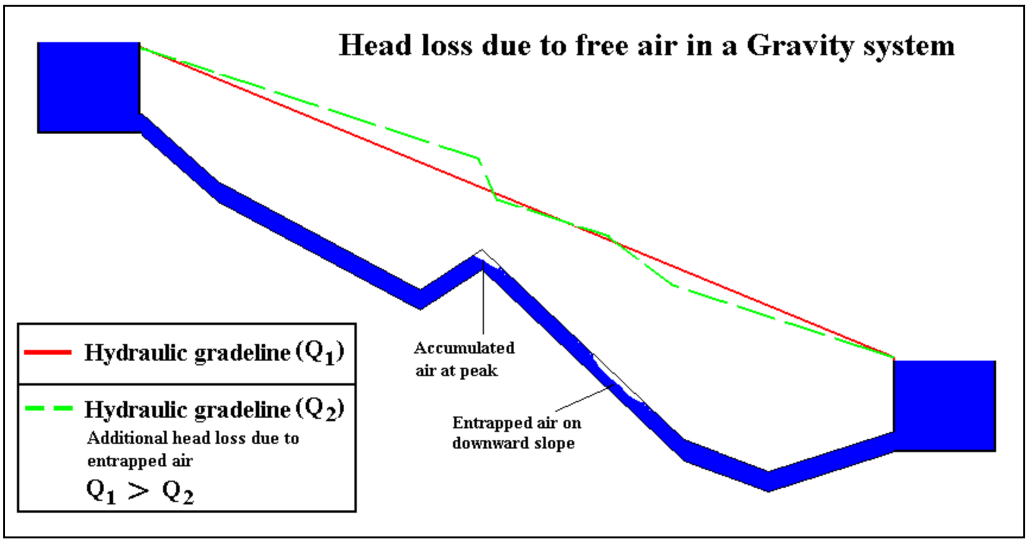


Figure 3.1: Head loss in a gravity system

Figure 3.1 illustrates the loss in capacity due to the restrictions resulting from air bubbles. Pipelines with steep gradients and numerous peaks are prone to experience these additional head losses. Correctly sized and placed air valves can, however, prevent these losses. In a pumping system, the trapped air pockets have a similar effect, see **Figure 3.2**. Trapped air cause additional head losses, requiring additional pumping head. The pump(s) has to operate at a different duty point on the pump curve (H_2, Q_2), (**Figure 3.3**).

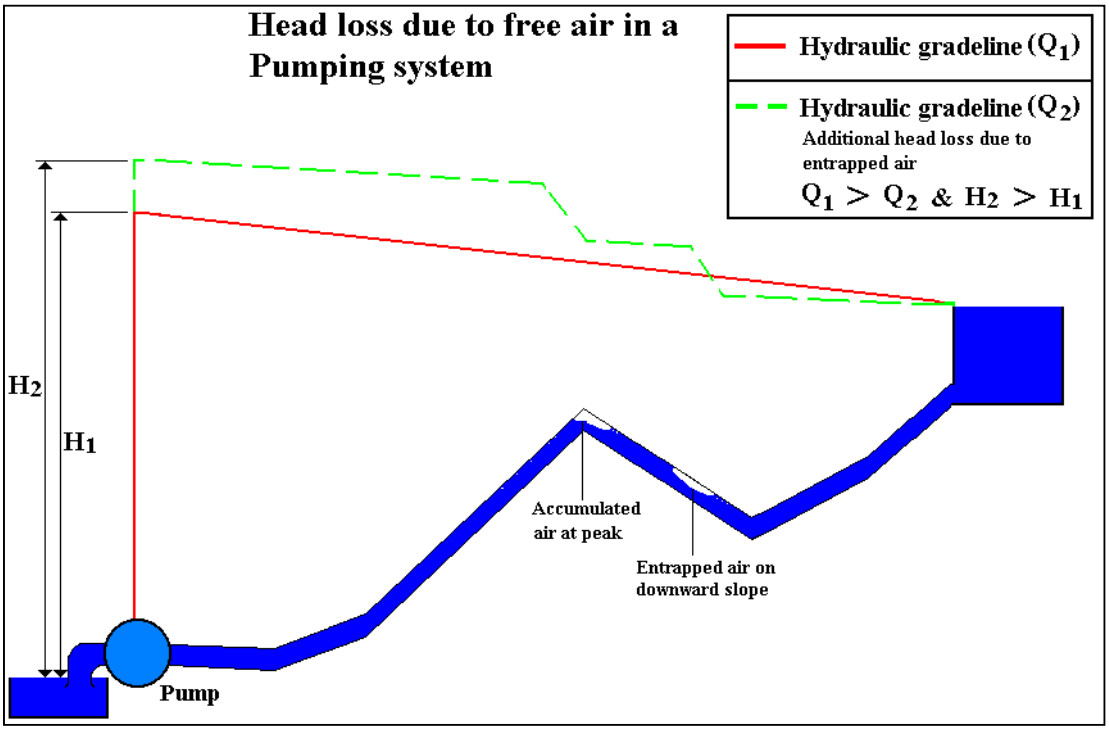


Figure 3.2: Head loss in a pumping system

Air pockets increase energy consumption resulting in a higher pump head, lower flow rate and longer pumping hours. In extreme cases, the air pockets can completely stop the flow, the so-called air lock condition (**Figure 2.1**).

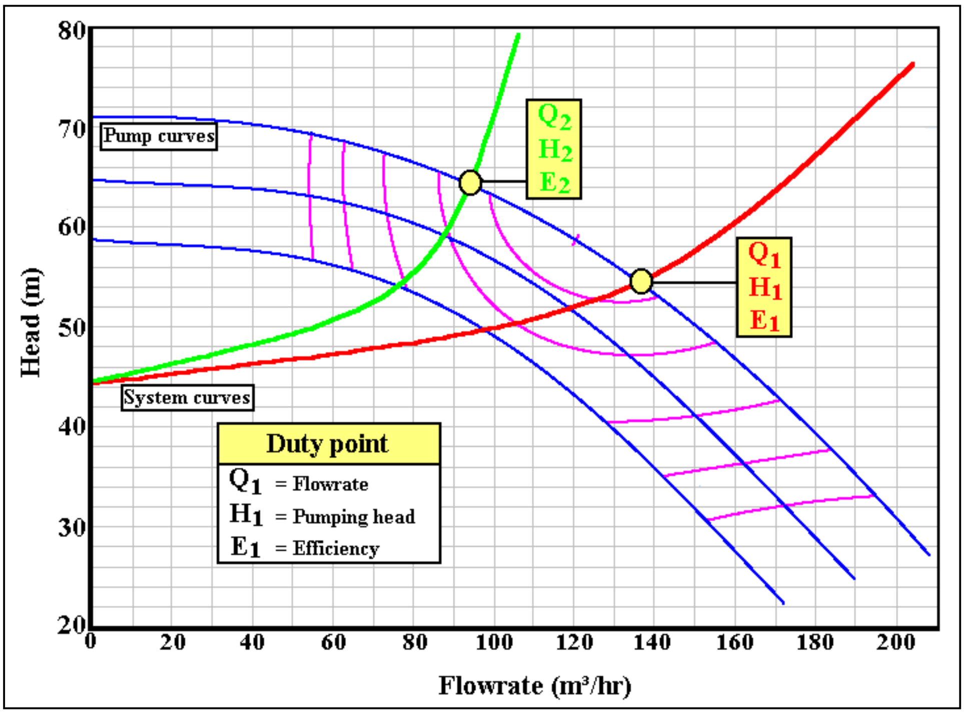


Figure 3.3: Change in duty point resulting from additional secondary losses at air bubbles

To be able to overcome the additional head loss due to the air pockets present in a pipeline, the pump will operate at a lower flow rate, as can be seen in **Figure 3.3**. This also implies that the pump will operate at a different efficiency. Pumping lines are usually designed to operate at the optimum pump efficiency, a change in duty point will more often than not result in a less efficient operating point.

3.3 Blowback and associated pressure fluctuations

Free air in pipelines also sometimes gives rise to surges and blowbacks. A pipeline, where free air could be released from solution, is typically a pipeline that would be at risk. These small air bubbles will be transported down a pipeline until they accumulate and grow into a large bubble, which will periodically travel back, causing pressure fluctuations (**Figure 3.4**).

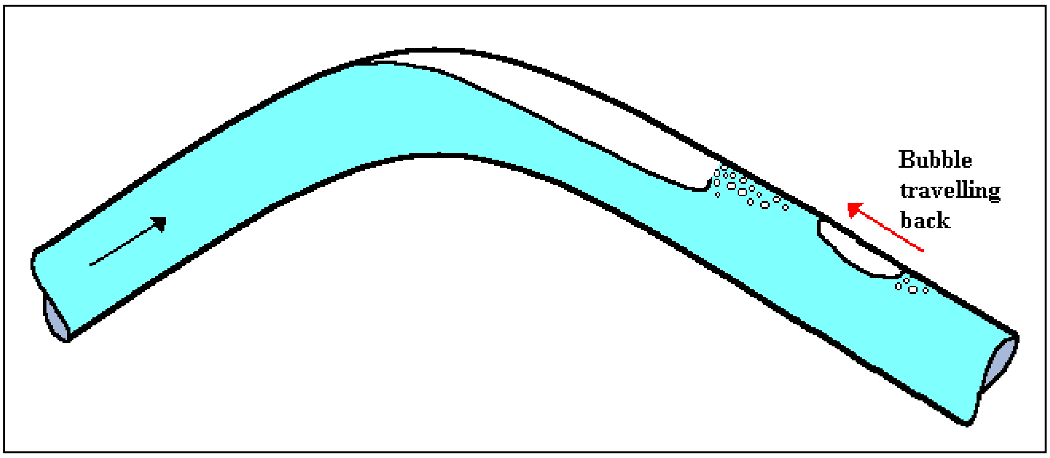


Figure 3.4: Air bubble travelling back causing pressure fluctuations

3.4 White water

White water has a milky white appearance due to large number of minute bubbles (**Figure 3.5**). Because this "water is aesthetically repulsive and chemically corrosive" provision must be made to determine the origin of the air intrusion into the system (Wisner, 1982a).

Figure 3.5: A photo of white water in surge tower (Buffalo River abstraction, East London, South Africa)

3.5 Water hammer and surge

When air is released from a pipeline in an uncontrolled manner (too high discharge rates), pressure surges are induced, which could lead to pipe failure (Van Vuuren, 1991). The difference between the characteristics of air and water will result in an almost instantaneous stoppage of the approaching water column at the point when all the air has been released. This is especially true for incorrectly sized (too large) vents/air valves.

3.6 Effect of uncontrolled air release from pipelines

When venting air through an air valve, a phenomenon referred to as blow-shut occurs when air is released too quickly. As highlighted (Van Vuuren, 1991), a serious problem of some large orifice air valves, is the inclusion of a dynamic shied to maintain large flow rates. When air is discharged at high rates, the float will be closed either as a result of the blow-shut phenomenon or at the point when all the air has been released. This will result in a dynamic pressure spike.

The development of three-stage air valves addresses this problem. The basic concept of these valves is to switch to the intermediate orifice through which the air can be released at high differential pressures, but due to the size of the intermediate orifice, the generated pressure surge is reduced.

3.7 Effect of free air on induced pressure surges

Free air in pipelines reduces the pressure surges due to the reduction of the wave celerity (Van Vuuren 1994). The influence of air on the celerity can be determined by comparing the celerity, based on the application of Equations 3.1 and 3.2.

Wave celerity in a pipeline with no air:

$$c = \sqrt{\frac{K}{\rho}\left[\frac{1}{1+\frac{K}{E}\frac{D}{t}}\right]} \quad \text{......(3.1)}$$

Wave celerity in a pipeline with free air:

$$c' = c\sqrt{\frac{1}{1+\left[\frac{RTKm}{\left(1+\frac{K}{E}\frac{D}{t}\right)\rho^2}\right]}} \quad \text{......(3.2)}$$

Where:

c = Celerity with no air (m/s)

c' = Celerity with free air (m/s)

K = Bulk modulus of water (MPa) (2 140 MPa)

E = Elasticity of the pipe material (MPa)

D = Pipe diameter (m)

t = Wall thickness (m)

m = Mass of free gas per unit mix (kg/m^3)

ρ = Fluid density (kg/m^3)

R = Gas constant (J/kg K) (287)

T = Temperature in ° Kelvin

An example of the effect that free air has on a system's celerity is shown in **Figure 3.6**, a 400 mm uPVC pipe with different percentages of free air.

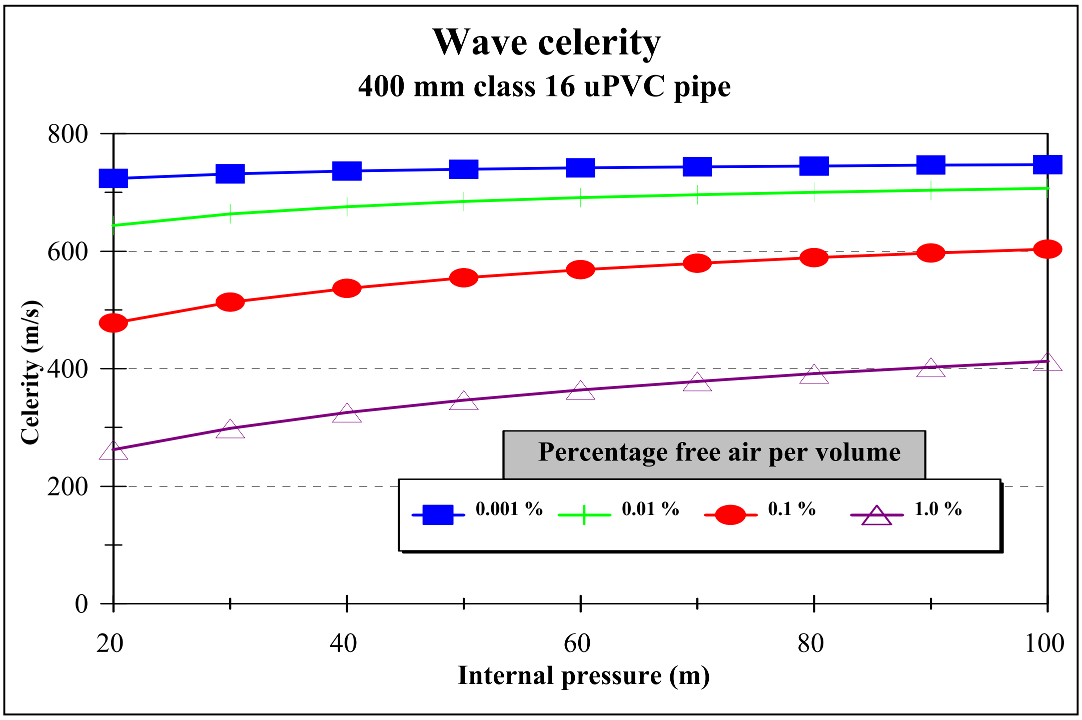


Figure 3.6: Effect of free air on a system's wave celerity

3.8 Other consequences of free air in pipelines

Reduction of pump efficiency

Deny and Young (1957) in Wisner (1982b) found that 1% of air is capable of reducing pump efficiency by 15 %.

Biological effects

If air is constantly present in a pipeline, growth of certain aerobic organisms may be promoted.

4. HYDRAULIC TRANSPORT OF AIR

4.1 Introduction

In the removal of air from pipelines, a distinction is made between *hydraulic removal* of air and *mechanical removal* of air. Hydraulic removal is associated with the transportation of air by means of fluid inertia. The free air may either be transported along the line until it reaches the end reservoir, or until it reaches an air valve where it will be removed mechanically. Mechanical removal of air therefore is associated with a device that contains a trap and a release feature.

Air may be present in pipelines in different sizes, from small bubbles to large air pockets. Air pockets can be stable or unstable depending on the flow rate, air pocket size and pipe diameter (Wisner, 1982b). Once an air pocket has reached a certain size, it can travel back up the pipeline due to buoyancy (blowback). The size of the air pocket is normally dynamic, due to bubbles generated at the tail of the air pocket and swept downstream thus reducing the size of the pocket. Bubbles developed upstream can however join the air pocket thus enlarging it again. Conditions required to hold an air pocket stable on an inclined slope (Wisner, 1982b) are the following:

a) The size remains constant, i.e. the volume of air received by the air pocket is equal to the volume of air swept downstream at the tail of the pocket.

b) The flow rate is such that the buoyancy force is equal to the shear force, which the water exerts on the air bubble.

4.2 Formula used for prediction of transportability of air

Numerous investigators have made recommendations regarding the so-called clearing velocity (the minimum velocity to clear an air pocket from a line). The most commonly used equations by practising engineers to determine the clearing velocity to transport the air are Equation 4.1 (Kalinske & Bliss, 1943) and Equation 4.2 (Wisner, Mohsen & Kouwen, 1975).

i) Kalinske and Bliss (1943) provided a relationship for the clearing velocity for different slopes.

$$\frac{Q_c^2}{gD^5} = 0{,}707 \tan\theta \quad \text{...}(4.1)$$

Where:

Q_c	=	Flow rate at which removal starts (m^3/s)
g	=	Gravitational acceleration (m/s^2)
D	=	Diameter of pipeline (m)
θ	=	Slope of pipeline (°)

This relationship was based on experimental work that was conducted on air bubbles with a dimension ratio (Y/D) between 1 and 0,65. *Y* refers to the dimension of the water depth relative to the pipe diameter.

ii) Wisner, Mohsen & Kouwen (1975) concluded that there is great diversity in the results of previous investigators and used a conservative approach in determining the clearing velocity by plotting all the available experimental results from previous investigators to obtain a lower bound for the clearing velocity (Equation 4.2).

$$\frac{V_c}{\sqrt{gD}} = 0{,}25\sqrt{\sin\theta} + 0{,}825 \quad \text{......(4.2)}$$

Where:

V_c	=	Clearing velocity, also called critical velocity (m/s)
g	=	Gravitational acceleration (m/s^2)
D	=	Diameter of pipeline (m)
θ	=	Slope of pipeline (°)

Van Vuuren (1995b), commented that these two equations provided contradictory results. The main reason for the difference in results obtained was the different size bubbles that were being tested. Wisner et al. investigated large air pockets whilst Kalinske and Bliss looked at small bubbles.

4.3 Proposed formula to use for the hydraulic transportability of air

From the experimental work that was conducted and described in the main report (Volume 1) a new equation has been proposed (Equation 4.3). Various sized bubbles (small, medium and large) were tested in the laboratory, and it was proposed that the relationship for the medium sized air bubble (Y/D of about 0,25) should be used for design calculations. Where Y is the vertical dimension of the air bubble and D is the diameter of the pipe.

$$V_{min} = a\sqrt{gD}\theta^b \quad (4.3)$$

Where:

V_{min}	=	Flow velocity at which point removal will start (m/s)
g	=	Gravitational acceleration (m/s²)
D	=	Diameter of pipeline (m)
θ	=	Slope of pipeline (°)
a	=	Constant (for medium sized bubble: a = 0,2178)
b	=	Constant (for medium sized bubble: b = 0,4007)

Experimental results were obtained for slopes of up to 15 °. A comparison of Equations 4.1 to 4.3 yielded Figure 4.1 for a 200 mm diameter pipe with a slope between 0° and 20°.

