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Working with water

Air problems in pipelines
A design manual

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Foreword

This manual was compiled by HR Wallingford in part fulfilment of a commission from the UK Department of Trade and Industry to produce guidance on how to minimise problems caused by the presence of air in pipelines. The manual is the result of collaborative effort by a number of individuals who were members of the Steering Group that was set to oversee this project. Their names and affiliations are given below and HR Wallingford gratefully acknowledges their invaluable contributions:

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Mike Little and Steve Murray - Black & Veatch Consulting (BVCs)
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Bernard Poole – MWH
Paul Fairhurst - BP, British Petroleum
Gavin Davies - Ove Arup & Partners
Nick Martin and Charlotte Howes - Thames Water Utilities
David Turtle - United Utilities

In addition to the above, acknowledgement is due to: Mr Richard May (formerly of HR Wallingford) who instigated this project, Dr Christine Lauchlan (formerly of HR Wallingford) for her contribution to the drafting of Chapters 1 to 4, and Mr Caesar Dabrowski (research fellow at HR Wallingford) for his contribution to Chapter 6.

The various chapters in the Guidance Manual were written by the following persons and reviewed by the members of the Steering Group:

Chapters 1 to 4 – Manuela Escarameia (HR Wallingford)
Chapter 5 – Professor Richard Burrows (University of Liverpool)
Chapter 6 – Manuela Escarameia (HR Wallingford)
Chapters 7 and 8 – Mike Little and Steve Murray (Black & Veatch)

Glossary

Air bubble	Approximately ellipsoidal or spherical volume of air (or other gas), typically smaller than 5 mm in diameter
Air pocket	Volume of air (or other gas) typically larger than 5 mm in diameter and with variable shape, resulting from coalescence of air bubbles or entrapment during filling of a pipe
Air column	Large air voids that occupy the whole of the pipe cross-section, thus interrupting the flow of water
Air valves	Devices used to automatically release air accumulated in pipelines and/or to admit air when the internal pressure drops below atmospheric
Air vessel	Also known as surge vessel, is a device used to suppress hydraulic transients in pipelines
Critical depth	Water depth at critical flow, i.e. when the Froude number is equal to unity; corresponds to the transition between subcritical and supercritical flow
Critical velocity (for air pocket movement)	Velocity of the flow required to remove an air pocket from a section of pipe
Downward sloping pipe	Pipe with flow moving from a higher point to a lower point
Energy grade line	Line defining the energy of the flow
Entrained air	Air present in pipelines by processes other than dissolution and pumping
Froude number	Non-dimensional number defined as the ratio of gravity and inertial forces, given as $(QB^{0.5})/(A^{1.5}\ g^{0.5})$, where Q is the flow rate, B is the surface width of the flow, A is the flow cross-sectional area and g is the acceleration due to gravity
Gravity pipe	Pipe designed to flow part-full or just full or, in the wider sense, a pipe in which flows are not pumped
Hovering velocity	Velocity of the flow required to sustain an air pocket in a stable location in a section of pipe
Hydraulic grade line	Line defining the level to which water would rise if unconstrained
Hydraulic jump	Standing wave that occurs when the flow changes from supercritical (Froude number > 1) to subcritical (Froude number <1)
Hydraulic transients	Pressure fluctuations caused by a flow change
Multi-phase flow	Flow consisting of mixture of water and air
Normal depth	Depth of flow at uniform depth, i.e. when the water surface is parallel to the pipe slope and does not vary with distance along the pipe
Pumped air	Air that is pumped directly into a pipeline to reduce the risk of cavitation damage
Pumping main	Pipe carrying pumped flow
Outfall	Pipe that conveys effluent to its final disposal point (e.g. sea, river, lake)

Glossary *continued*

Reflux (or check) valves	Valves installed downstream of pump units to prevent backflow
Rising main	Pumping main carrying wastewater
Soluble air	Air dissolved in water flows; the saturation level corresponds to 2% concentration
Upward sloping pipe	Pipe with flow moving from a lower point to a higher point