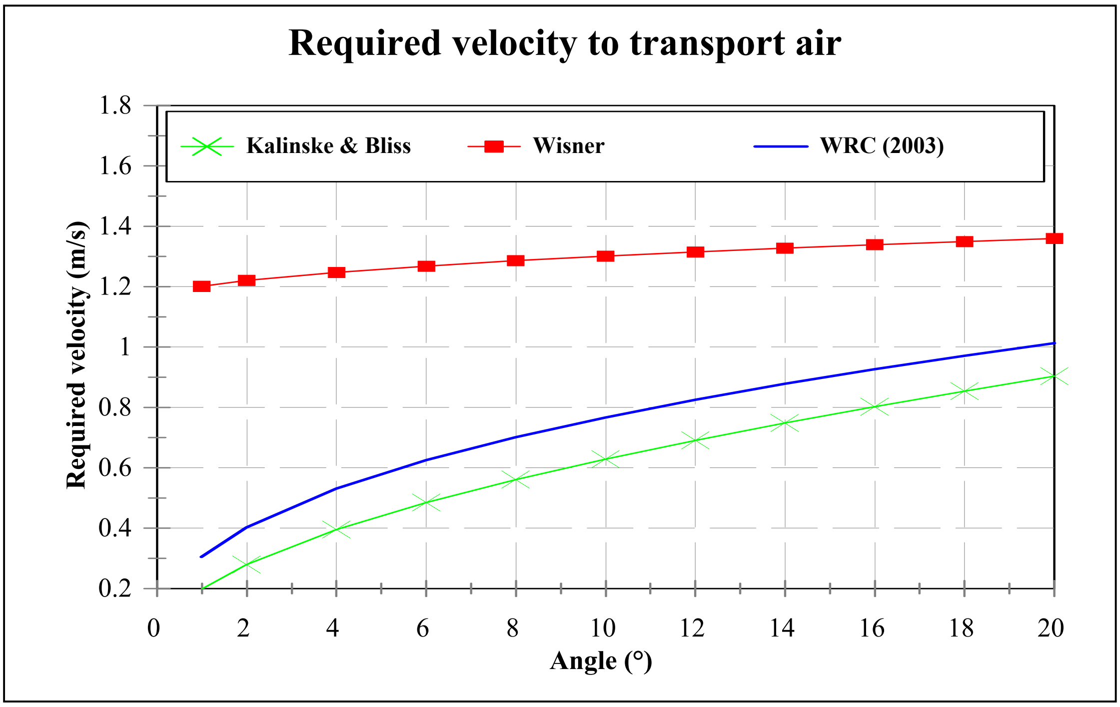


Figure 4.1: Required flow velocity to remove air

In **Table 4.1**, a comparison is reflected of the critical velocity to transport air, using the Equations 4.1 to 4.3 for different pipe diameters and slopes. In **Figure 4.2** a comparison is made between the bubble sizes of Kalinske & Bliss and Wisner et al.

Table 4.1: Comparison of the critical velocity to transport air

Investigator	Equation	Slope (°)	Pipe diameter (m)	Critical velocity (m/s)
Kalinske & Bliss	4.1	5	250	0,496
WRC (2003)	4.3			0,650
Wisner et al.	4.2			1,408
Kalinske & Bliss	4.1		350	0,587
WRC (2003)	4.3			0,769
Wisner et al.	4.2			1,665
Kalinske & Bliss	4.1		500	0,701
WRC (2003)	4.3			0,919
Wisner et al.	4.2			1,991
Kalinske & Bliss	4.1	10	250	0,704
WRC (2003)	4.3			0,858
Wisner et al.	4.2			1,455
Kalinske & Bliss	4.1		350	0,833
WRC (2003)	4.3			1,015
Wisner et al.	4.2			1,722
Kalinske & Bliss	4.1		500	0,995
WRC (2003)	4.3			1,214
Wisner et al.	4.2			2,058
Kalinske & Bliss	4.1	15	250	0,868
WRC (2003)	4.3			1,010
Wisner et al.	4.2			1,491
Kalinske & Bliss	4.1		350	1,026
WRC (2003)	4.3			1,195
Wisner et al.	4.2			1,764
Kalinske & Bliss	4.1		500	1,227
WRC (2003)	4.3			1,428
Wisner et al.	4.2			2,109

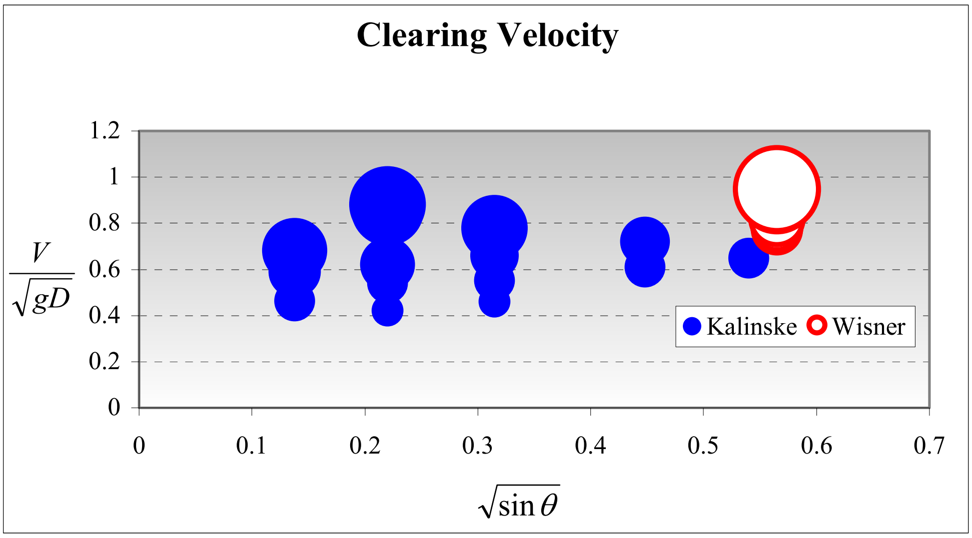


Figure 4.2: Bubble size comparison of Kalinske & Bliss and Wisner et al. equations

5. AIR VALVES

Air valves functions to release air from pipelines and to prevent vacuum conditions inside a pipeline. The reason why air valves do not feature in a distribution networks is because sufficient outlets are available to release the free air. On main supply lines, it is important to provide features to remove the air from the system.

Mechanical removal of air is achieved through the use of air valves, which are available in different shapes and sizes.

5.1 Valve types

There are basically two types of air release valves, the so-called large orifice air valve and the small orifice air valve. The difference between the two types is the manner in which they function. The large orifice valve releases or admits air during the charging or emptying of water mains, while the small orifice valve automatically releases air whilst under normal operating conditions/pressures. The two valves therefore each has a distinct function in keeping the system operational. There are, however, numerous variations of the design of these valves, which are not discussed in this document. To highlight the differences, the function of the air valve is discussed by referring to the operational conditions:

- Discharging the air during the filling of the line.
- Releasing air during normal operation of the pipeline.
- Preventing pipe collapse by allowing air to enter the pipe.

5.1.1 Large orifice air valves

Large orifice valves are designed to release or admit air during the charging or filling of the pipeline. Large orifice air valves are also referred to as vacuum breaker valves when used to prevent low pressures. The large orifice air valve will only function to release air when the line is under very low pressure. The function of the valve can be divided into two design considerations, namely releasing air during the filling and admitting air during draining.

Since the air valve has a large orifice, only a low internal pressure is required to keep the float closed (see **Figure 5.1**). Only when the pressure within the valve reaches atmospheric pressure, will the float drop.

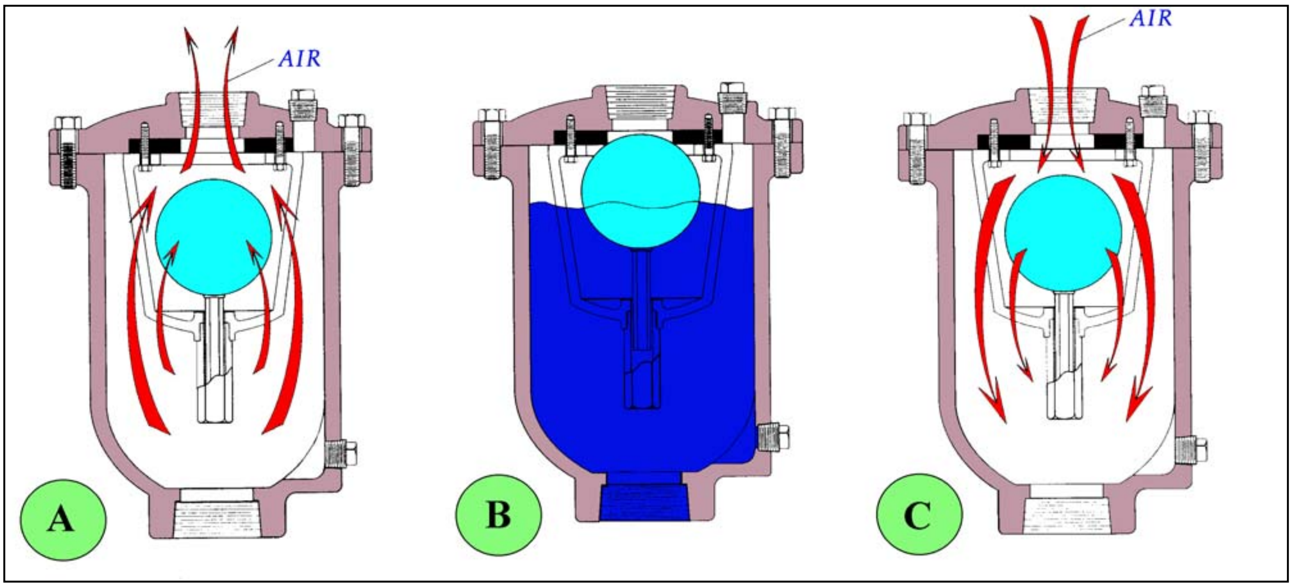


Figure 5.1: Large orifice air valve (Val-Matic, 1993)

a) Filling of pipelines

A pipeline can be filled from either the upstream side or the downstream side depending on the location of the supply. In a pumping line the pumping station might be used to fill the line, by throttling the flow with an isolating valve downstream of the pump. The filling rate of pipelines is usually set to between 5 and 15% of the design discharge (Wisner, 1982b).

Filling a pipeline at a high rate can lead to devastating consequences. The ideal orifice in terms of the filling of the line will be the orifice that remains open until all the air has been discharged. A serious shortcoming in the functioning of the large orifice is the tendency to blow shut at a small differential pressure. The reason why this occurs is because the float should be lightweight (hollow steel ball) in order to be buoyant.

The blow-shut phenomenon is utilized by some valve manufacturers to step down the area of the large orifice, thus limiting the induced pressures to acceptable levels (Van Vuuren, 1995b).

The three-stage air valve (see Vent-O-Mat, 1996) was developed with a staged closure of the large orifice, to limit the discharge to such an extent that the induction of high pressures is limited. **Figure 5.2** below is a typical relationship between the differential pressure and the discharge for a two-stage large orifice air valve (Van Vuuren, 1995b).

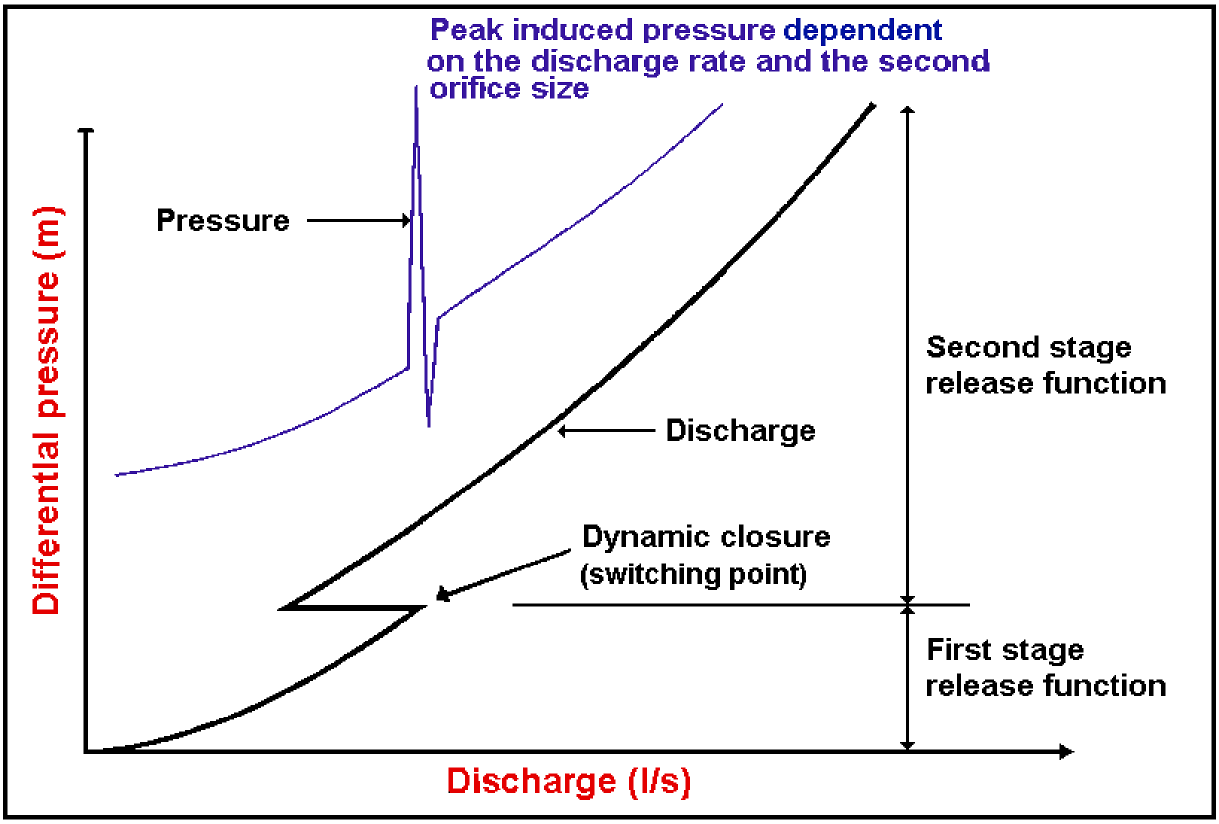


Figure 5.2: Differential pressure - discharge relationship for a two-stage large orifice air valve

b) Draining of pipelines

The draining of a pipeline can be either a controlled release through a scour valve, or an uncontrolled drainage resulting from a pipe failure.

i) Controlled draining

During a controlled release, the large orifice air valve has to admit air into the pipeline to prevent a vacuum from forming. The pipeline is usually drained at a scour valve with an outlet diameter smaller than the pipe diameter. On a 300 mm diameter pipe, the outlet diameter will typically be 80 mm. The sizing of the air valve to prevent the formation of a vacuum is discussed in Section 7.

ii) Uncontrolled draining

During an uncontrolled release, the large orifice air valve has to admit air into the pipeline to prevent a vacuum from forming. The pipe can fail at any point along the line. The failure can be as a result of poor construction, faulty pipe, or due to a design error. The pipe failure will result in the large orifice valve opening and admitting air into the pipeline. The break size (water release opening) is not known beforehand and should be selected to reflect a realistic condition.

5.1.2 Small orifice air valves

Under normal operating conditions, the small orifice air valve will release small quantities of air when they accumulate in the valve. Small orifice air valves are also called automatic air release valves since air is regularly released during normal operation of the pipeline system. The basic concept of a small orifice air valve is that a float (ball or disc) is used to close the orifice (**Figure 5.3**). The float is held in position by the buoyancy forces exerted on it by the water. Air accumulates in the valve and at a certain stage the mass of the float and atmospheric pressure exerted from the outside is greater than the buoyancy force, keeping it pressed against the opening. At this point, the float drops and the accumulated air is released. The water level rises again and lifts the float to close the opening again. Some developers have employed a slit opening as the small orifice, which results in the float peeling the seal from the opening when the float drops (Van Vuuren, 1995b). Small orifice air valves generally have an opening diameter of between 2 and 4 mm. The float system must be carefully designed for the specific pressure range in which the valve will operate. If the orifice is too large, the air pressure in the air valve could cause the valve to stay closed.

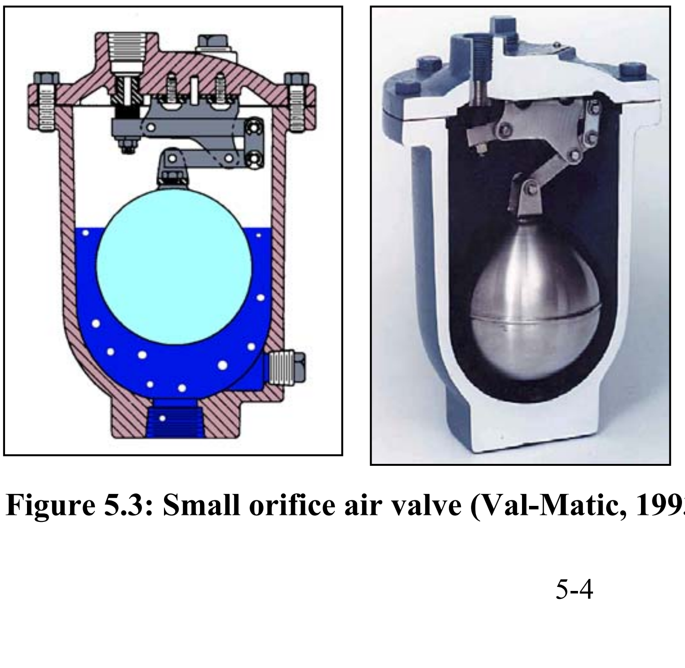


Figure 5.3: Small orifice air valve (Val-Matic, 1993)

5.1.3 Combination air valves

A combination air valve is exactly what its name suggests, a combination of the small and large orifice function in one air valve or together on a manifold. Combination air valves (dual air valves) are installed where both functions (small and large) are required (**Figure 5.4** and **Figure 5.5**).

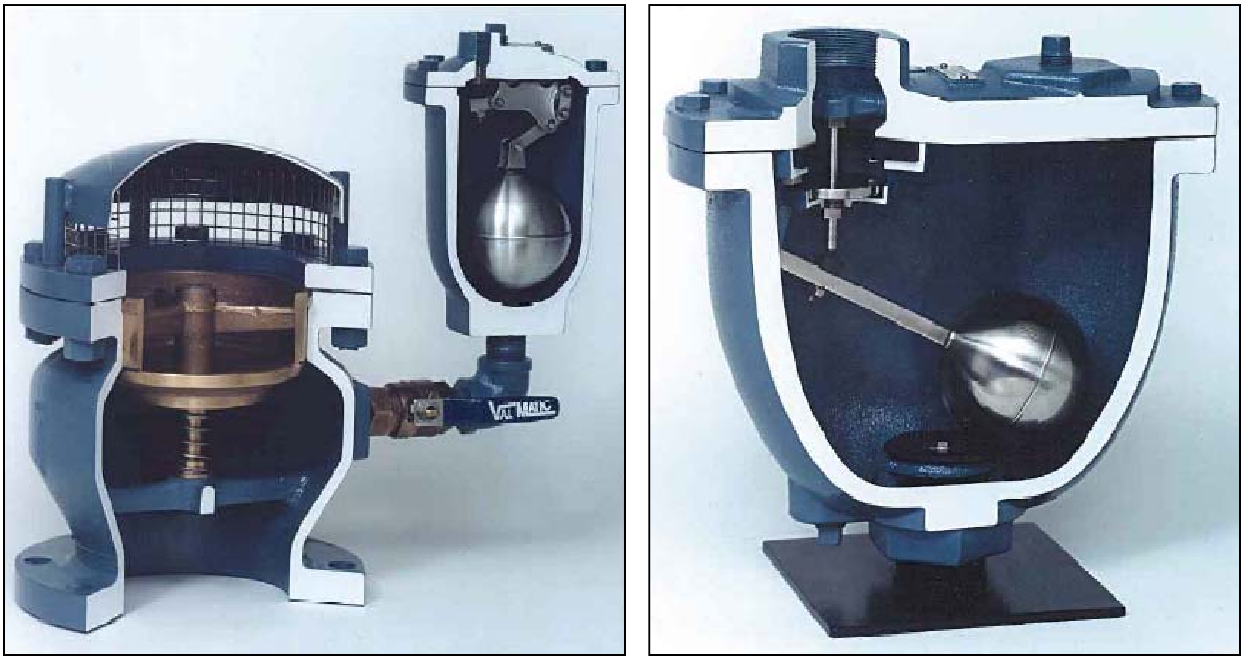


Figure 5.4: Combination air valve (Val-Matic, 1993)

Figure 5.5: Combination air valve (ARI, 1998)

5.1.4 Special types

Valve manufacturers have developed various types of valves to meet the requirements of the designer. It has been indicated that fast closing of the large orifice of an air valve results in high-pressure spikes. Some valve manufacturers have developed so called slow-closing air valves or anti-slam air valves. Below are some of these generic valve types.

a) Slow-closing air valve (APCO design)

The slow closing air valve (APCO, 2003), is a standard air and vacuum valve mounted on a surge check unit (**Figure 5.6**). The air and vacuum valve operates in the normal fashion allowing air to escape freely at any velocity (maximum discharge velocity is approximately 91 m/s at 0,46 bar). The surge check unit operates on the interphases between the kinetic energy in the relative velocity flows of air and water.

The surge check is a normally open valve, spring loaded, so that air passes through unrestricted, but when water rushes into the surge check unit, the disc commences to close against the spring and reduces the rate of flow of water into the air valve by means of throttling holes in the disc. This normally ensures gentle closing of the air and vacuum valve. As soon as the air and vacuum valve is closed, the pressure on both sides of the surge valve disc equalizes and the disc automatically returns to its open position. As soon as the pressure in the pipeline nears atmospheric pressure the air/vacuum valve opens, preventing a vacuum from forming in the pipeline

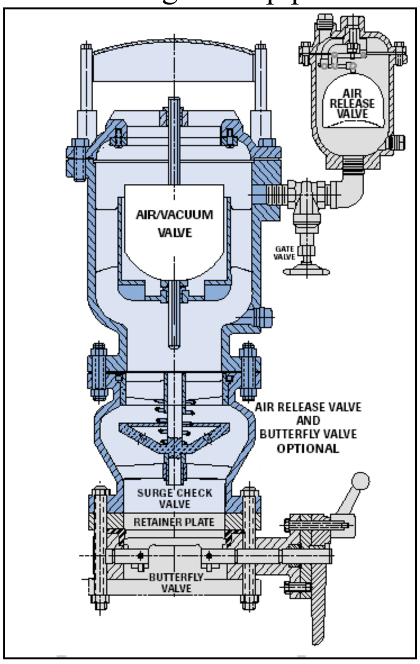


Figure 5.6: Slow closing valve (APCO, 2003)

A disadvantage of this valve is that unwanted surge pressures can still be generated if the throttling in flow rate is too rapid or the air/vacuum float closes to rapidly.

b) Hydraulically controlled air valve

The operating principle of this valve is the same as the conventional air and vacuum valve, with one exception. Hydraulically controlled air and vacuum valves (see **Figure 5.7**) are normally open (because the heavy cast float is not buoyant), and slowly close, only after spilling a regulated volume of water, to prevent a pressure surge. According to APCO (2003), this valve provides excellent pipeline protection against primary and secondary surge pressures, which usually occur when filling or draining a pipeline. The closing time of this valve is variable and adjustable by means of a hydraulic control system.

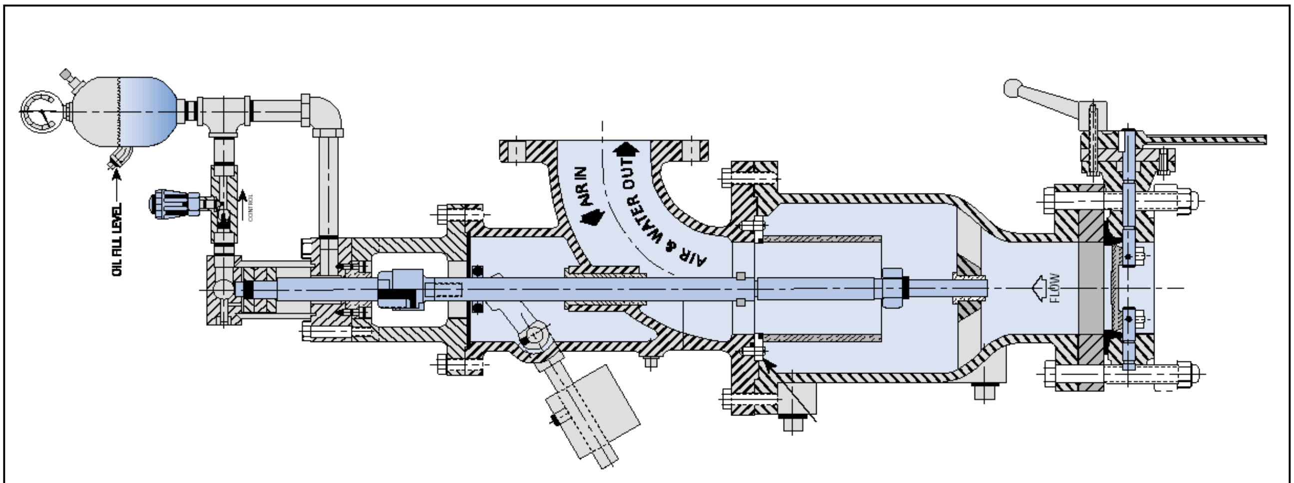


Figure 5.7: Hydraulically controlled air valve (APCO, 2003)

c) 3-stage air valve (Vent-O-Mat design)

The Vent-O-Mat design of a 3-stage air valve acts similar to a conventional air valve with one alteration. It controls the rate of discharge, i.e. dissipating the energy of the surge whilst the approaching water column is decelerated. Air would leave the air valve initially at sub-critical velocities when the large orifice is operating. If the approaching water column excessively increases the flow velocity through the air valve, the large orifice will close and the air will be forced through the intermediate orifice (anti-shock orifice). The approaching water will therefore decelerate due to the decrease in flow rate through the air valve. Once the pipeline is filled the liquid will enter the valve and close the intermediate orifice and will allow the valve to function as a small orifice during normal operating conditions (see **Figures 5.8a – c**).

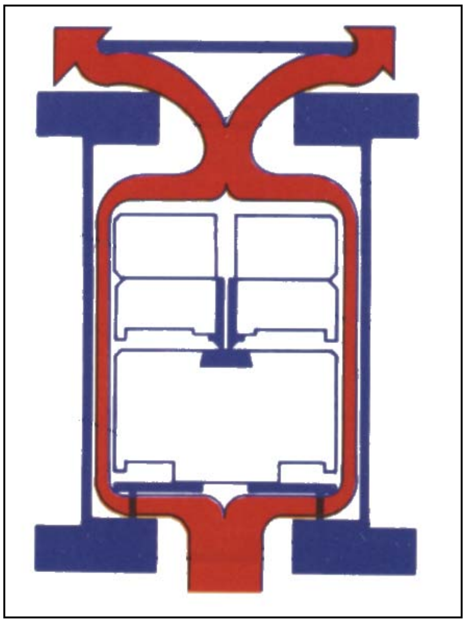


Figure 5.8a: Venting of a filling pipeline (Sub-critical water approach velocity) (Vent-O-Mat, 1996)

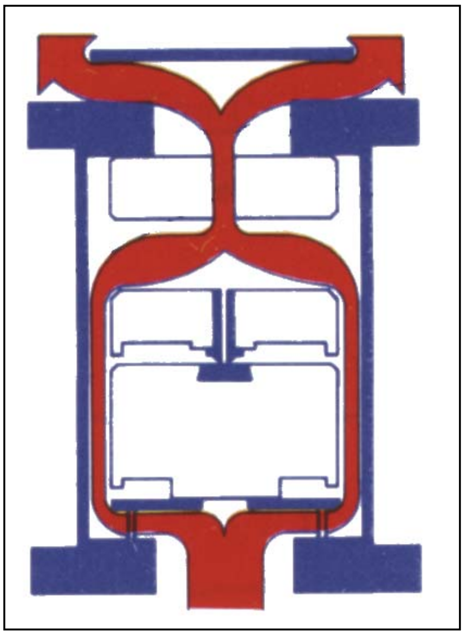


Figure 5.8b: Venting of a filling pipeline (Excessive water approach velocity) (Vent-O-Mat, 1996)

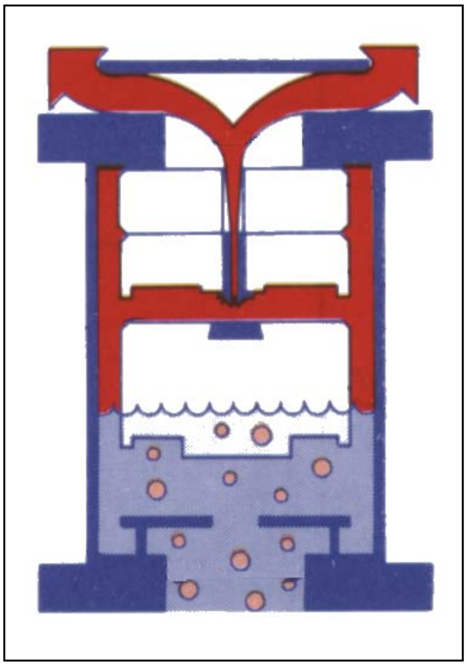


Figure 5.8c: Pressurised air release from a full pipeline (Vent-O-Mat, 1996)

5.2 Operational limitations

Air valves have some operational limitations, which should be taken note of.

- The pressure class of the air valve should be selected to cater for dynamic pressures or the static condition, which ever is the highest. There are a number of standard pressure classes: 10 bar, 16 bar, 25 bar, 40 bar and 64 bar.
- Air valves should be sized for burst, drain and filling at an acceptable differential pressure across the valve, typically of about 0,35 bar. Standard size air valves are: 25 mm, 50 mm, 80 mm, 100 mm, 150 mm, and 200 mm. When a higher intake capacity is required more than one valve can be installed on a manifold (see Section 8)
- There are different valve manufacturers and subsequently different valve types available on the market. Air valves are distinguished by their operational characteristics and are sometimes referred to as:
  - Vacuum valves – operate to allow air intake
  - Large orifice air valves – to release air at high flow rate and a low differential head
  - Small orifice air valves – valves used to de-aerate air under operating conditions
  - Combination air valves – combine the inlet and outlet functions referred to above.

  Different features have been added to some of the air valve products of which the following has a major benefit for pipeline operation:
  - Bios mechanism that restrains the valve from leaking under low internal pressure.
  - Anti-shock feature that controls the release rate and prevent the creation of high induced pressures during filling.

Some problems, which might cause the air, valve to malfunction:

- If the air valve chamber is flooded and the air valve is submerged, the air valve's inlet characteristics will change. Contaminated water will intrude trough the air valve when low operating pressures occur.
- Air valves sizes are not always what their nominal size reflect. Some products quoted as a 100 mm air valve has in- and outlet diameters, which are smaller than 100 mm diameter.
- Varies air valves uses a ball type float. The ball is prone to blow shut during high air outlet velocities leading to ball deformation. The premature closure of these types of floats forces operational and maintenance staff to restrict the ball from closing by inserting an object.

- Impurities can get stuck between the float and the seal, causing the air valve to leak.
- If the drop test is not requested from the manufacturer, the valve might not function at all.

5.3 Maintenance of air valves

It is extremely important to ensure that air valves are functioning properly to fulfill their intended function. The air valve requires a clean operating environment with sufficient ventilation and should not be submerged in water. Typical problems experienced are:

- Leaking at gaskets (filling up the valve chamber)
- Leaking at seal between float and valve body, due to debris and sediment
- Leaking at seal between float and valve body, due to deformed float
- Isolating valve underneath air valve not working (closed valve thus isolating the air valve)

How to check whether or not the air valve is in a working condition:

- If air is released, the small orifice is working
- If there is any air in the accumulator underneath the air valve, it indicates the air valve is not releasing the air. Tappings should be provided on the disc to check the working of the valve. A small ball valve on the tapping can be opened to determine if the air has been released effectively.
- Ensure that the isolating valve is fully open. This should not in any way restrict the flow of air during drainage of the pipeline.
- Check to see if the float of the large orifice can be pushed down. If this is possible the system is not under pressure, because the isolating valve is probably closed or the operating pressure is low. This might lead to leakage.
- If the valve is leaking at the large orifice and there is no debris or sediment entrapped, the line pressure might be insufficient to keep it properly sealed. An option might be to install a bias mechanism.

Regular inspection (bi-annually) of the air valve chambers is required to monitor any changes that could hamper the working of the valve. The important aspects to monitor are:

- Leaks
- Operating status

- Isolating valve's operating status
- External aspects, high water table and ventilation ports on the valve chamber.

5.4 Procedures for testing air valves

5.4.1 Introduction

Air valves are used to de-aerate pipelines and prevent the formation of vacuum zones in pipelines. The release of air from a pipeline is normally associated with either the filling of the line or during operation where air is released from the system while it is operating at high pressures. For a low differential pressure across the air valve (less that about 10 to 15 kPa) the air will be released through the large orifice while the small orifice is used to expel air at system pressures. Physical laws govern the maximum size of the small orifice. In the application of these laws it can be shown that the maximum size of the small orifice is governed by the operating pressure of the system, atmospheric pressure and the gravitational force that works on the float arrangement of the specific valve. Based on the balance of forces it can be shown that the size of the small orifice normally needs to be less than 4 mm in diameter. Different operating conditions barely create opportunities to change this parameter of the air valve and by increasing the potential generation of high dynamic pressures, the initiative to increase the small orifice is reduced.

It is extremely important, however, to accurately size the intake of the air valve, since an undersized vacuum break function will result in the failure of the seals that will be displaced in the couplings and in the possible collapse of the pipe itself under low internal pressure. It is therefore accepted that air valves should be sized for intake, because at any stage, the atmospheric pressure is the available energy to prevent the formation of a vacuum in a pipeline by forcing air into the pipeline through the inlet orifice of the air valve.

This is a critical aspect of pipeline design and hence it is included in this document. In the following paragraph, the procedures for the testing of the release and intake capacity of air valves are reviewed.

5.4.2 Release of air from pipes

It was indicated above that when reference is made to the release of air from a pipeline, a distinction has to be made between the release of air during the filling of the pipeline and the release of air during the normal operation of the system. These two operational conditions are markedly different. **Table 5.1** reflects some characteristics of these two operating conditions with respect to the release of air.

Table 5.1: Operating condition characteristics during the release of air from a pipeline

Operational status	Pressure in the pipe line	Orifice used for the release of air	Availability of the orifice	Air flow phenomena
Filling of the pipeline	10 to15 kPa (Gauge)	Large orifice or the intermediate orifice for the three stage air valves (Vent-O-Mat, 1996)	The large or intermediate orifice can only be available after the internal pressure has dropped to atmospheric pressure	Sub-sonic for the large orifice. In the case of the intermediate orifice, the release can be sonic
Operation of the pipeline	Operating pressures which will normally be much higher than, 100 to 1 000 kPa	Small orifice	The small orifice's contribution to air release is significant only after the large and intermediate orifices have closed. Internal pressure will result in these orifices remaining closed and the small orifice will then function to release the air until a low pressure is created (about atmospheric pressure) to activate the large orifice valves. The small orifice is available for air release only.	The release will in most cases be sonic. Sonic conditions will occur when the pressure in the pipeline is about 1,894 times the atmospheric pressure.

As the internal pressure in a pipeline increases, the shear force of the expelling air will tend to blow shut the large orifice. One of the tests for the air valve therefore focuses on the dynamic closure of the large orifice. High-induced pressures can be created by the closure of the large orifice, which pioneered the approach that it is appropriate for the protection of the pipeline, that the large orifice close at a low differential pressure rather than a high pressure. **This reflects that the value of dynamic shields to prevent dynamic closure of the large orifice creates the possibility of high-induced pressures and should therefore be discarded.**

The functionality of the small orifice should be evaluated by employing the “drop tests”. The drop test is conducted by pressurizing the system, with the valve that has to be tested installed onto the system, to the operational pressure (or pressure class of the valve) and then introducing air into the system. When this is done, the small orifice float should drop and the air should be released through the small orifice.

Since the release through the small orifice will be sonic and because the physical forces and the objective to minimize induced pressures govern the size of the small orifice, the release rate is not important at all.

5.4.3 Testing procedure for the intake capacity of air valves (large orifice function)

During low pressures in the pipeline, the floats will drop and air can then enter the pipeline through the large orifice. The entry of air at a sufficient rate will limit the negative pressure/ vacuum inside the pipeline. Vacuum break valves are sized for intake and the accepted criteria is to limit the differential pressure across the valve to 40 kPa.

The determination of the intake capacity through the large orifice is one of the problems in the quantification of the characteristics of air valves. International standards for the determination of the capacity of air intake of air valves suggest that the outlet should be pressurised (European Standard, 2000). This concept is incorrect, due to the compressibility of air and the results from these tests can at best be used to compare valves, but surely not to determine the intake capacity of the valves.

If the procedure contained in the European Standard document prEN 1074-4 is evaluated and compared to the application of physical laws, the discrepancy can be identified. **Figures 5.9** and **5.10** reflect the differences between the criteria used in prEN 1074-4 and the utilization of physical laws. *Procedure 1* refers to the prEN 1074-4 standard, while *Procedure 2* refers to the calculation of the intake capacity using physical laws. Determining the intake capacity of air valves should be based on the following relationships as reflected in **Figure 5.9**:

Procedure 1: Theoretically Calculated Intake Capacity of Orifice Plate according to mass flow rate

Unchoked conditions (p_a/p < 1.894)

$$m = Cd_i A_i \left\{ 2 p_a \rho_a \left(\frac{k}{k-1} \right) \left[\left(\frac{p}{p_a} \right)^{2/k} - \left(\frac{p}{p_a} \right)^{(k+1)/k} \right] \right\}^{0.5}$$

Choked conditions (p_a/p >= 1.894)

$$m = Cd_i A_i \left\{ k p_a \rho_a \left[\frac{2}{k+1} \right]^{(k+1)/(k-1)} \right\}^{0.5}$$

Where:

Ai = Flow area for intake orifice(m²)
Cdi = Discharge coefficient for the inflow orifice
k = Isentropic constant (ratio of specific heats = 1.4 for air)
m = Mass flow rate (kg/s)
p = Absoulte pressure of air in the valve (Pa)
p_a = Atmospheric pressure (Pa)
ρ_a = Density of the air at atmospheric pressure = 1.204 kg/m³

Input data:

p_a =	101325	Pa	Cdi =	0.50	(A realistic value)
ρ_a =	1.204	kg/m³	Diameter =	100.00	mm
k =	1.4		Area =	0.007854	m²

Procedure 2: Theoretically Calculated Intake Capacity of Orifice Plate according to European Standards (prEN 1074-4)

Unchoked conditions (p/p_a <= 1.894)

$$m = Cd_0 A_0 \left\{ 2 p \rho \left(\frac{k}{k-1} \right) \left[\left(\frac{p_a}{p} \right)^{2/k} - \left(\frac{p_a}{p} \right)^{(k+1)/k} \right] \right\}^{0.5}$$

Choked conditions (p/p_a > 1.894)

$$m = Cd_0 A_0 \left\{ k p \rho \left[\frac{2}{k+1} \right]^{(k+1)/(k-1)} \right\}^{0.5} \qquad \frac{p_a}{p} = \left(\frac{\rho_a}{\rho} \right)^k$$

Where:

A0 = Flow area for outflow orifice(m²)
Cd0 = Discharge coefficient for the outflow orifice
k = Isentropic constant (ratio of specific heats = 1.4 for air)
m = Mass flow rate (kg/s)
p = Absoulte pressure of air in the valve (Pa)
p_a = Atmospheric pressure (Pa)
ρ = Density of the air in air valve under line head conditions (kg/m³)

Input data:

p_a =	101325	Pa	Cd0 =	0.50	(A realistic value)
ρ_a =	1.204	kg/m³	Diameter =	100.00	mm
k =	1.4		Area =	0.007854	m²

		INTAKE CAPACITY : PROCEDURE 1			INTAKE CAPACITY : PROCEDURE 2			
Differential pressure (Bar)	**Differential pressure (Pa)**	**Absolute pressure (Pa)**	**Condition**	**Intake rate (nl/s)**	**Absolute pressure (Pa)**	**Density (kg/m³)**	**Condition**	**Intake rate (nl/s)**
		101325	Unchoked		101325	1.204	Unchoked	
0.05	5000	96325	Unchoked	348.30	106325	1.246	Unchoked	354.8
0.10	10000	91325	Unchoked	478.63	111325	1.288	Unchoked	497.6
0.15	15000	86325	Unchoked	568.62	116325	1.329	Unchoked	604.6
0.20	20000	81325	Unchoked	635.65	121325	1.369	Unchoked	692.7
0.25	25000	76325	Unchoked	686.51	126325	1.409	Unchoked	768.6
0.30	30000	71325	Unchoked	724.63	131325	1.449	Unchoked	835.9
0.35	35000	66325	Unchoked	751.99	136325	1.488	Unchoked	896.5
0.40	40000	61325	Unchoked	769.79	141325	1.527	Unchoked	951.9
0.45	45000	56325	Unchoked	778.75	146325	1.565	Unchoked	1002.9
0.50	50000	51325	Choked	780.06	151325	1.603	Unchoked	1050.3
0.55	55000	46325	Choked	780.06	156325	1.641	Unchoked	1094.6
0.60	60000	41325	Choked	780.06	161325	1.678	Unchoked	1136.3
0.65	65000	36325	Choked	780.06	166325	1.715	Unchoked	1175.6
0.70	70000	31325	Choked	780.06	171325	1.752	Unchoked	1212.8
0.75	75000	26325	Choked	780.06	176325	1.788	Unchoked	1248.2
0.80	80000	21325	Choked	780.06	181325	1.825	Unchoked	1281.9
0.85	85000	16325	Choked	780.06	186325	1.860	Unchoked	1314.2
0.90	90000	11325	Choked	780.06	191325	1.896	Unchoked	1345.1
0.95	95000	6325	Choked	780.06	196325	1.931	Choked	1374.7
1.00	100000	1325	Choked	780.06	201325	1.966	Choked	1403.2