Notation

A	Cross-sectional area of flow (in m^2)
a	Numerical coefficient in Equation 6.1 (non-dimensional)
B	Surface width of flow (in m)
D	Pipe diameter (in m)
D_s	Diameter of sloping chamber (in m)
d_o	Normal depth (in m)
d_{cr}	Critical depth (in m)
Fr	Froude number, defined as $(QB^{0.5})/(A^{1.5}g^{0.5})$ or defined as $V/(gD)^{0.5}$ in Equation 7.1 (non-dimensional)
Fr_1	Froude number in Equation 6.6, defined as $U_1/(gR_1)^{0.5}$ (non-dimensional)
g	Acceleration due to gravity (in m/s^2)
H_{lost}	Total energy lost (in m)
h_f	Friction loss (in m)
k_s	Hydraulic roughness coefficient (in mm)
L	Length (in m)
L_a	Aeration zone downstream of hydraulic jump (in m)
n	Parameter associated with air pocket size, defined as $4V_{air}/(\pi D^3)$
Q	Flow rate of water (in m^3/s)
Q_{air}	Flow rate of air (in m^3/s)
Re	Reynolds number, defined as the ratio of viscosity and inertial forces (non-dimensional)
R_1	Hydraulic radius upstream of hydraulic jump, defined as the ratio of the cross-sectional area and the wetted perimeter (in m)
S	Pipe slope angle measured in relation to the horizontal (in degrees or radians)
S_f	Safety factor (non-dimensional)
S_u	Submergence below water level (in m)
U_1	Flow velocity upstream of hydraulic jump (in m/s)
U_2	Flow velocity downstream of hydraulic jump (in m/s)
V	Critical velocity for air pocket movement; flow velocity (in m/s)
V_{air}	Volume of air pocket (in m^3)
V_h	Hovering velocity (in m/s)
V_p	Air pocket velocity (in m/s)
α	Proportionality coefficient in Equation 6.7 (non-dimensional)
β	Proportionality coefficient in Equation 6.2 (non-dimensional)
σ	Surface tension (in N/m)

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1. Introduction

The entry, control and release of air from pipelines is a major, though often hidden, problem in pipelines used for water supply, foul water drainage and effluent discharge. Considerable costs are incurred in providing air release valves and chambers, and in deepening pipe trenches so as to provide the minimum gradients that are thought necessary to enable air bubbles and pockets to move towards the valves. Air valves require regular maintenance, but in practice this is rarely undertaken and there are numerous instances of their leaking and/or failing to operate correctly. In certain cases, vibration of the valves during start-up or shut-down of pumps can cause air to be drawn into a pipeline – the exact opposite of what is intended.

Where effluent and water transfer pipelines need to be laid under water in coastal or tidal areas, air valves cannot be used at all and the bed topography may result in very flat pipe gradients. Also, air valves cannot be used on potable water systems in situations where they might admit ground water into the pipeline.

It is therefore very important for professionals involved in the design and construction of water and wastewater pipelines to understand the potential problems caused by the presence of air (either as bubbles or large pockets), identify its sources and then take measures to reduce or eliminate as much as possible the presence of air. Since the removal of all sources of air may prove impossible in many cases, it will be necessary for practitioners to know how to design for air/water mixtures and minimise air's detrimental effect. This manual aims to provide engineers with concise and up-to-date advice. However, it is realised that much is not yet known in this complex field of multi-phase flow and the guidance provided represents a simplification of what is an extremely complex, though fascinating, subject.

1.1 PERCEIVED PROBLEMS

The main problems associated with air in pipelines are related to:

- Loss of carrying capacity and increased uncertainty on capacity

Air pockets reduce the effective pipe cross section, which results, for large air pockets, in a reduction in pipe capacity. Air can produce false readings on measuring devices.