Figure 5.9: Intake capacity calculations

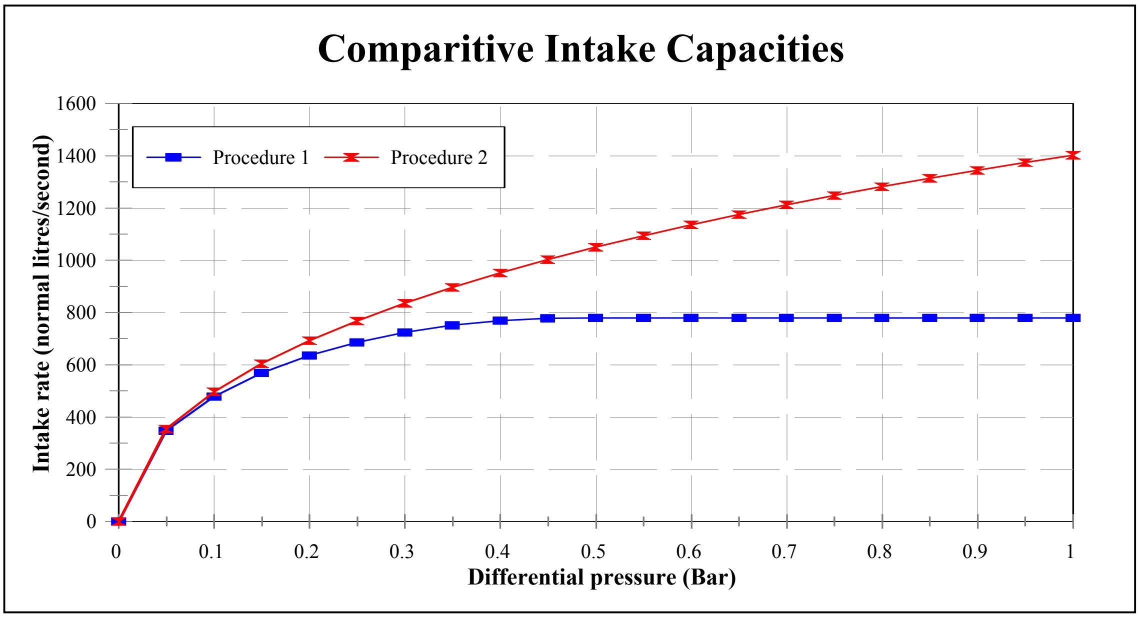


Figure 5.10: Comparative intake capacities

5.4.4 Conclusion

From the above, it is apparent that the European Standard method of testing air valve intake capacities is incorrect. When selecting an air valve, the intake rates supplied by the air valve manufacturer should be checked, to ensure that it has been determined with the correct procedure. It is proposed that the intake capacities of air valves be checked, by applying Equation 5.1 and 5.2. As a guideline, the intake values in **Table 5.2** below can be used. These intake values were calculated using a discharge coefficient of 0,5 and typical inlet diameters.

Table 5.2: Typical intake values for air valves

Air valve diameter (mm)	Differential pressure (bar)	Intake capacity (nm^3/h)
25	0,35	169
50	0,35	677
80	0,35	1 733
100	0,35	2 707
150	0,35	6 019
200	0,35	10 829

Choked conditions ($p_a/p < 1,894$) [Intake]

$$\dot{m} = Cd_i A_i \left\{ 2 p_a \rho_a \left(\frac{k}{k-1} \right) \left[\left(\frac{p}{p_a} \right)^{2/k} - \left(\frac{p}{p_a} \right)^{(k+1)/k} \right] \right\}^{0,5} \quad \text{.................................(5.1)}$$

Unchoked conditions ($p_a/p \geq 1,894$) [Intake]

$$\dot{m} = Cd_i A_i \left\{ k p_a \rho_a \left[\frac{2}{k+1} \right]^{(k+1)/(k-1))} \right\}^{0,5} \quad \text{...(5.2)}$$

Where:

A_i	=	Flow area for intake orifice (m²)
Cd_i	=	Discharge coefficient for the inflow orifice (0,5 to 0,6)
k	=	Isentropic constant (ratio of specific heats = 1,4 for air)
$\dot{m}$	=	Mass flow rate (kg/s)
ρ_a	=	Density of air at atmospheric pressure (1,04 kg/m³)
p	=	Absolute pressure of air in the valve (Pa)
p_a	=	Atmospheric pressure (Pa)

By applying these formulae, the intake capacities for air valves can be determined. Similar equations can be used for calculating the discharge capacities of air valves. In this case, the inside of the air valve is pressurized exhausting air to atmospheric pressure on the outside. It must, however, be remembered that at a certain stage the system will become sonic and will blow the float shut against the seat.

Choked conditions ($p/p_a \leq 1,894$) [Release]

$$\dot{m} = Cd_0 A_0 \left\{ 2 p \rho_v \left(\frac{k}{k-1} \right) \left[\left(\frac{p_a}{p} \right)^{2/k} - \left(\frac{p_a}{p} \right)^{(k+1)/k} \right] \right\}^{0,5} \quad \text{...(5.3)}$$

Unchoked conditions ($p/p_a > 1,894$) [Release]

$$\dot{m} = Cd_0 A_0 \left\{ k p \rho_v \left[\frac{2}{k+1} \right]^{(k+1)/(k-1))} \right\}^{0,5} \quad \text{and} \quad \frac{p_a}{p} = \left(\frac{\rho_a}{\rho_v} \right)^k \quad \text{.................................(5.4)}$$

Where:

A_0	=	Flow area for outflow orifice (m²)
Cd_0	=	Discharge coefficient for the outflow orifice (0,5 to 0,6)
k	=	Isentropic constant (ratio of specific heats = 1,4 for air)
$\dot{m}$	=	Mass flow rate (kg/s)

ρ_v = Density of air in the air valve under line head conditions (kg/m^3)

p = Absolute pressure of air in the valve (Pa)

p_a = Atmospheric pressure (Pa)

6. IMPLEMENTATION OF A NEW PIPELINE

6.1 Filling of a pipeline

The velocity through the air valve is limited to ± 30 m/s according to Wisner (1982b). It must be remembered that specifying a maximum filling velocity of say 0,5 m/s for a 300 mm pipeline will result in a discharge velocity of 18 m/s through a 50 mm air valve. Using the same filling velocity for a 400 mm pipeline will, however, result in a flow velocity of 32 m/s through the same air valve. To prescribe a specific flow rate or velocity is difficult since the filling of a pipeline is determined by:

- The pipeline profile (topography);
- Positions from where the pipeline is filled;
- Characteristics of the air valves; and
- Air valve closing sequence.

If air valves are oversized this could lead to unwanted surges when these valves suddenly close when all the air has been expelled. Even if these valves have the anti-shock function, over sizing will result in the air valve not switching to the intermediate orifice.

Since no general prescribed fill rate for pipelines can be defined, the selection of the required air valve size for filling the line should be based on analysing various filling scenarios and identifying the requirement to capture and release at each air valve node (see Section 7).

The designer should also be aware of possible unsteady flow with associated pressure fluctuations, which might occur. Filling at a “safe filling rate” of say 35 l/s for the 300 mm diameter pipeline, as shown in **Figure 6.1** at first seems to be conservative. The topographic profile, however, could result in an unstable situation where an air pocket is trapped leading to a sudden increase in flow rate for which the air valves were not designed which might result in blow-shut and associated high-induced pressures. The operator of the pipeline should also be cautious of increasing the filling rate when it seems as if there is a decrease, which in fact may only be a large air pocket, which is trapped.

The valid suggestion remains “***The slower a pipeline can be filled the better***”.

The conservative approach to fill the line as slow as possible can however be impractical and it should be compared with other options to allow water to be flushed through the system, ensuring the transfer of momentum to localised air pockets that can be released at selected positions along the line. Filling is a site-specific problem and should be handled as such

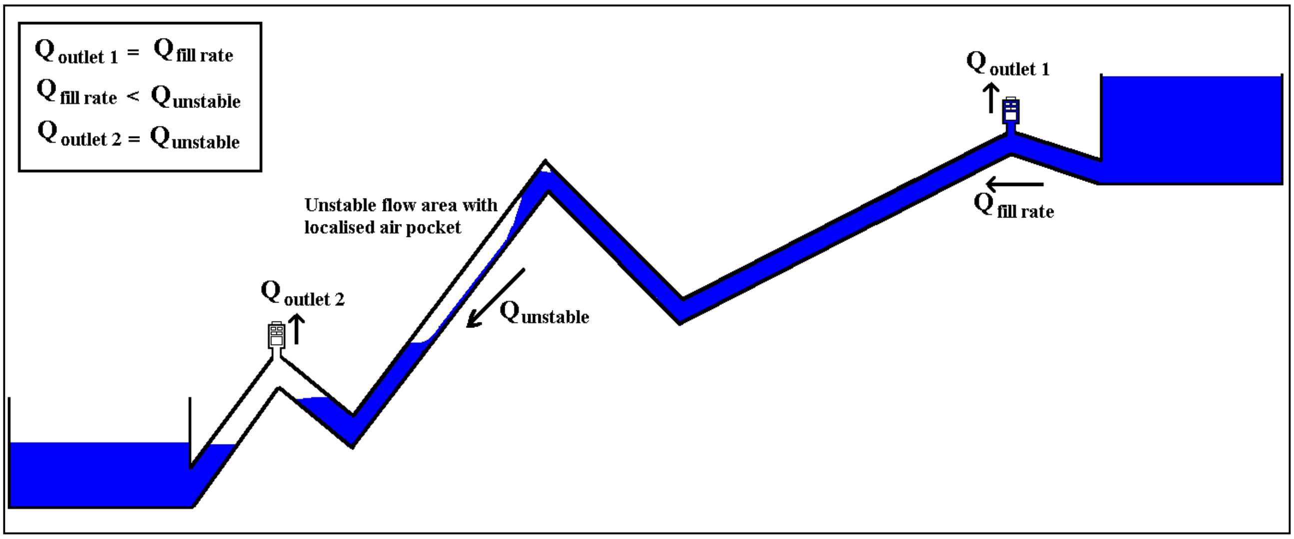


Figure 6.1: Unstable flow scenario during the filling of the pipeline

6.2 Hydrostatic testing of pipelines

The test section should be filled with water and care should be taken to ensure that all the air has been removed from the pipeline. Experience indicates that the presence of air in the pipeline can result in surge pressures when the air is expelled from a pressurized section in an uncontrolled manner. The time spent to ensure de-aeration of the test section would in the end reduce the costly delays.

6.2.1 Purpose of hydrostatic testing

After construction of a pipeline and prior to the backfill of the pipeline, it is essential that the pipeline be tested to ensure that the pipe material has maintained its integrity and that the installation was conducted in such a manner that the system will not leak excessively. This test is referred to as the hydrostatic test. The hydrostatic tests will show up any latent problems that might have resulted from the handling of the pipe or any construction defect, especially at the joints. Improper bedding and backfilling of the pipe normally shows up later, and this test does not signify total acceptance of the whole installation.

6.2.2 Selection of test sections

In undulating terrain and steep long gradients in pipeline profile, the selection of sections to be hydrostatically tested is influenced by the profile. If the test section has been arbitrary selected it can happen that it will be impossible to pressurize the higher-lying sections to the desired pressure while the lower elevated sections might be over-pressurized.

Hydrostatic testing of pipelines is a major operation and if it is not planned accurately, it can be costly.

Small leaks are difficult to detect and temperature changes can appear as a leak. Furthermore, with large volumes of air in the test section, it is extremely difficult to increase the pressure in the line with a hand pump.

If the temperature does vary during the testing, it should be taken into account. The following relationship can be used to determine the change in pressure due to a change in temperature (normally a drop in temperature). Distinction is made between a restrained (not allowing expansion) and an unrestrained pipe (Kenneth K Kienow).

Restrained pipes

$$D_P = [B - 2e(1+\mu)]\left\{\frac{K}{\left(1+\frac{DK}{Et}\right)(1-\mu^2)}\right\}\Delta T \ldots\ldots (6.1)$$

Unrestrained pipes

$$D_P = (B - 3e)\left\{\frac{K}{\left(1+\frac{DK}{Et}\right)(1{,}25-\mu)}\right\}\Delta T \ldots\ldots (6.2)$$

Where:

B	=	Coefficient of volume thermal expansion of liquid (dV/Vdt, /°C (2,10E-04))
e	=	Coefficient of volume thermal expansion of pipe wall material (dL/Ldt, /°C)
μ	=	Poisson's ratio
K	=	Bulk Modulus of liquid (dP/(dV/V), MPa (2.07E+09))
E	=	Modulus of Elasticity of pipe wall (MPa)
D	=	Inside diameter (mm)

t	=	Wall thickness (mm)
ΔT	=	Change in temperature (°C)

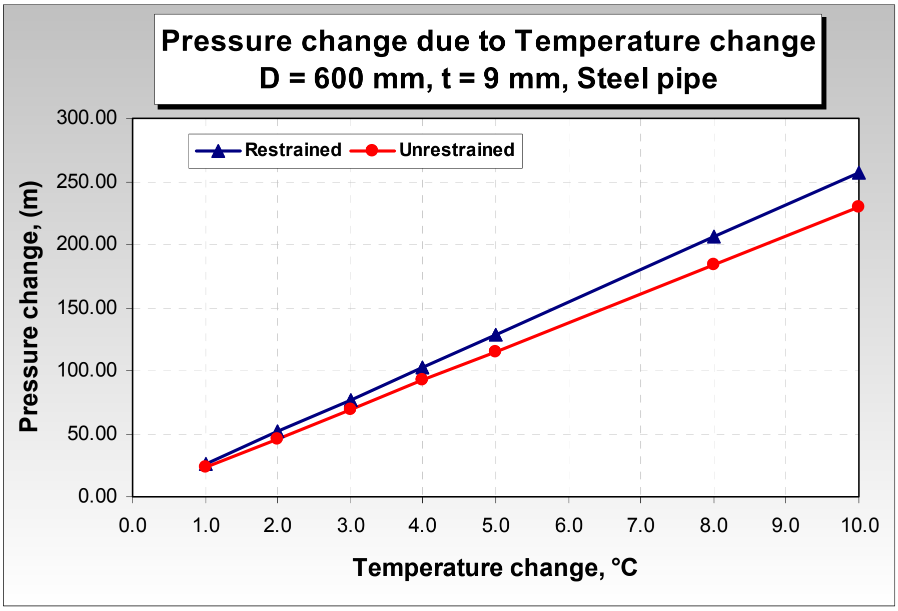


Figure 6.2: Pressure change due to temperature change

6.2.3 Specifications for hydrostatic pressure testing

Different specifications apply to different fluids transported and pipe materials used. In this document, focus is on the conveyance of water and the criteria associated with water mains.

Manufacturers normally define the maximum working pressure in terms of a percentage of the yield strength of the material. A norm is to set the maximum operating pressure equivalent to between 50 and 75 % (and sometimes lower) of the yield stress of the pipe material. For different pipe materials the pressure class rating of the pipe, is related to the maximum operating pressure.

Depending on the setting of the maximum operating pressure with respect to the yield strength of the material, the hydrostatic pressure in the pipeline is defined. The hydrostatic pressure is normally set at 1,25 the maximum operating pressure and restricted to less than 1,5 times the maximum operating pressure.

According to SABS 1200 L (7.3.2.1), the test pressure should be applied for 3 hours or such time as is required for inspection of the pipeline. Provision is made to reduce the time for a pipe with a diameter less than 400 mm.

The reduction in the time is proportional to the diameter with the assumption that the test needs to be conducted for 3 hours on a 400 mm diameter pipeline. However, the minimum time for which the test section should be pressurized is 1 hour.

During the hydrostatic pressure tests, the damaged pipes might rupture or leak and the joints, thrust blocks and specials will reflect the installation shortcomings. The permissible leakage is dependent on the type of installation. For jointed pipes in steel, cast iron, ductile iron and all the thermoplastic materials, the following relationship is proposed to define the permissible leakage volume for the prescribed test period.

$$Vol_L = 0{,}01\, D\, L \sqrt{P} \quad \ldots\ldots (6.3)$$

Where:

Vol_L	=	Permissible leakage (litres)
D	=	Inside diameter (m)
L	=	Length of pipe (m)
P	=	Pressure (MPa)

In the case where different sections of the test section are at different pressures, Equation 6.3 can be extended to be able to calculate the permissible leakage:

$$Vol_L = 0{,}01\, D \sum \left(L_i \sqrt{P_i} \right) \ldots\ldots (6.4)$$

Where:

"i" refers to the different pipe sections and pressures for these sections.

In the case where the diameter changes as well the equation can be changed to:

$$Vol_L = 0{,}01 \sum \left(D_i\, L_i \sqrt{P_i} \right) \ldots\ldots (6.5)$$

6.2.4 Practical aspects related to hydrostatic pressures

The major problem with hydrostatic pressure tests can be related to insufficient planning, defect testing equipment, lack of water for the test, and insufficient documentation of the tests. **Table 6.1** reflects a pro-forma data sheet that can be used for the documentation of the hydrostatic pressure test.

Table 6.1: Pro-forma data sheet for the hydrostatic pressure test

Hydrostatic pressure test (Water)		Test reference number: ……………	
Project:		Pipeline:	
Pipe Test section	From:…………(km)	To: …………(km)	Date: ……
Length of section, L	………………(m)	Diameter of section, D	………(m)
Pipe classes:		Max working pressure, (m)	
Hydrostatic test pressure, P (MPa)			
Allowable leakage, $Vol_L = 0,01*L*D*(P)^{0.5}$		= …………………	
Date when pipe was filled: ……………………..		Pipe filled from chainage: …………….	

Isolation of the test section	Upstream	Down stream	De-aeration of the pipeline	Yes	No
End cap			Air valves Installed		
Isolating valve			Air valves Operational		
Other			Other		

Pipeline installation (Tick the box)			
Pipeline uncovered		Pipeline covered up to blanket fill	
Pipeline covered with joints open		Pipeline completely backfilled	

Source for test pressure: ……………………...		**Gauging of pressure**: …………………
Location		Location
Pump ID		Gauge description
Hand pump ID		Date of calibration
Has this pipeline been tested before?		Units of measurement

Yes	No	When	Test Reference ………………..	Failure recorded	Burst
					Leaks

Test sequence	Time	Pressure (units)	Temperature °C	**Remarks:**
Start of test				
End of test				

Time sequence of events during the testing					
Time	Pressure (m)	Temperature (°C)	Time	Pressure (m)	Temperature (°C)

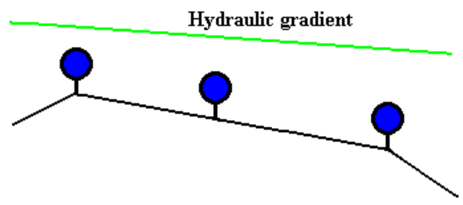
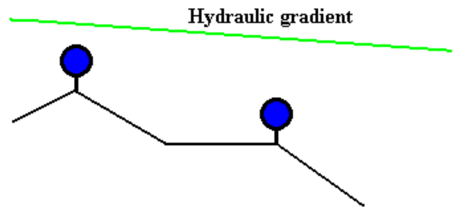
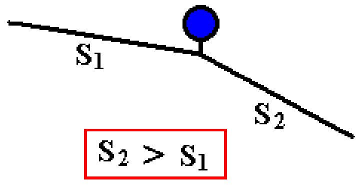
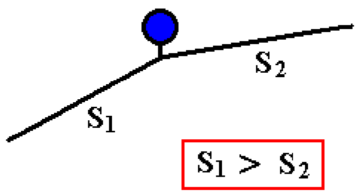
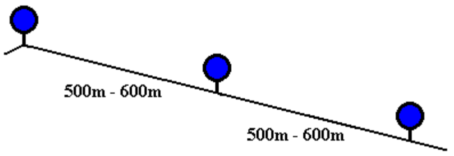
Consultants representative			Contractors
Signed:			Signed:
Date:			Date:
Failure report Reference			Planned actions for further tests:
Test Accepted	Yes	No	

7. SIZING AND POSITIONING OF AIR VALVES

7.1 Historical approach of air valve sizing and positioning

In the past air valve sizing and positioning was based on a few set guidelines. These guidelines as described in Stephenson (1981) and Marcus (1998), are listed below (mainly focussed on each individual node at a time) see **Table 7.1**.