- Changes in the properties of the fluid

The bulk properties of the fluid (a mixture of air and water) are changed from the original design assumption. This change concerns mainly the density and the elasticity of the fluid. The presence of air changes the structure of flow turbulence and possibly the wall shear as well. Air bubbles introduce vertical momentum into the flow due to their buoyancy and may thus have significant effects on the flow field. In hydraulic transients, the presence of large air pockets results in pressure waves that are strongly damped and deformed. However, it has also been found that small accumulations of air may have an adverse effect on pressure transients, actually enhancing the surge pressures experienced.

- Disruption to the flow

Air accumulation in a system may lead to disruption of the flow and to such effects as blow-out or blow-back. For instance, air entrained at a hydraulic jump may not be able to move downstream with the flow and instead 'blow back' through the jump. This can lead to vibration and structural damage and cause instabilities of the water surface.

Sealing, a transition from part-full to pipe full flow, can cause vibrations of the structure and surging of the flow.

- Problems in the performance of filters and membranes

The surges produced by varying air pressure make it difficult to maintain good filter operations. Also, bubbles can become trapped in sand filters, reducing their efficiency.

- Reduction of pump and turbine efficiency

When air-mixed water is fed into a turbine, there is a drop in output and efficiency is reduced. It can also cause waterhammer pressures. Admission of air to a pump can cause loss of priming.

- Effect on pipe materials and pipelines

In ferrous pipelines, the presence of air enhances corrosion by making more oxygen available for the process. The introduction of additives in cooling water systems as an anti-corrosion measure is common practice but leads to an increase in foaming of the water. Air is associated with buoyancy effects for underwater pipelines, such as outfalls.

- Effect on discharges

Transported air will be released at the discharge location. This raises environmental concerns including: bad odours from wastewater and sewage; foaming, particularly in conjunction with algal activity; negative visual impact as the appearance of the water can be very aerated (i.e. white water).

Figure 1.1 Pipeline with horizontal and sloping section

Figure 1.2 Example of sea outfall

1.2 SCOPE AND TARGET AUDIENCE

This manual gives practical information to designers and contractors on potential problems for water pipelines arising from the presence of air and suggests means of reducing or controlling its negative effects. “Water” is considered here in its broadest sense and includes:

- raw water
- potable water
- cooling water
- effluent
- wastewater
- storm water.

Similarly to water, air is considered here in a broad sense to include air, vapour and gas generated from effluent, with all of these gases being treated as air for the sake of simplicity.

The types of pipeline covered are:

- gravity pipes
- pumping mains

where both full-bore and locally part-full flows can be found. With regard to the location of the pipelines, these can be above ground, below ground and below water, with specific guidance being given for the various types of location listed.

It is hoped that the contents of this Guidance Manual will be of interest to all professionals concerned with the design, construction and maintenance of pipelines conveying water and wastewater. It covers a complex subject in a specialist field which is still insufficiently understood, but the guidance was devised so that it should be accessible to those with little experience. In effect, this document would have achieved its objectives if it succeeds in directing engineers in the beginning of their careers towards the need to take measures for exclusion of air or, this not being possible, for suitable management of air in pipelines.

1.3 USE OF THE MANUAL

The Manual is structured so that the first three chapters introduce the kind of problems that are associated with the presence of air in pipelines (Chapter 1), identify where air can originate from (Chapter 2), and lists the types of pipeline where the various problems can have particular impact (Chapter 3). Some brief background on the general characteristics of air-water mixtures and the movement of air in pipes from an engineer's point of view is provided in Chapter 4 and supplemented by Appendices A and B.

Chapter 5 deals specifically with the effect that air can have on the pressure transients that are caused by the interruption to fluid flow. The information in this Chapter is supplemented by Appendix C, which describes recent work that highlighted the potential enhancement effect of air pockets of a certain size on pressure surges and the need for designers to carefully consider this factor when designing or assessing the performance of existing pipelines.

The main design guidance is given in Chapters 6 and 7. Chapter 6 presents performance criteria that the designer needs to consider for the effective removal of air from sections of pipelines both under full bore conditions and in situations where a hydraulic jump is formed in the pipeline. Given the complexity of air movement in pipes, some further information/background on the performance criteria discussed in Chapter 6 is provided in Appendices D and E. A list of the equations recommended in this Manual is presented in Appendix F, to enable quick reference once the text of the document has been assimilated. It is not advised to use the equations in Appendix F without first being clear about their limitations and applicability.