Table 7.1: Typical air valve sizing and positioning guideline (historical approach)

Sections of pipeline which run parallel to the hydraulic gradient	
Section of pipeline which forms a peak	
Section of pipeline which changes from a negative slope to a larger negative slope	
Section of pipeline which changes from a positive slope to a less positive slope	
Long descending or ascending sections	

7.2 Air valve sizing and positioning procedure (ASAP)

In this section the proposed procedure for air valve sizing and positioning will be described. The pipeline will be analysed as a whole and not as individual isolated sections. The basic sizing for the large orifice air valves is based on drainage (burst and scouring) and filling, while the small orifice valves are designed to release air during operating conditions. A step-by-step worked example is provided in Section 7.3 of this document, to demonstrate this proposed procedure. The procedures, with some modifications were also used in the development of computer software for modelling the correct sizing and positioning of air valves (Section 7.4).

The procedure is referred to ASAP, acronym for **A**ir valve **S**izing **a**nd **P**ositioning Procedure, and is described in the paragraphs below. The basic methodology used in the sizing, selection and positioning of air valves is summarised below:

Objectives of the ASAP procedure

The main objective of the ASAP procedure is:
To determine the size and the position of the air valves in order to

- prevent excessive vacuum conditions in the pipeline during draining of the line;
- provide sufficient discharge capacity during filling; and to
- enable effective release of air under operating pressures.

In order to meet these objectives, certain input data is required in the procedure and several calculations need to be performed.

Input data requirements for the ASAP procedure

Flow characteristics, pipe characteristics, longitudinal profile of the pipeline and other relevant information such as the allowable maximum negative pressure and the pipe rupture size.

Calculations performed in the ASAP procedure

The ASAP procedure firstly evaluates the intake requirements for the pipeline under draining and burst conditions. The following steps are followed:

- The positions and type of all valves (i.e. isolating-, drainage- and non-return valves) are determined that will be used to control the filling and draining of the pipeline or isolation of sections thereof. Positions along the pipeline where water will be abstracted are also defined.

- The burst analysis is based on the principle that the potential flow rate in all the sections can be determined by utilising the continuity of energy. Using the Darcy Weisbach relationship (or something similar) the potential flow is calculated for each pipe section and assuming the rupture size of the burst (percentage of pipe diameter) the potential flow is reduced linearly with the ratio of the burst area and the pipe area. The required intake capacity of the air valve should be able to handle this flow rate.
- In the draining analyses, the potential maximum flow rate at which a section can be drained/scoured is calculated and subsequently the required intake capacity of the air valve is determined.
- The required intake capacities for the burst and drain analysis, for all the apex points and other points where slope changes require an air valve, are combined for the final determination of the required air valves.

Secondly the required discharge capacity of the air valves is evaluated for the filling of the pipe. The procedure entails the following steps:

- Identifying all possible sections that can be isolated and the possible ways how these sections can be filled.
- Determining the maximum discharge rates through the air valve to safely fill the pipeline.

Next, the position of the air valves to release air under operating conditions need to be determined. Apex points are the most appropriate positions to accumulate air and to release it during operation. The positions for the small orifice air valves are then determined by:

- Determining the ability of the fluid to transport the air hydraulically, using the newly developed transportability relationship as described in Section 4 (Equation 4.3).
- If the air cannot be transported an air release valve will be positioned at the said node.
- The designer's preference for the spacing between air release valves is accommodated in the analysis of the different analyses.

The last step is to combine the results and to determine the correct air valve (type and size) to be installed, by comparing the calculated intake and discharge capacities with that of the air valve manufacturer's values and then to select a suitable valve.

Typical results from the ASAP procedure

A profile plot, as well as a table with all the results indicating the required valves along the pipeline (pressure class, size, type and position), is provided.

Figure 7.1 reflects a flow diagram of the proposed ASAP procedure.

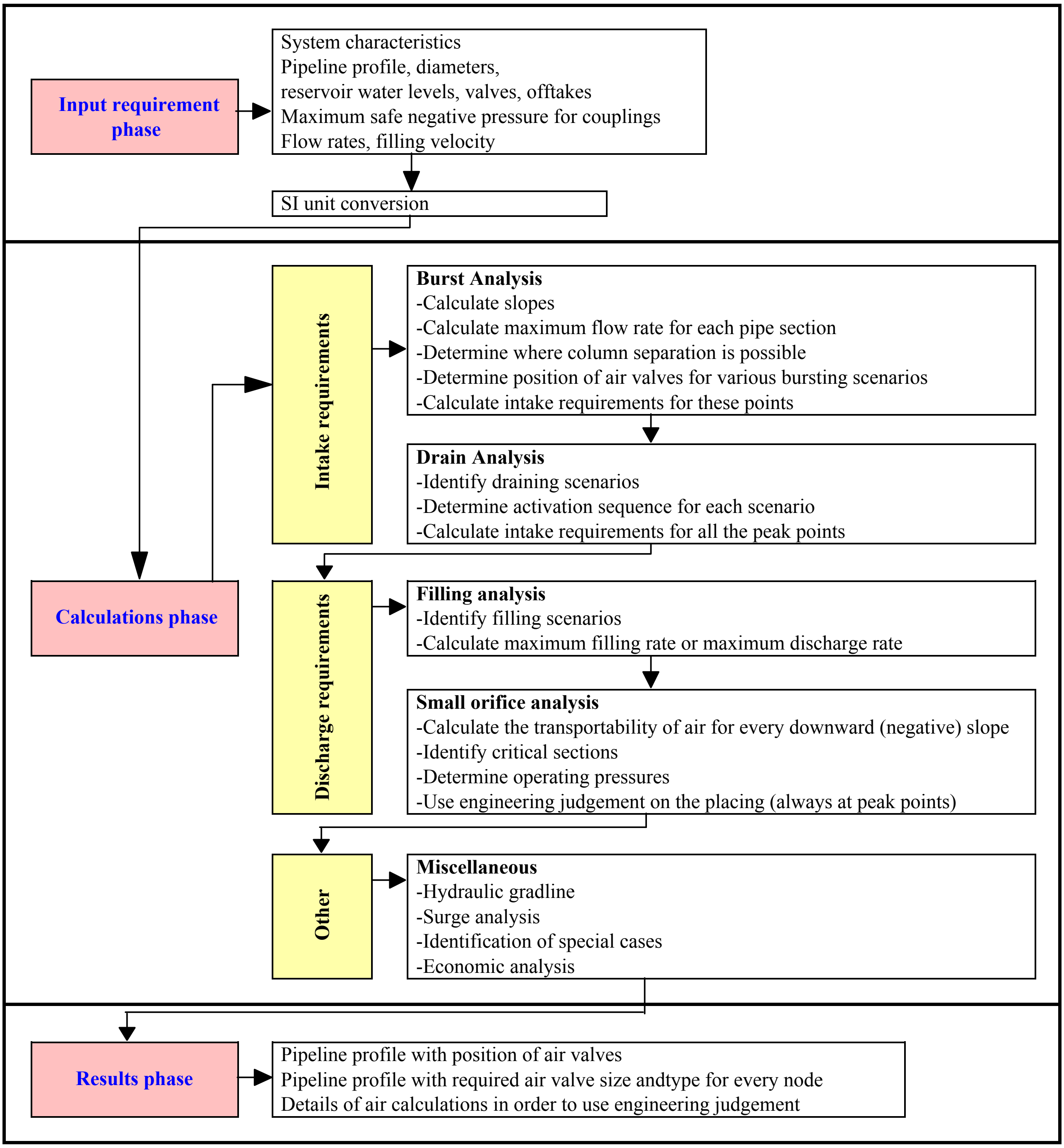


Figure 7.1: Flow diagram of the ASAP procedure

7.2.1 ASAP input requirements

As indicated in the ASAP procedure flow diagram (**Figure 7.1**), the first step in determining the air valve requirements for a pipeline is to obtain the system characteristics shown in **Figure 7.2** and listed in **Table 7.2**.

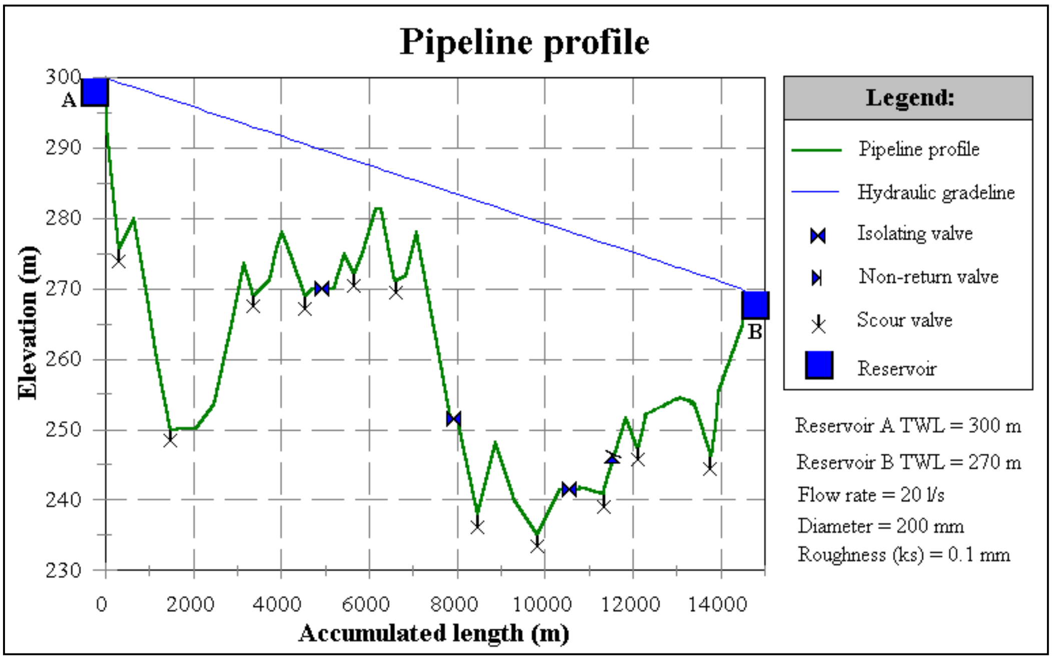


Figure 7.2: Pipeline profile

Table 7.2: Typical ASAP input requirements

Type	Information
Pipeline profile	Elevation, pipe segment lengths
Pipe details	Diameters, roughness, pipe type, allowable negative pressure
Valves, off-takes and connections	Positions of isolating-, scour- and non-return valves, off-takes or supply connections on the pipeline.
Flow characteristics	Operating flow rate.
Boundary controls	Pump station and reservoir water levels,
Optional data for the economic analysis	Discount rates, inflation rate and labour -, mechanical -, and electricity escalation. Analysis period, future demand and unit tariff of the water

The allowable negative pressure that the pipe can withstand must be obtained from the pipe manufacturer and is used as the maximum differential pressure over the air valve for intake conditions. The maximum differential pressure is the maximum safe sub-atmospheric pressure that the pipe can withstand before collapsing, or before the seal is displaced in the coupling. It must be emphasised that this pressure might be limited not necessary by the pipe strength, but also by the joint seals, which can be damaged or displaced when, the internal pressure is negative. The objective under intake conditions is to maintain subsonic flow conditions and to prevent the float from blowing shut.

External forces on the pipeline and the construction/installation conditions of the pipe also influence the maximum allowable negative pressure. High water tables and excessive negative pressures can also result in intrusion of contaminated water into the pipeline.

7.2.2 ASAP calculations

The pipeline is taken as a whole to ensure that the air valve system of the pipeline performs adequately. Each pipeline node is split into an upstream and a downstream node for calculation identification. The evaluation for burst, drain, filling and air release under operating conditions is then executed and the air intake and discharge requirements for the upstream (US) and downstream (DS) sides of each node determined. Either the drain or the burst requirements will define the required intake capacity of the air valves.

Calculating each node's upstream and downstream requirements allows the design engineer to make informed engineering decisions about the correct air valve size and its exact position. Should the results indicate extremely large air intake requirements at a node, consideration should be given to reduce the outlet size of the scour/draining valves.

In the ASAP procedure the operation of the system is visualized for all possible flow scenarios. The importance of analysing the pipeline as a whole will be reflected in the sample problem, which was set-up in SI units although other units are also accommodated in the procedure.

7.2.2.1 Burst analysis (uncontrolled flow release from the pipeline)

When a pipe burst occurs, water flows from the pipe. To prevent the pipe from collapsing due to the development of sub-atmospheric pressures, air should be allowed to enter the pipe at such a rate as to prevent extreme low pressures that might displace the seals or lead to pipe failures.

The factors, which will influence the outflow rate at the burst or fracture, are the effective size of the rupture, available energy, installation conditions (above ground or below ground) and the friction loss in the pipe. Since it is impossible to predict where a pipe fracture will occur, all low lying positions should be investigated. The steps that should be followed to determine the intake capacities for rupture along a pipeline, require:

- o Calculation of pipe slopes (This will be the maximum hydraulic gradeline for each pipe section and hence the maximum flow rate, i.e. $S_0 = S_f$ or pipe slope = friction slope)
- o Calculate the maximum flow rate in each pipe section due to burst on that pipe section based on Equation 7.1 (Modified Darcy-Weisbach equation) which incorporates a reduction factor $A_{rupture}/A$.

$$Q_{burst} = \sqrt{\frac{g\pi^2 D^5 S_0}{8\lambda}} \frac{A_{rupture}}{A} \qquad (7.1)$$

Where:

Q_{burst}	=	Flow rate due to burst (m^3/s)
g	=	gravitational acceleration (m/s^2)
D	=	Inside diameter of pipe (m)
S_0	=	Slope of pipe (m/m)
λ	=	Friction factor
$A_{rupture}$	=	Area of the rupture (m^2) (See **Table 7.3** reflects typical default rupture sizes which can be used in the analysis). The standard Darcy-Weisbach equation has been modified by adding this outlet coefficient to the equation. This factor represents the influence of the layout of the system and the time dependence of the outflow (the hole develops with time), which is complex to define and hence it is suggested that a sensitivity analysis should be conducted on this factor.
A	=	Area of the pipe (m^2)

The friction factor can be calculated with the Karman Prandtl equation for rough turbulent flow conditions (Equation 7.2), or some similar equation:

$$\lambda = \left(\frac{1}{2\log\left(\frac{3{,}7D}{k_s}\right)} \right)^2 \quad \text{.......} \quad (7.2)$$

Where:

λ = Friction factor

D = Inside diameter of pipe (m)

k_s = Absolute roughness of pipe (m)

Table 7.3: Rupture size as a percentage of pipe diameter (suggested default values that should be checked by conducting a sensitivity analysis)

Pipe type	Rupture size (percentage of pipe diameter) Below ground installation	Rupture size (percentage of pipe diameter) Above ground installation
Cast / ductile iron	15%	50%
Corroded steel	15%	50%
Fibre cement	40%	50%
HDPE	15%	50%
GRP	20%	50%
LDPE	15%	50%
New-, Medium- steel	15%	50%
uPVC, mPVC	15%	50%

o For the various bursting possibilities the required intake capacities required along the pipeline are determined. **Figure 7.3** below is an example of a section of pipeline where the maximum flow rate in each pipe section (***A*** to ***D***) due to burst was calculated.

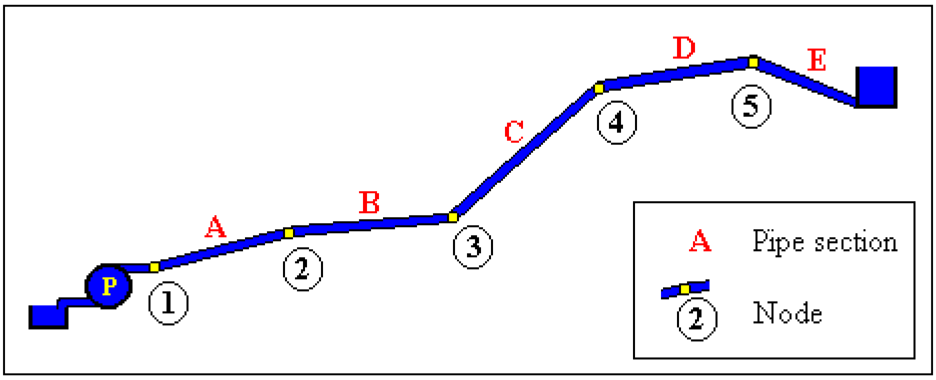


Figure 7.3: Bursting (example pipe section)

- Start at node 1, the upstream node and proceed downstream.
- If a pipe break occurs on pipe section ***A,*** the following will take place:
  - The maximum flow rate at which pipe section ***A*** will drain is X m³/s. Water from section ***B*** will flow into section ***A*** at a maximum rate of Y m³/s.
  - The flow rate required to prevent a cavity from forming at node ***2,*** i.e. to prevent column separation is calculated by limiting the change in kinetic energy to 0,5 m. With Equation 7.3 this change in energy can be calculated.

$$\frac{V_2^2 - V_1^2}{2g} \leq 0{,}5 \qquad (7.3)$$

Where:

V_2 = velocity in steep section, Section **A** (m/s)

V_1 = velocity in less steep section, Section **B** (m/s)

g = gravitational acceleration (m/s²)

  - In this case pipe section ***B*** will be able to supply sufficient water to section ***A*** to prevent column separation at node ***2***.

- Moving further downstream along to node ***3***, where the pipeline changes from a positive slope to an even larger positive slope no intake point is required. The steeper slope (section ***C***) will always be able to supply water at a greater flow rate to pipe section ***B,*** since the maximum flow rate is based on the slope of the pipe. This is the only case when all the other pipe characteristics as used in Equation 7.1 remain the same (pipe diameter and roughness).
- At node ***4,*** the pipeline changes from a positive slope to a less positive slope similar to the change at node ***2***. At this point, however, the change is great enough for column separation to occur (change in kinetic energy is greater than 0,5). Equation 7.3 is used again and the air intake requirement is determined to prevent a cavity from forming i.e. the rate at which pipe section ***C*** will drain minus the flow rate that can be supplied via section ***D***.

Figure 7.4 reflects the importance of reviewing the whole pipeline when the positioning of air valves is evaluated.

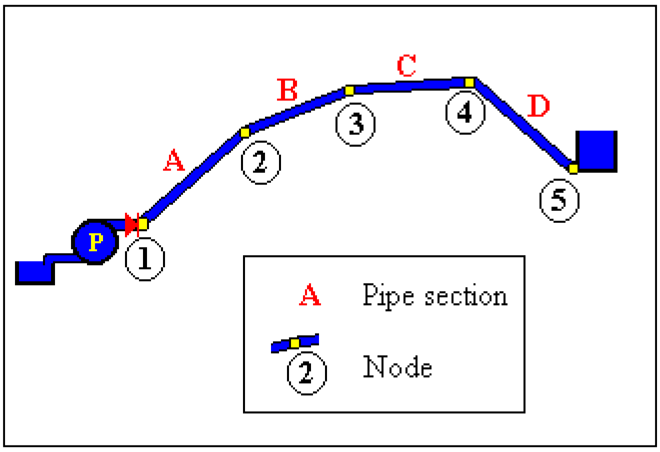


Figure 7.4: Illustrating the value of looking at a pipeline as a whole (Example)

When a pipe burst occurs on section ***A*** the change in slope at node ***2*** will not result in column separation. The change in slope at node ***3*** will also not result in column separation. The accumulated change in energy will however result in a cavity forming at node ***3,*** since it can not supply sufficient flow for the steeper slope of section ***A***. If only one node at a time was analysed, this intake requirement would not have been anticipated and subsequently would not have been designed for.

7.2.2.2 Drain analysis (controlled air release)

In the controlled drainage analysis the following procedure is followed.

- o Identify possible drainage scenarios that result from isolating different sections and opening various scour valves. The example in **Figure 7.5** has four possible draining scenarios, which are reflected in **Table 7.4**.