2. Sources of air

In order to measure, control or dispose of air that is found in pipelines, it is important to understand the various ways in which air can enter a pipe system. There are several ways, which are listed below. It should be noted that throughout this document “air” is taken to mean atmospheric air as well as other gases that may be present or generated in water and wastewater pipelines.

2.1 SOLUBLE AIR

Water used in civil engineering applications is likely to contain a certain amount of dissolved air (at normal temperatures the saturation level of dissolved air in water is approximately 2%) which can come out of solution, usually as a result of a pressure drop. Low pressure zones can be created by changes in pipe elevation, partially-open valves, variations in flow velocity as a response to pipe diameter changes. Temperature increases, as well as pressure drops, can however also promote the release of “air” (or more precisely water vapour), as the vapour pressure of water increases with temperature (at 15^{o}C this is 1.70kN/m^2 whereas at 30^{o}C it is 4.24kN/m^2). This means that at 30^{o}C the potential volume of air to be released is 2.5 times greater than the volume that can be released from water at 15^{o}C. This can be an important consideration for pipeline design in hot climates or when pipes are subjected to high thermal variations.

In the case of wastewater it is worth noting that its temperature tends to be higher than that of the local air temperature, except in the hottest months. It varies between 10^{o}C and 21^{o}C, with 15^{o}C being usually taken as a representative value for design purposes (Metcalf and Eddy, 1991). In addition to considering air as a potential problem, in wastewater carrying pipes, bacterial activity may lead to the formation of gases. Optimum temperatures for bacterial activity are within the range 25^{o}C to 35^{o}C. However, for design of pipelines it is common practice to treat all gases as air.

Information on general properties of air can be found in fluid mechanics textbooks (e.g Douglas, Gasiorek & Swaffield, 1998, titled “Fluid Mechanics”) and are not covered in this manual.

2.2 ENTRAINED AIR

Air can be entrained from the atmosphere by the flow at the following locations and by the processes listed below:

- at the inflow location such as a drop chamber, inlet or intake.
- at the outflow location; for instance, sea outfalls may operate under varying tidal levels and the outlet may become unsubmerged.
- by vortices at an inlet or intake; this can occur at pump shafts, for example if there is insufficient submergence.
- by turbulence in shafts.
- downstream of gates.
- at hydraulic jumps; the flow within a pipe system may change from gravity to surcharged flow and under these conditions a hydraulic jump may form.
- at sections under negative pressure, where air can leak in at joints, fittings and pump glands.

Figure 2.1 Physical model tests showing air entrainment at discharge shaft and outlet pipe