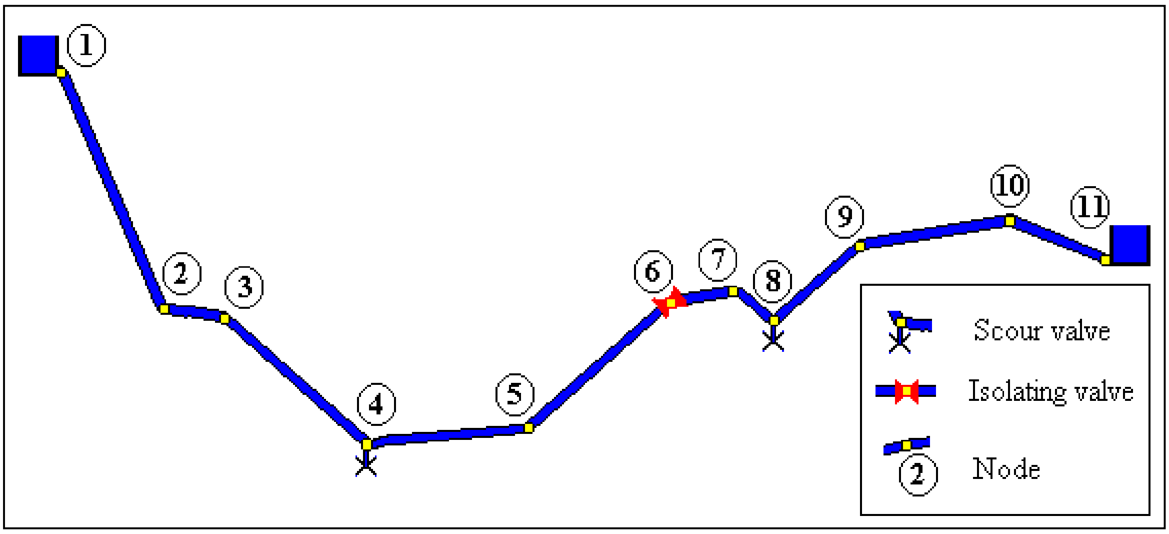


Figure 7.5: Drainage (example)

Table 7.4: Possible drainage scenarios

Scenario	Drainage point	Upstream control point	Downstream control point
1	Node 4	Node 1 (Reservoir)	Node 11 (Reservoir)
2	Node 8	Node 1 (Reservoir)	Node 11 (Reservoir)
3	Node 4	Node 1 (Reservoir)	Node 6 (Isolating valve)
4	Node 8	Node 6 (Isolating valve)	Node 11 (Reservoir)

- For each of the drainage scenarios, the sequence in which the air valves will start to function should be determined. Using the pipeline illustrated in **Figure 7.5** and drainage scenario 1, the following air valve activation sequence can be determined. The first node that will be activated is node 1, then node ***10***, and the last node to be activated is node *7*. The sequence is obtained by visualizing a horizontal line that represents the available energy moving down as the water drains. This peak in the controlled drainage section, will first be activated.
- The initial outlet (scour valve) at the drainage point is assumed to function as an orifice. The maximum discharge rate is calculated utilizing the available head for the various drainage scenarios by using Equation 7.4.

$$Q_{drain} = C_D \sqrt{2g\Delta h}\left(\frac{\pi D_{outlet}^2}{4}\right) \quad (7.4)$$

Where:

Q_{drain} = Flow rate due to controlled drainage (m^3/s)

C_D = Discharge coefficient for an orifice (0.6)

g = Gravitational acceleration (m/s^2)

Δh = Available energy between peak and drainage point (m)

D_{outlet} = Inside diameter of outlet pipe (m)

- The intake requirement at each peak in this drainage scenario can now be calculated. This is repeated for every possible drainage scenario identified. The activation sequence is very important since a valve that is activated first on a specific side of the drainage point (upstream or downstream) will be required to supply the total out flow rate. If a peak on the other side is activated next, the drainage flow rate is halved for this air valve for the available energy, since air can now be supplied from both sides of the drainage point. This is only true when the pipe slopes at both sides of the drainage valve are the same, i.e. drop in water level will cause the same volume change in both sections.

- o Comparing the various scenarios and obtaining the maximum intake capacity required at each of the apex points, determines the maximum intake requirement for every peak.

The selection of the valves is made on the above analyses and is then used to evaluate the filling of the pipeline. It has to be emphasised that the procedure does not include the requirements for air intake that is associated with transient conditions.

7.2.2.3 Filling analysis

During the filling of a pipeline, the air must be released in such a way that pressure surges do not occur.

Similar to the drainage analysis, all possible filling scenarios must be identified. Pipelines can be filled from any side or even from two sources at the same time. It can be filled via a bypass valve, by cracking an in-line valve, or through the flow supplied by the pumps (in a pumping system). Numerous researchers/designers have reflected the importance to *"fill the pipeline slowly"*. The question now is ***"what is slowly?"***

According to Wisner (1982b) the filling rate of pipelines is usually limited to between 5 and 15% of the design discharge. Various problems arise when a pipeline is filled and air is allowed to be exhausted in an uncontrolled manner. Wisner (1982) also specified a flow velocity of 30 m/s through the air valve as a limiting factor. If the surge pressures that might be caused by the filling of the pipeline are used as the limiting criteria, the fill rate of a pipeline can be set equal to the discharge rate of the air valve. The discharge rate of the air valve can be derived as follows (Equation 7.5):

$$Q_{discharge} = A_o C_o \left(\frac{2\Delta P}{\rho_a} \right)^{0.5} \quad \text{..........} \quad (7.5)$$

Where:

$Q_{discharge}$	=	Discharge through air valve (m^3/s)
A_o	=	Orifice area of the air valve (m^2)
C_o	=	Discharge coefficient (assumed to be 0,6)
ΔP	=	Pressure differential across the air valve (kPa)
ρ_a	=	Air density (1,2 kg/m^3)

It is suggested that the maximum pressure differential across the valve should be limited to 0,5 m (5 kPa). This limitation is to prevent blow-shut and high-induced pressure spikes due to a rapid closing of the large orifice at high velocities.

It is important to visualize the filling process. Some topographic characteristics of the pipeline may limit the filling velocity creating for instance a siphon. The filling analysis procedure is as follows:

- o Identify all possible filling scenarios for the sections that can be isolated. The pipeline example in **Figure 7.6**, has five possible filling scenarios, see **Table 7.5**.

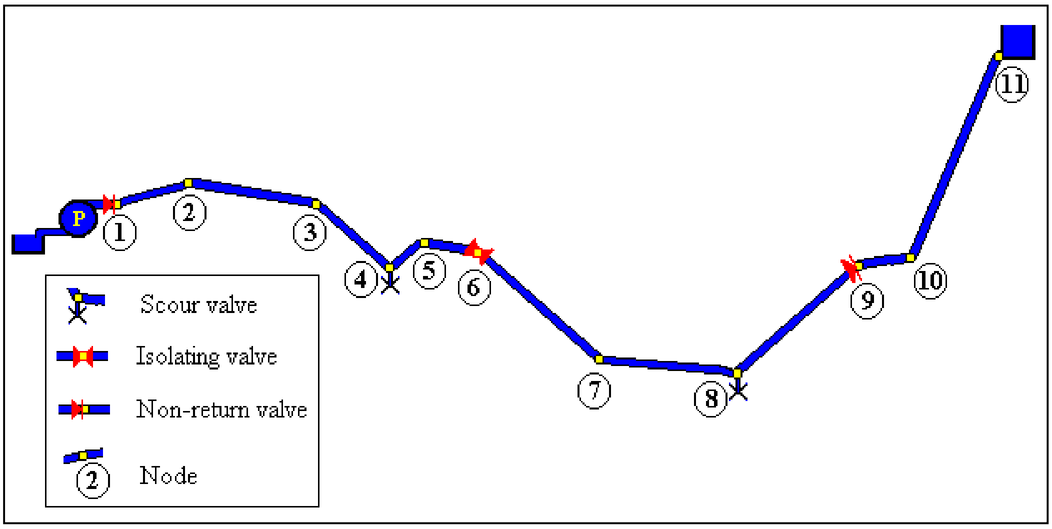


Figure 7.6: Filling (example)

Table 7.5: Possible filling scenarios for the sections that can be isolated

Scenario	Isolated section to be filled	Upstream filling point	Downstream filling point
1	Node 1 –6	Node 1 (Pump)	Node 6 (Isolating valve)
2	Node 6 -11	Node 6 (Isolating valve)	Node 11 (Reservoir must be empty)
3	Node 6 - 9	Node 6 (Isolating valve)	Node 9 (Bypass around Non-return valve)
4	Node 9 - 11	Node 9 (Bypass around non-return valve)	Node 11 (Reservoir)
5	Node 1 -11	Node 1 (Pump)	Node 11 (Reservoir)

- o Distinction should be made between first-time filling of the pipeline and subsequent fillings where sections of the line can cause a water lock. In cases where water locks can occur every air valve should be selected to ensure that the filling rate could be expelled.
- o For each of the filling scenarios the sequential filling of the pipeline sections should be identified, to determine where air would be discharged. Using the pipeline illustrated in **Figure 7.6** and filling scenario 1, the following filling of the pipeline sections can be identified. This is obtained by visualizing the water filling the pipe and determining which peak in the controlled section will release air.
    - The pipe section from node ***1*** to node ***6*** can be filled from the downstream side through backflow through node ***6*** or from the flow that is supplied from the pump.
    - When the pipeline is filled from the pump station, the air valve at node 2 will be the last to close. Initially, all the air valves in this pipeline section will release air but the valve closing last will be required to release air at the same rate as the filling rate. If this cannot be achieved the filling time will increase.
    - If the pipeline is filled from the end of the section, node 6, the last valve to close will again be the valve at node ***2***.
- o Calculating the hydraulic gradeline and subtracting the pipeline elevation will provide the pressure whereby the valve will be exhausting air.
- o The maximum discharge rate before blow-shut will occur, is based on a calculation with a maximum differential pressure of 0,5 m (Equation 7.5). The maximum outflow rate for the selected valve at that node is then used as the limit for the filling rate. From the valve supplier's outlet characteristic curve a suitable valve(s) can be selected to prevent this phenomenon.

7.2.2.4 Small orifice air release analysis

During operation, air can be released through the small orifice air valve only. For this to occur, the air should be "stationary" at the valve, although the pipeline simultaneously continues to handle the design flow. This emphasizes the need to provide a collection chamber underneath the valve, where the air can be captured temporarily and then released through the air valve. **Although under normal conditions water can contain 2-3% per volume free air, it is unrealistic to install small orifice air valves to provide such a discharge rate!**

The requirement of small orifice air valves is governed by the principle that air should be released mechanically if it could be transported hydraulically to the air valve. The following approach should be used to determine the position of small orifice air-release valves:

- Determine if free air in the pipeline can be hydraulically transported through the pipeline along the downward sloping-sections. Equation 7.6 has been derived from experimental work and should be used to determine whether the air can be hydraulically removed. All the negative slopes should be evaluated to ensure that provision be made to release the air mechanically at a position prior to the steep sloped sections where it will be impossible to transport the air hydraulically.

$$V_{\min} = a\sqrt{gD}\theta^{b}$$

Where:

V_{min}	=	Flow velocity at the point where removal will start (m/s)
g	=	Gravitational acceleration (m/s²)
D	=	Diameter of pipeline (mm)
θ	=	Slope of pipeline (°)
a	=	Constant (for medium sized bubble: a = 0,2178)
b	=	Constant (for medium sized bubble: b = 0,4007)

- The nodes identified in the step above at which free air cannot be transported, constitutes a position where a small orifice air valve is required.
- If the calculated distance between small orifice air valves is short (say 250 m), it is not necessary to provide a small orifice air valve at all the identified points, provided that the line is effectively filled and that the upstream small orifice air valve effectively captures and releases all the air that reaches it.
- Small orifice air valves are nearly always required at apex points along the pipeline, because these are the points where air is most likely to accumulate, especially for low flow velocities. The apex points are also used to prevent vacuum formation, by allowing air into the pipeline and hence the positioning of a combination air valve is provided at these points.

7.2.2.5 Special consideration

A large orifice air valve, when used as an alternative for a one-way surge tank (or discharge tank) to prevent negative pressures resulting from a power failure in a pump station, should be placed just downstream from the pump check valve.

The results of surge analyses reflect where sub-atmospheric pressures might occur and it is suggested that large orifice air valves should be provided wherever the pressure drops are in excess of 4,0 m.

7.2.2.6 Conclusion

It is believed that if a pipeline is analysed as a whole, using the ASAP procedure the pipeline system will meet all the requirements in terms of air release and intake requirements to adequately protect the system and provide an effective de-aerated system.

7.2.3 ASAP results

Typical ASAP results will be a pipeline profile indicating the exact position/location of the air valves (**Figure 7.7**) as well as valve class, valve type, valve size, accumulator details/requirements etc. (**Table 7.6**). The operating & maintenance manual should describe the drainage and filling procedures for the pipeline system.

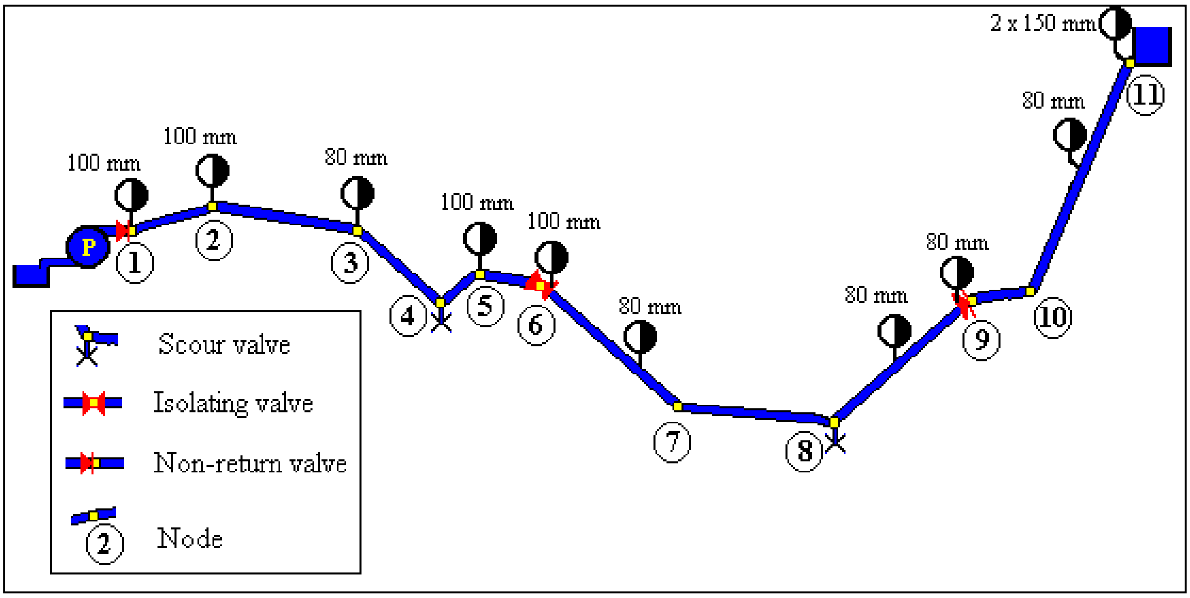


Figure 7.7: Typical ASAP result (Pipeline profile)

Table 7.6: Typical ASAP result (valve requirements)

Nr	Point description	Accumulated length (m)	Elevation (m)	Air valve	Size (mm)	Valve class	Model number
1	Pump station	0	1400,00	RBX Double acting	100	25 bar	100RBX2501
2		500	1420,00	RBX Double acting	100	16 bar	100RBX1601
3		1250	1410,00	RBX Double acting	80	25 bar	080RBX2501
4	Drainage (150mm)	1700	1370,00	No air valve	-		-
5		1800	1380,00	RBX Double acting	100	25 bar	100RBX2501
6	Isolating valve	2100	1375,00	RBX Double acting	100	25 bar	100RBX2501
		2625	1341,25	RBX Double acting	80	40 bar	080RBX4001
7		2800	1330,00	No air valve	-		-
		3150	1324,17	RBX Double acting	80	40 bar	080RBX4001
8	Drainage (150mm)	3400	1320,00	No air valve	-	-	-
		3675	1337,20	RBX Double acting	80	40 bar	080RBX4001
9	Non return valve	4200	1370,00	RBX Double acting	80	25 bar	080RBX2501
10		4400	1275,00	No air valve	-	-	-
		4900	1425,00	RBX Double acting	80	16 bar	080RBX1601
11	End reservoir	5600	1495,00	2 x RBX Double acting	150	16 bar	150RBX1601

7.3 Hand calculation

7.3.1 Introduction

The aim of this section is to provide the design engineer with an example of the proposed air valve sizing and positioning procedure. The pumping system as shown in **Figure 7.8** is an example of the application of the proposed procedure for air valve sizing and positioning as described in Section 7.2, performed by hand calculation. The calculations are performed step-by-step, highlighting the required location of the air valves and rationale of the air valve sizing and positioning (ASAP) procedure.

7.3.2 Input data

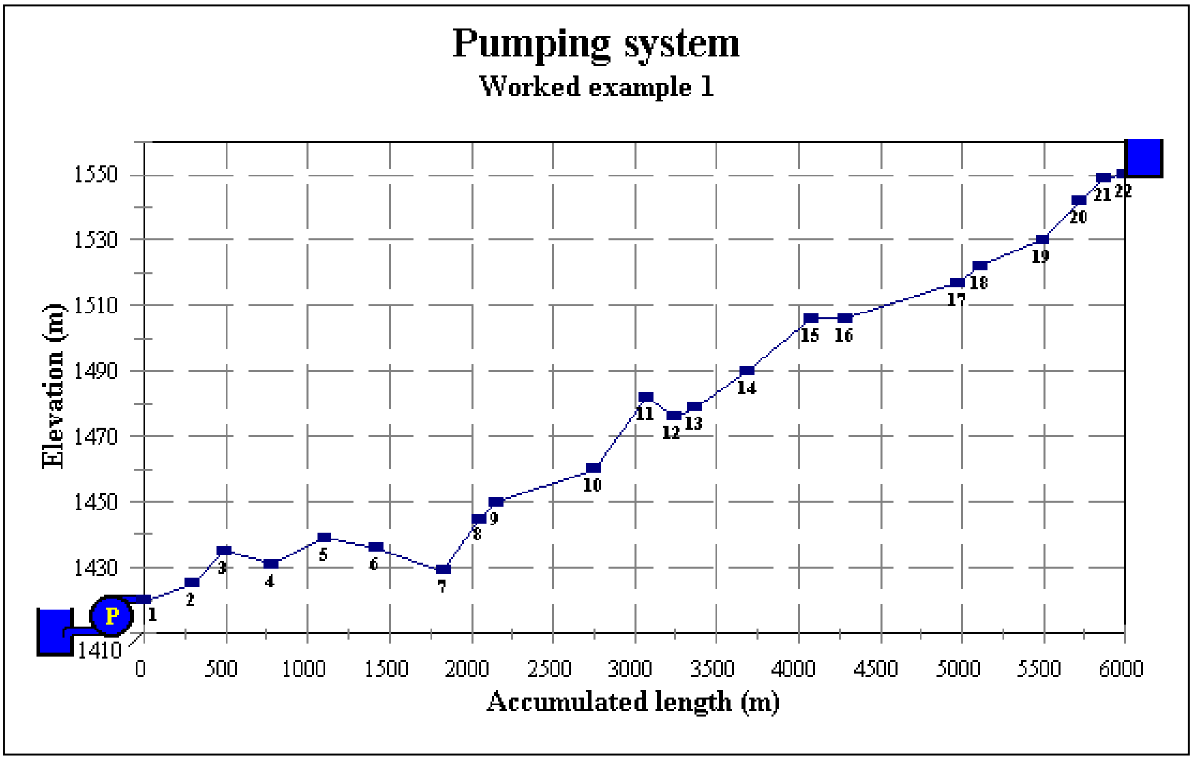


Figure 7.8: Pumping system pipeline profile

The pumping system reflected in **Figure 7.8** consists of a pumpstation that supplies water to a reservoir approximately 6 km away, through a 250 mm uPVC pipeline.

The system flow characteristics are as follows:

Operating flow rate: 0,1 m³/s

Operating flow velocity 2,04 m/s

Fluid type: water

Filling velocity: 0,3 m/s (15 % of flow rate)

The pipe characteristics are:

Pipe type: uPVC

Anticipated rupture size: 15% of pipe diameter

Pipe roughness: 0,03 mm

Along the 6 km of pipeline are a number of isolating valves (2) as well as scour valves (3) and one non-return valve, indicated in **Table 7.7**.

Table 7.7: Pipeline profile and details

Node Nr	Description	Accumulated length (m)	Elevation (m)	Diameter (mm)
1	Pumpstation (TWL 1420 m)	0	1 420	250
2		300	1 425	250
3		490	1 435	250
4	Scour valve (100 mm)	780	1 431	250
5	Isolating valve	1 105	1 439	250
6		1 420	1 436	250
7	Scour valve (100 mm)	1 830	1 429	250
8		2 050	1 445	250
9		2 150	1 450	250
10		2 750	1 460	250
11		3 070	1 482	250
12	Scour valve (100 mm)	3 240	1 476	250
13		3 370	1 479	250
14		3 690	1490	250
15	Non-return valve	4 080	1 506	250
16	Isolating valve	4 290	1 506	250
17		4 980	1 517	250
18		5 110	1 522	250
19		5 500	1 530	250
20		5 720	1 542	250
21		5 870	1 549	250
22	Reservoir (TWL 1555 m)	6 000	1550	250

The static height difference between the reservoir at the pumpstation and the end reservoir is 135 m.

7.3.3 Calculations

The required input data, as defined in the ASAP flow diagram, Figure 7.1, is obtained from Table 7.7. The information is used to analyse the pipeline for the various operating conditions, i.e. burst, drainage, filling and small orifice air release analyses.

Burst Analysis:

- Calculate all the pipeline slopes for pipe sections 1 – 21. If a section is horizontal, it is assumed that it has a slight positive slope. Such a slope will result in the air being transported downstream to the end of the horizontal sloped section.
- Calculate the maximum discharge rate using the modified Darcy-Weisbach equation (Equation 7.1) and the Karman Prandtl equation (Equation 7.2), assuming thus that the hydraulic gradelines and pipe slopes for each specific section are equal for the maximum discharge rate in these pipe sections

$$Q_{burst} = \sqrt{\frac{g\pi^2 D^5 S_0}{8\lambda}\frac{A_{rupture}}{A}} \quad \text{and} \quad \lambda = \left(\frac{1}{2\log\left(\frac{3.7D}{k_s}\right)}\right)^2$$

The results of these calculations are reflected in **Table 7.8**.

Table 7.8: Intake requirements for every pipe section in case of a burst

Pipe No	Start node no	End node no	Length (m)	Elevation difference (m)	Slope (m/m)	Burst rate (m³/s)	Burst rate (m³/h)	Velocity (m/s)
1	1	2	300	5	0.0166667	0.0189	68.04	0.385
2	2	3	190	10	0.0526316	0.0336	120.92	0.684
3	3	4	290	-4	-0.0137931	0.0172	61.90	0.350
4	4	5	325	8	0.0246154	0.0230	82.69	0.468
5	5	6	315	-3	-0.0095238	0.0143	51.44	0.291
6	6	7	410	-7	-0.0170732	0.0191	68.87	0.390
7	7	8	220	16	0.0727273	0.0395	142.14	0.804
8	8	9	100	5	0.0500000	0.0327	117.86	0.667
9	9	10	600	10	0.0166667	0.0189	68.04	0.385
10	10	11	320	22	0.0687500	0.0384	138.20	0.782
11	11	12	170	-6	-0.0352941	0.0275	99.02	0.560
12	12	13	130	3	0.0230769	0.0222	80.07	0.453
13	13	14	320	11	0.0343750	0.0271	97.72	0.553
14	14	15	390	16	0.0410256	0.0297	106.76	0.604
15*	15	16	210	0	0.0000001	0.0000	0.17	0.001
16	16	17	690	11	0.0159420	0.0185	66.55	0.377
17	17	18	130	5	0.0384615	0.0287	103.37	0.585
18	18	19	390	8	0.0205128	0.0210	75.49	0.427
19	19	20	220	12	0.0545455	0.0342	123.10	0.697
20	20	21	150	7	0.0466667	0.0316	113.86	0.644
21	21	22	130	1	0.0076923	0.0128	46.23	0.262
		Total	**6000**	* If it has a zero slope the slope is made slightly positive				

Although the slope is positive, a burst in the section can occur at the beginning of the section resulting in the requirement to introduce air downstream from the burst. Assess the intake requirement at all nodes along the pipeline, starting at node ***1***, moving downstream. Air valves are usually placed at peaks and where the change in kinetic energy is more than 0,5 m (assumed value) to prevent column separation. If the change in kinetic energy is less than 0,5 m it is used in the analysis of the next point, to determine if an intake is needed there. The way in which this is done is to accumulate the kinetic energy differences until a node is reached where an air intake is incorporated. For instance, if in two adjacent nodes accumulated change in energy exceeds 0,5 m, a large orifice function is required at the higher node. With Equation 7.3 this change in energy can be calculated.

$$\frac{V_2^2 - V_1^2}{2g} \leq 0{,}5$$

Each pipe section is checked to see whether or not it can supply sufficient flow to its adjacent pipe sections. At a peak, this cannot be achieved, and therefore at peaks a large orifice function is usually required. If, however, the elevation difference is such that the maximum allowable negative pressure in the pipe section is not exceeded, a large orifice function might not be required. **Table 7.9** illustrates the intake requirements on the upstream and downstream of every node due to burst.

Table 7.9: Intake requirements for every node (US and DS) due to burst analysis

<table>
<tr><th rowspan="2">Node Nr</th><th rowspan="2">Slope change</th><th rowspan="2">Description</th><th rowspan="2">Change in energy (m)</th><th colspan="2">Result of column separation</th><th colspan="2">Requirements for burst analysis</th></tr>
<tr><th>Individual</th><th>Accumulated</th><th>US (m³/h)</th><th>DS (m³/h)</th></tr>
<tr><td>1</td><td></td><td>Starting point</td><td>0.0000</td><td></td><td></td><td></td><td>0.0000</td></tr>
<tr><td>2</td><td>+ to + +</td><td></td><td>0.0163</td><td>< 0.5 thus OK</td><td>< 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>3</td><td>+ to -</td><td>Peak point</td><td></td><td></td><td></td><td colspan="2">120.917</td></tr>
<tr><td>4</td><td>- to +</td><td>Low point</td><td></td><td></td><td></td><td colspan="2">0.000</td></tr>
<tr><td>5</td><td>+ to -</td><td>Peak point</td><td></td><td></td><td></td><td>82.693</td><td>68.8687</td></tr>
<tr><td>6</td><td>- to - -</td><td></td><td>0.0034</td><td>< 0.5 thus OK</td><td>< 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>7</td><td>- to +</td><td>Low point</td><td></td><td></td><td></td><td colspan="2">0.000</td></tr>
<tr><td>8</td><td>+ + to +</td><td></td><td>0.0103</td><td>< 0.5 thus OK</td><td>< 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>9</td><td>+ + to +</td><td></td><td>0.0151</td><td>< 0.5 thus OK</td><td>0.0254 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>10</td><td>+ to + +</td><td></td><td>0.0236</td><td>< 0.5 thus OK</td><td>0.0490 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>11</td><td>+ to -</td><td>Peak point</td><td></td><td></td><td></td><td colspan="2">142.139</td></tr>
<tr><td>12</td><td>- to +</td><td>Low point</td><td></td><td></td><td></td><td colspan="2">0.000</td></tr>
<tr><td>13</td><td>+ to + +</td><td></td><td>0.0051</td><td>< 0.5 thus OK</td><td>< 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>14</td><td>+ to + +</td><td></td><td>0.0030</td><td>< 0.5 thus OK</td><td>0.0081 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>15</td><td>+ + to +</td><td></td><td>0.0186</td><td>< 0.5 thus OK</td><td>0.0267 < 0.5 (OK)</td><td>106.756</td><td>0.0000</td></tr>
<tr><td>16</td><td>+ to + +</td><td></td><td>0.0072</td><td>< 0.5 thus OK</td><td>0.0072 < 0.5 (OK)</td><td>0.053</td><td>0.0000</td></tr>
<tr><td>17</td><td>+ to + +</td><td></td><td>0.0102</td><td>< 0.5 thus OK</td><td>0.0102 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>18</td><td>+ + to +</td><td></td><td>0.0081</td><td>< 0.5 thus OK</td><td>0.0183 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>19</td><td>+ to + +</td><td></td><td>0.0154</td><td>< 0.5 thus OK</td><td>0.0338 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>20</td><td>+ + to +</td><td></td><td>0.0036</td><td>< 0.5 thus OK</td><td>0.0374 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>21</td><td>+ + to +</td><td></td><td>0.0177</td><td>< 0.5 thus OK</td><td>0.0550 < 0.5 (OK)</td><td colspan="2">0.000</td></tr>
<tr><td>22</td><td></td><td>End point</td><td>0.0000</td><td></td><td></td><td>123.096</td><td></td></tr>
</table>

Comments on **Table 7.9**:

- Only peaks require large orifice functions in this example, since at no change in pipe gradient will cavities occur when there is a pipe break anywhere on the line.
- At node 5 there is an isolating valve. Node ***5*** is also at a peak and will therefore require a large orifice function on both sides (i.e. both up- and downstream) unless the downstream section can provide the flow and the elevation difference between node ***5*** and node *7* is less than the allowable negative pressure.
- The peak at chainage 3 070 m (Node ***11***) is sized for the maximum flow rate on its upstream side (the slope of pipe section **7** between node *7* and ***8***). This is steeper than the slope on its downstream side (pipe section **11** between node ***11*** and ***12***). No large orifice functions were required at any of the slope changes between node *7* and ***11*** (upstream side of node ***11***). For this reason, node ***11*** is sized to supply the maximum intake requirement on that side. If there was a valve at, for instance, node ***9***, node ***11*** would have been sized for pipe section **10** which is steeper than section **9** and **11**. The valve at node ***9*** would have provided sufficient intake capacity for sections *7* and ***8***.
- The non-return valve at node ***15*** only requires intake capacity on its upstream side. As soon as the downstream side reaches a lower pressure than the upstream side the non-return valve will open again. When a non-return valve is placed on a pipe section that has a negative slope, no air valve is required on either side.
- From node ***16*** (isolating valve) to node ***22*** (end reservoir) there are a number of slope changes. The cumulative change in kinetic energy (nodes ***17*** to ***21***) due to these slope changes are, however, not sufficient to cause column separation (0,055m < 0,5 m set criteria). The end reservoir intake requirement is, however, determined by the steepest slope of these pipe sections (pipe section **19**, i.e.123,1 m³/h).
- On the upstream side of the last node, node ***22***, at the end reservoir, an intake capacity of 123,1 m³/h is required. If the reservoir has an uncontrolled outlet with either top or bottom entrance into the reservoir, no air valve is required. The required intake capacity will in this case be supplied via the top inlet, which is open to the atmosphere or water will be supplied in the case of an outlet below the water (bottom outlet). If the outlet is controlled in any way, however, this intake requirement must be provided for.

Drain Analysis:

- Identify possible drainage scenarios. The pipeline example in **Figure 7.8** initially seems as if it has nine possible draining scenarios (see **Table 7.10**). The first three scenarios are not possible, however, due to the non-return valve at node ***15*** preventing any backflow from pipe sections **15** to **21** when draining upstream of node ***15***.

Table 7.10: Possible draining scenarios

Scenario	Drainage point	Upstream control point	Downstream control point
~~**1**~~	~~Node 4 (100 mm)~~	~~Node 1 (Reservoir)~~	~~Node 22 (Reservoir)~~
~~**2**~~	~~Node 7 (100 mm)~~	~~Node 1 (Reservoir)~~	~~Node 22 (Reservoir)~~
~~**3**~~	~~Node 12 (100 mm)~~	~~Node 1 (Reservoir)~~	~~Node 22 (Reservoir)~~
4	Node 4 (100 mm)	Node 1 (Reservoir)	Node 5 (Isolating valve)
5	Node 4 (100 mm)	Node 1 (Reservoir)	Node 15 (Non-return valve)
6	Node 7 (100 mm)	Node 1 (Reservoir)	Node 15 (Non return valve)
7	Node 12 (100 mm)	Node 1 (Reservoir)	Node 15 (Non return valve)
8	Node 7 (100 mm)	Node 5 (Isolating valve)	Node 15 (Non return valve)
9	Node 12 (100 mm)	Node 5 (Isolating valve)	Node 15 (Non return valve)

For each of the drainage scenarios, the activation sequence is determined. **Table 7.11** indicates the activation sequence for each drainage scenario.

Table 7.11: Activation sequence for every drainage scenarios

Scenario	Drainage point	Upstream peaks (activation sequence)	Downstream peaks (activation sequence)
~~**1**~~	~~Node 4~~	~~3 (4th)~~	~~22 (1st), 11 (2nd) & 5 (3rd)~~
~~**2**~~	~~Node 7~~	~~5 (3rd)~~	~~22 (1st) & 11 (2nd)~~
~~**3**~~	~~Node 12~~	~~11 (2nd)~~	~~22 (1st)~~
4	Node 4	5 (1st)	3 (2nd)
5	Node 4	3 (3rd)	15 (1st) & 11 (2nd)
6	Node 7	3 (3rd)	15 (1st) & 11 (2nd)
7	Node 12	11 (2nd)	15 (1st)
8	Node 7	5 (3rd)	15 (1st) & 11 (2nd)
9	Node 12	11 (2nd)	15 (1st)

- For draining scenario ***5***, the first node that will be activated is the upstream side of node ***15***, and then node ***11***, and the last node to be activated is the node on the upstream side of the drainage point node ***3***. This is obtained be visualizing a horizontal line as the level of the water, this line is then moved down, as the water is released, determining which peak in the controlled drainage section will first be activated for this controlled section which has been isolated.
- The outlet (scour valve) at the drainage point is assumed to be an orifice (a realistic value for the discharge coefficient (C_D) is 0,6). The maximum discharge rate is calculated utilizing the available head for various drainage scenarios with Equation 7.4.

$$Q_{drain} = C_D \sqrt{2g\Delta h}\left(\frac{\pi D_{outlet}^2}{4}\right)$$

- The intake requirement for each peak in this control section (scenario) can now be calculated. This is repeated for every possible drainage scenario identified. The activation sequence is very important, since a valve that is activated first on a specific side of the drainage point (either upstream or downstream) will be required to supply the total flow rate. If a peak on the other side is activated next, the drainage flow rate is halved (if drained slopes are equal) for this air valve since air can now be supplied from both sides (up- and downstream) of the drainage point. **Table 7.12** is a summary of all these calculations.
- The maximum intake requirement for every peak is now determined by comparing the various scenarios and obtaining the intake rate.

Table 7.12: Intake requirements on the upstream and downstream of every node due to controlled drainage

Node nr	4			5			6			7			8			9		
	dH (m)	US (m³/h)	DS (m³/h)	dH (m)	US (m³/h)	DS (m³/h)	dH (m)	US (m³/h)	DS (m³/h)	dH (m)	US (m³/h)	DS (m³/h)	dH (m)	US (m³/h)	DS (m³/h)	dH (m)	US (m³/h)	DS (m³/h)
1																		
2																		
3	4.0		75.1	4.0		75.1												
4																		
5	8.0	212.5					10.0		118.8				10.0		118.8			
6																		
7																		
8																		
9																		
10																		
11				51.0	536.6		53.0	547.1		6.0		92.0	53.0	547.1		6.0		92.0
12																		
13																		
14																		
15				75.0	650.8		77.0	659.4		30.0	411.6		77.0	659.4		30.0	411.6	
16																		
17																		
18																		
19																		
20																		
21																		
22																		

From the burst and drain analysis the pipeline's intake requirements were now calculated. The next step is to determine the discharge requirements.

Filling Analysis:

The first step in the filling analyses is to identify all the possible filling scenarios. The possible filling scenarios are shown in **Table 7.13**.

Table 7.13: Possible filling scenarios

Scenario	Empty section	Upstream filling point	Downstream filling point
1	Node 1 - 5	Node 1 (Pump)	Node 5 (Isolating valve)
2	Node 5 -16	Node 5 (Isolating valve)	Node 16 (Isolating valve)
3	Node 16 - 22	Node 16 (Isolating valve)	Node 22 (Reservoir)
4	Node 1 - 22	Node 1 (Pump)	Node 22 (Reservoir)
5	Node 5 - 22	Node 5 (Isolating valve)	Node 22 (Reservoir)
6	Node 15 - 16	Node 15 (Non-return valve)	Node 16 (Isolating valve)
7	Node 15 - 22	Node 15 (Non-return valve)	Node 22 (Reservoir)
8	Node 5 - 15	Node 5 (Isolating valve)	Node 15 (Non-return valve)
9	Node 1 - 15	Node 1 (Pump)	Node 15 (Non-return valve)

Looking at the first scenario the following filling sub-scenarios of this section can be identified (**Table 7.14**):

Table 7.14: Sub-scenarios of Scenario 1

Filling from	Last activated air valve	Description of filling
1	US 5	First time filling
1	3	Water lock 3-5
5	US 5	First time filling
5	US 5	Water lock 3-5
5	US 5	Water lock 1-3

The point on the pipeline where the entire fill rate should be exhausted should be identified, such as node 3 and node 5 in this filling scenario. Subsequent filling of the pipeline will, in most cases, be the design criterion since a water lock will force one air valve to provide the total outlet capacity of 14,7 l/s.

Small orifice air release analysis:

- o Determine whether free air in the pipeline can be hydraulically transported through the pipeline along the downward sloping-sections by using Equations 4.3. All the negative slopes should be evaluated to ensure that provision is made for releasing the air mechanically at a position prior to the steep sloped sections where it will be impossible to transport the air hydraulically.

$$V_{min} = a\sqrt{gD}\theta^b$$

Where:

V_{min}	=	Flow velocity at the point where removal will start (m/s)
g	=	Gravitational acceleration (m/s²)
D	=	Diameter of pipeline (m)
θ	=	Slope of pipeline (°)
a	=	Constant (for medium sized bubble: a = 0,2178)
b	=	Constant (for medium sized bubble: b = 0,4007)

Therefore for this example the pipe diameter remains constant and the operating velocity is 2,037 m/s.

Table 7.15: V_{min} for pipe sections with negative slopes

Pipe no	Slope (m/m)	V_{min} (m/s)	Status
3	-0,01379	0,310	OK
5	-0,00952	0,267	OK
6	-0,01707	0,338	OK
11	-0,03529	0,452	OK

- o The pipes identified in the step above are all capable of transporting air, in other words does not require a small orifice air valve.
- o Small orifice air valves, however, are nearly always required at apex points along the pipeline since these points are where air is most likely to accumulate, especially for low flow velocities. The apex points are also used to prevent vacuum formation by allowing air into the pipeline and therefore the positioning of a combination air valve is provided at these points.
- o Free air reduces the capacity of the system and therefore the placing of small orifice air valves at intervals of 600 m is a good design practice.

7.3.4 Results

Summarise the valve requirements at each node and at intermediate points along the pipeline, by graphical (**Figure 7.9**) and table format (**Table 7.16**).

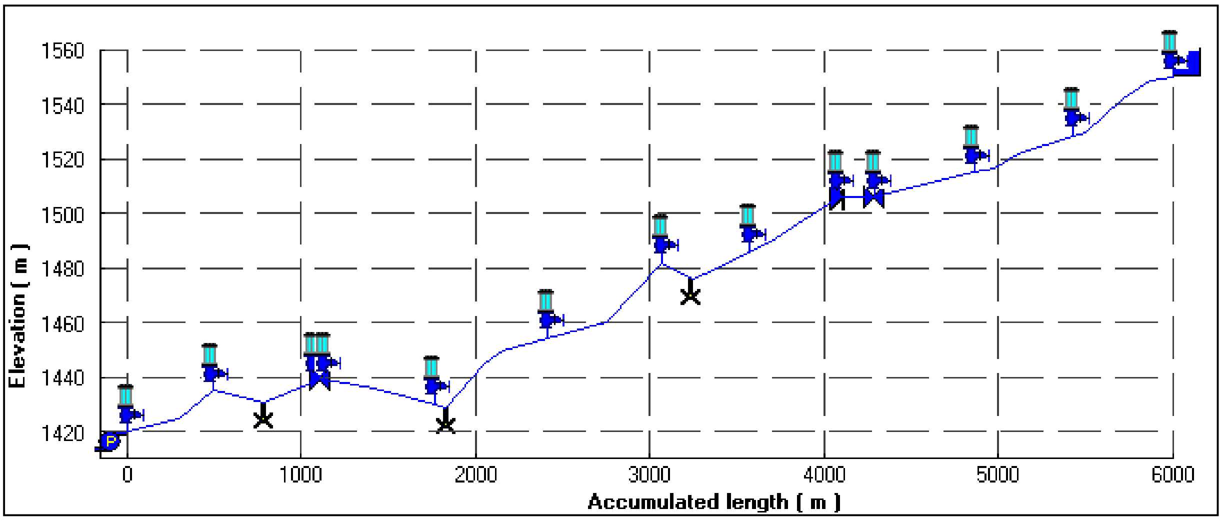


Figure 7.9: Pipeline profile with air valves (Vent-O-Mat Utility Programs, 2003)

Table 7.16: Air valve requirements (Vent-O-Mat Utility Programs, 2003)

Nr	Point description	Accumulated length	Elevation	Air valve	Size	Valve class	Model number
1	Pumpstation	0.000	1420.000	RBX Double Acting airvalve	50 mm	25 Bar	050RBX25 1
2		300.000	1425.000	No airvalve required	-	-	-
3		490.000	1435.000	RBX Double Acting airvalve	50 mm	25 Bar	050RBX25 1
4		780.000	1431.000	No airvalve required	-	-	-
5		1105.000	1439.000	RBX Double Acting airvalve	50 mm	25 Bar	050RBX25 1
5		1105.000	1439.000	RBX Double Acting airvalve	50 mm	25 Bar	050RBX25 1
6		1420.000	1436.000	No airvalve required	-	-	-
7		1760.000	1430.195	RBX Double Acting airvalve	25 mm	25 Bar	025RBX25 1
8		1830.000	1429.000	No airvalve required	-	-	-
9		2050.000	1445.000	No airvalve required	-	-	-
10		2150.000	1450.000	No airvalve required	-	-	-
11		2415.000	1454.417	RBX Double Acting airvalve	25 mm	16 Bar	025RBX16 1
12		2750.000	1460.000	No airvalve required	-	-	-
13		3070.000	1482.000	RBX Double Acting airvalve	80 mm	16 Bar	080RBX16 1
14		3240.000	1476.000	No airvalve required	-	-	-
15		3370.000	1479.000	No airvalve required	-	-	-
16		3575.000	1486.047	RBX Double Acting airvalve	25 mm	16 Bar	025RBX16 1
17		3690.000	1490.000	No airvalve required	-	-	-
18		4080.000	1506.000	RBX Double Acting airvalve	80 mm	16 Bar	080RBX16 1
18		4080.000	1506.000	No airvalve required	-	-	-
19		4290.000	1506.000	RBX Double Acting airvalve	25 mm	16 Bar	025RBX16 1
19		4290.000	1506.000	No airvalve required	-	-	-
20		4860.000	1515.087	RBX Double Acting airvalve	25 mm	16 Bar	025RBX16 1
21		4980.000	1517.000	No airvalve required	-	-	-
22		5110.000	1522.000	No airvalve required	-	-	-
23		5430.000	1528.564	RBX Double Acting airvalve	25 mm	16 Bar	025RBX16 1
24		5500.000	1530.000	No airvalve required	-	-	-
25		5720.000	1542.000	No airvalve required	-	-	-
26		5870.000	1549.000	No airvalve required	-	-	-
27	End reservoir	6000.000	1550.000	RBX Double Acting airvalve	50 mm	16 Bar	050RBX16 1

7.4 Air valve sizing and positioning software

Software, which incorporates the ASAP procedure, was developed and is freely available from two leading valve manufacturers, Vent-O-Mat (local manufacturer) and ARI Flow Control Accessories (Israel based). The ASAP procedure is not bound to any valve manufacturer, since the valve selection of the required valves are only performed once all the intake and discharge capacities have been determined. The ASAP procedure, as described in the previous sections, has been used in the software programs but has, however, been adapted to meet the valve manufacturers' requirements. An example is the exclusion of the filling analysis for the Vent-O-Mat CATT program due to the ability of the 3-stage anti-shock function to control the outflow rate.

For more information on air valve sizing and positioning software programs visit the following web sites:
http://www.up.ac.za/academic/civil/divisions/water/airvalves.html

7.5 Economic value of effective de-aeration

It is a known fact that general maintenance and preventative maintenance on pipelines is poor and sometimes non-existent. The yearly allocated budget is simply used to maintain a running system. Time and money is hardly spent on monitoring the pipeline regularly.

It has been found during some fieldwork carried out under this project, that maintenance crew often closed air valves because they were leaking. If the air cannot be transported hydraulically down the pipeline in such a case, the air will be trapped resulting in additional head loss and loss in capacity. Previous older installations of typical air valve layouts were not effectively capturing the free air leading to hydraulic under performance and to higher additional head loss.

Experimental studies performed at the Department of Water Affairs Hydraulic Laboratories, see Section 4.5, indicated that the secondary loss k-value was in excess of 6,0 for a localised air bubble situated at an apex point in the line and a low flow rate. It is not only the air bubble volume that governs the secondary loss, but to a large extent the form of the air bubble. If the flow velocity is increased the bubble lengthens and the calculated secondary loss coefficient k, reduces. The results, however, indicate that if a system is not effectively de-aerated, additional head loss will occur resulting in additional pumping head and/or a loss in hydraulic capacity.

It is however extremely difficult to predict the exact additional loss associated with insufficient de-aeration. The following procedure could, however, be followed to address this uncertainty:

- Compare the design capacity with the existing capacity obtained from the pipeline system. If the existing capacity is less than the design capacity the reason for the decrease in capacity must be found.
- Identify a section of pipeline where there are no abstractions and no possibility for air accumulation (only positive slope) i.e. a clean section. The section should preferably also contain no isolating valves or other control points.
- Utilizing pressure transducers or other accurate pressure gauges to measure the pressure drop across the selected pipe section.
- Perform a back calculation of the friction value.

- Use the calculated friction value and recalculate the capacity for the entire pipeline. If the calculated capacity corresponds with the current capacity, then the loss in capacity is solely due to the increased roughness of the pipe. If not, then air might be a problem or some other localised obstruction in the pipeline such as a half closed isolating valve or even leakage might be responsible for the under performance.
- If it is suspected that air is the reason then follow the following steps:
  - Check the size and location of the air valves based on the procedures as described in Section 7.2 (especially the hydraulic transportability of the air).
  - During a site visit verify that every air valve on the pipeline is operational. Check the small orifice's function and that the large orifice will release air during filling and that the float will drop during emptying of the line.
  - Check to see that the discontinuity and accumulator is adequate to capture the transported air.
  - Isolate the sections where leaks or air could still have an influence on the capacity. Use methods such as inverse transients or calculate the pressure drop across short sections along the pipeline until a section is found where the obtained pressure drop results in a steeper hydraulic gradient than the rest of the pipeline.

8. TYPICAL INSTALLATION DETAILS OF AIR VALVES

After the air valve size and location has been determined the following aspects should be considered:

- Discontinuity requirement
- Size of the accumulator
- Air valve installation and valve chamber design

It is assumed that the procedures discussed before has been used to determine the size and location of the air valve.

8.1 Discontinuity

From the experimental work conducted under this project as well as Computerized Fluid Dynamic (CFD) numerical modelling of various discontinuities the proposed discontinuity to capture the air should be at least 35 % of the pipeline diameter.

The reasons why a discontinuity/entrapment area is required is:

- To allow time for the air to enter the accumulator. As the bubble reaches the discontinuity it has to change flow direction and due to buoyancy be forced out of the pipe
- The air that enters through the discontinuity has to displace the water through the same discontinuity back into the pipe.
- From the experimental work it was evident that due to turbulent conditions, the air bubbles do not travel at the crown of the pipe and does not flow in a straight line. For this reason a large enough discontinuity is required.

There are a number of factors that will influence this required size of the discontinuity:

- Flow velocity
- Turbulence in the approach towards the discontinuity
- Slope of the pipeline

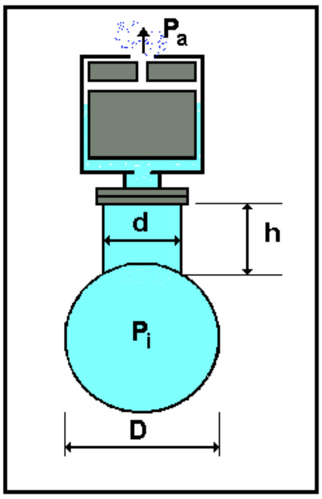
The minimum discontinuity required for smaller pipes (D < 300 mm diameter) should be an equal T, because when a smaller discontinuity is used the air will not be capable of displacing the water in the riser pipe.

The required discontinuity is larger for higher flow velocities since the "time available" to force the air into the discontinuity is less while it is also true that the bubble size reduces as the velocity increases. The complex nature of air movement thus forces the requirement of discontinuity to be selected conservatively. It is proposed that for diameters between 300 mm and 1 500 mm the discontinuity should be equal to 60% while for pipes in excess of 1 500 mm the discontinuity should at least be 35% of the pipe diameter.

8.2 Size of accumulator

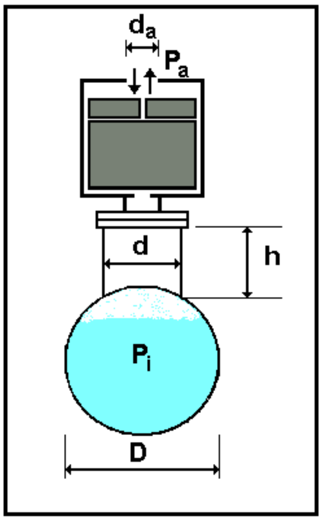
During normal operation, air can be released only through the small orifice air valve. For this to occur, the air should be "stationary" at the valve, although the pipeline simultaneously continues to handle the design flow. This emphasises the need to provide a collection chamber underneath the valve where the air can be captured temporarily and then released through the air valve. **Although water can contain 2-3% per volume free air, it is not necessary to install small orifice air valves to provide such a discharge rate!** It is assumed that the approach discussed in Section 7 was used to determine the position of small orifice air-release valves.

Ensuring the effective operation of the small orifice air valve necessitates the provision of a collector chamber to capture all the air. **Figure 8.1** and **8.2** provides a graphical presentation of the suggested installation layout for air valves.



VARIABLE	SMALL ORIFICE FUNCTION
Location	As topography requires. Determined by the procedure described in Section 7
h	h ≥ 1,0D h ≥ 150 mm
d	d = D for D ≤ 300 mm d = 0,6D for 300 < D ≤ 1500 mm d ≥ 0,35D for D > 1500 mm

Figure 8.1: Graphical presentation of installation details (small orifice function)



VARIABLE	LARGE ORIFICE FUNCTION	
	VACUUM BREAK	AIR RELEASE
Differential pressure for the calculation of the outlet orifice	$P_a - P_i \leq 40$ kPa	$P_i - P_a \leq 5$ kPa *
Location	Between shut-off valves or to allow free draining	High points on an isolated pipeline
h	$h \geq 1{,}0D$ $h \geq 150$ mm	$h \geq 1{,}0D$ $h \geq 150$ mm
d	$\frac{\pi d^2}{4} \geq \frac{\pi d_a^2}{4}$	See requirement for small orifice function
Note: * To prevent dynamic closure of the large orifice. Refer to manufacturers details		

Figure 8.2: Graphical presentation of installation details (large orifice function)

Special installation considerations might have to be considered for systems where intermittent operation might lead to dynamic induced pressures. In these cases, where negative pressures are created during the down surge, consideration should be given to incorporate an additional volume to maintain some air. The captured air will reduce the induced positive pressure. The layout in **Figures 8.4** and **8.6** can be used for the application by extending the vertical riser above the branch off to the air valves by 3-5 times the diameter.

8.3 Installation and valve chamber design

It is extremely important to properly design the air valve chamber. The chamber should fulfill the following functions:

- Protect the installed valve against the elements as well as vandalism and theft.
- Create an effective operating environment for the air valve.
- Create a working area for pipeline maintenance to be carried out with ease.

Some features which are crucial (see **Figure 8.3**):

- Proper drainage of the chamber (layer of stone or other impervious material as a floor)
- Allowance for a pump sump for drainage purposes
- Entrance manhole with step ladder if more than 0,5 m deep
- Vents for in and out flow to create a flow through the chamber. These vents should be larger than the nominal air valve area, or the combination of nominal air valve areas. This is done to ensure that the vents do not restrict the capacity of the air valve system.
- Vent openings should be covered with a mesh to prevent insects or birds from entering the valve chamber.

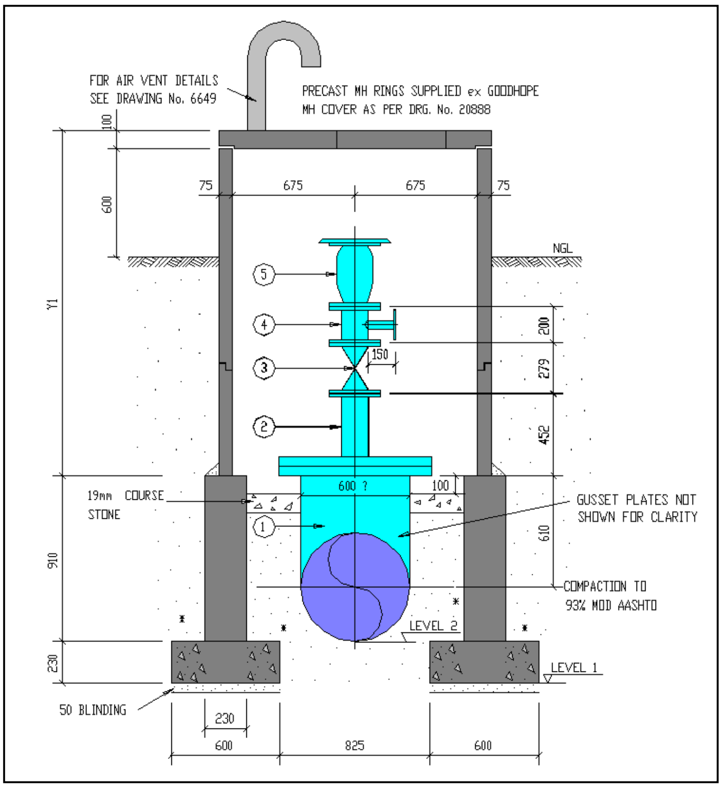


Figure 8.3: Well-designed air valve chamber (Umgeni Water)

Figures 8.4 and **8.5** are some alternative designs.

Figures 8.4: Two air valves on a manifold (above ground installation)

Figure 8.5: Four air valves on a manifold (above ground installation)

For even larger type installations, the air valve chamber can also be used as access points see **Figure 8.6**. The air valves were also placed on different levels on the accumulator, which will prevent all the air valves closing simultaneously when the water reaches them during filling of the pipeline. This installation is above ground in other words, preventing flooding of the chamber.

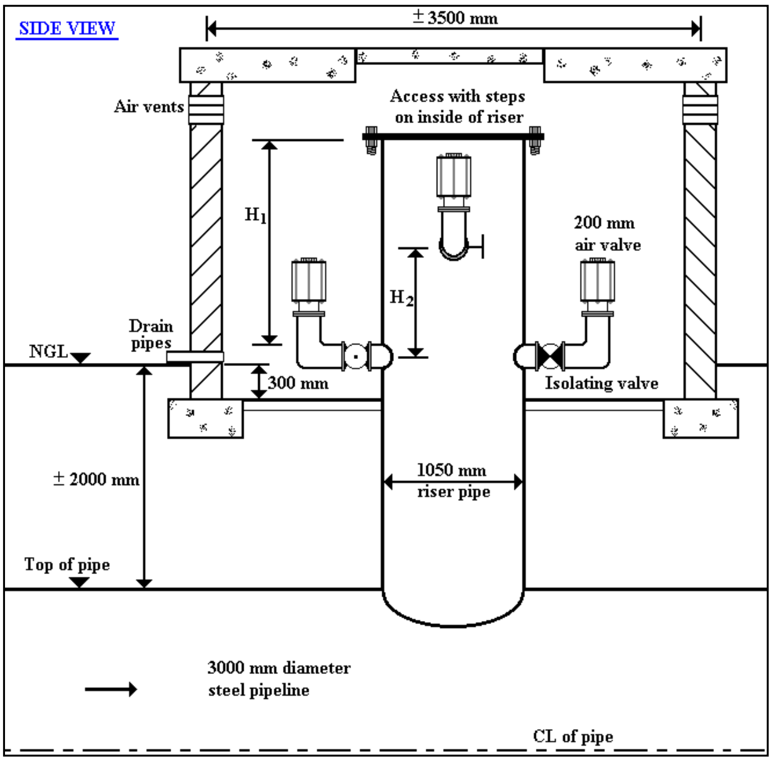


Figure 8.6: Schematic layout of larger type installation above ground

9. USER COMMENTS

This is still a provisional guideline for air valve sizing, selection and positioning. The project team would like to receive your comments in order to improve the document. Please complete this form below and fax/post to:

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10. REFERENCES

Basson M.S., Van Niekerk P.H. & Van Rooyen J. (1997). *An Overview of the Water Resources availability and utilisation in South Africa*.

Chadwick A. & Morfett J. (1994). *Hydraulics in Civil and Environmental Engineering.* (Second Edition). London: E & FN Spon.

Denny D.F. & Young, G.A.J. (1957). *The prevention of vortices in intakes*. Proceedings 7th Congress of the International Association of Hydraulic Research.

Kalinske A.A. & Bliss P.H. (1943). *Removal of air from pipelines by flowing water*. ASCE, 13. p.480

Kalinske A.A. & Robertson J.M. (1943). *Closed Conduit Flow*. ASCE Transactions V108.

Kienow, K.K., (Editor). (1990). *Pipeline design and installation*. International Conference on Pipeline Design and Installation, Las Vegas, Nevada, 1990.

Marcus, N. (1998). *Air and Air Valves in Pipe Lines*. Israel Water Commission.

Myles K.(Ed.). (1994). *Valves - Principles & Practice*. K. Myles and Associates. Northcliff.

Prosser M.J., (1977). The Hydraulic Design of Pump Sumps and Intakes. BHRA and CIRIA. London.

Richards R.T. (1957). *Air Binding in Large Pipe Lines Flowing under Vacuum*. Journal of the Gydraulic Division. ASCE.

Stephenson, D. (1981). *Pipeline Design for Water Engineers*. (Second Edition). Amsterdam: Elsevier Scientific Publishing Company.

Val-Matic. (1993). *Air in Pipelines - Sources, System Impact and Removal*. Available from Valmatic Valve and Manufacturing Corporation.

Val-Matic. (1996). *Val-Matic Glossary of Valve Related Terms*. Available with “airValve - Air valve Sizing program Version 5.0".

Val-Matic. (1997). *Theory, Application and Sizing of Air Valves*. Available from Valmatic Valve and Manufacturing Corporation.

Van Vuuren, S.J. (1989). *Induced pressures in pipelines resulting from the fast release or air*. Original document was published in Afrikaans. PhD Thesis. University of Pretoria.

Van Vuuren, S.J. (1990). *The effect of air in water pipes*. South African Institution of Civil Engineers (SAICE) and Fibre-Cement Association (FCA). One-day course on pipeline Engineering.

Van Vuuren, S.J. (1991). *The Purpose and Location of Air Valves in Pipelines*. SAICE - Lecture notes. University of the Witwatersrand.

Van Vuuren, S.J. (1994). *Control of Air in Pipeline Design*. Unpublished notes.

Van Vuuren, S.J. (1995a). *Air in Pipeline Design - Part 1*. AC Pipes brochure - AC Underground. Volume 8.

Van Vuuren, S.J. (1995b). *Air in Pipeline Design - Part 2*. AC Pipes brochure - AC Underground. Volume 9.

Vent-O-Mat. (1995). *Points to Consider when Sizing & Positioning Air Release & Vacuum Break Valves for Water Pipelines*. Available from Vent-O-Mat Mulric Hydro Projects (Pty) Ltd.

Vent-O-Mat. (1996). *Air Valve Technology Reviewed*. Available from Vent-O-Mat Mulric Hydro Projects (Pty) Ltd.

Veronese, A. (1937). *Sul motto delle bolle d’aria nelle condotte d’acqua* (in Italian). Estrato dal fasciacolo X. Vol. XIV, p.XV.

Wisner, P.E. (1982a). *Causes, Consequences and Studies on Air Entrainment*. Department of Civil Engineering - University of Ottawa - Lecture notes Chapter 11.

Wisner, P.E. (1982b). *Removal of Air from Pipelines (Air Pockets and Air Vents)*. Department of Civil Engineering - University of Ottawa - Lecture notes Chapter 12.

Wisner, P.E.; Mohsen, F.N. & Kouwen, N. (1975). *Removal of Air from Water Line by Hydraulic Means*. Journal of the Hydraulic Division. Proceedings, ASCE, Volume 101, February 1975, pp 243-257