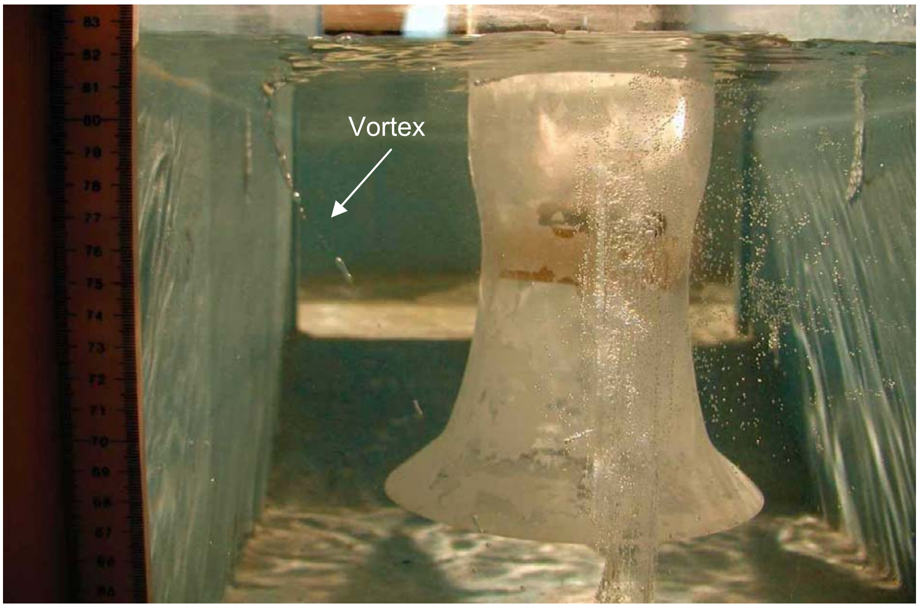

Figure 2.2 Air entrainment through surface vortices at pump chamber during physical model investigations

2.3 PUMPED AIR

Direct pumping of air into a system may be done in some cases to reduce cavitation pressures but this can cause accumulation of air in high points which may prove difficult to remove.

2.4 ACCUMULATED AIR

Air transport can occur during filling and emptying of pipelines. The air movement along the pipeline can be slow during filling and therefore air can become trapped at high points in the system. This issue is discussed further in Chapter 7.

3. Air problems in different types of pipeline

3.1 GENERAL PROBLEMS FOR DIFFERENT PIPE SYSTEMS

Some of the problems typically associated with the presence of air in a pipeline have previously been mentioned in Chapter 1. Not all types of pipeline experience these problems or are seriously affected by them and Table 3.1 summarises the main issues for the different types of pipeline system.

A problem, not always immediately identified, regards the environmental impact of releases from air valves installed in sewerage systems. These releases can reach heights of several metres and be problematic on two accounts: the noise levels of the expelled air can reach unacceptable levels for nearby residents, passers-by and wildlife (for example, noise levels of 80 dbA have been recorded at 3m distance); and the odour of the jet can be very unpleasant and generate complaints from local residents. Figure 3.1 shows a release from an air valve (although unfortunately, or fortunately, the bad odour and noise cannot be reproduced here!).

Figure 3.1 Example of release from air valve in sewerage pipeline (courtesy of Dean & Dyball)

Table 3.1 Summary of air problems affecting different types of pipe system

Types of problem	Different types of pipe system where air can be a problem			
	Water pipelines	Cooling water systems	Wastewater pipes	Underwater pipes
Loss of carrying capacity	✓	✓	✓	✓
Potential for false readings on measuring devices	✓	✓	✓	
Effects on pressure transients	✓	✓	✓	✓
Disruption to the flow – leading to damage	✓	✓	✓	✓
Reduction in filter/screen efficiency		✓	✓	
Reduction in pump and turbine efficiency	✓	✓	✓	
Enhanced erosion for ferrous pipes	✓	✓	✓	✓
Increased biological activity – leading to odours/corrosion	✓		✓	✓
Increased foaming for flow with chemical dosing		✓		✓
Buoyancy effects				✓
Effects on discharge to water or atmosphere – bad odours, foaming, aerated water	✓	✓	✓	✓

Measures can however be taken to address the above problems. For example, where part-full flow is suspected to have developed in a pipeline that was designed to flow full and the flow measuring devices are no longer providing reliable readings, non-intrusive surface water flow meters have successfully been used. Similarly, anti-foaming devices can be installed in shafts; given their complex geometric shape (e.g. helix shape), it is advisable to test them in a physical model. In sewerage pipelines where obnoxious smells from air release valves cause distress to the local population, it is possible to fit odour-control devices, but these need regular maintenance if they are to be effective.

4. Hydraulics of air/water flows

4.1 CHARACTERISTICS OF AIR-WATER MIXTURES

The relative proportion of air and water being transported in a pipe system gives rise to a range of different flow patterns. These patterns also vary depending on the slope of the pipeline. Authors such as Falvey (1980) and Rouhani & Sohal (1983) provide reviews of the possible flow patterns. A summary of typical flow patterns and their definitions are given below. It should be noted that the terminology used herein might differ from that used in some publications and this could be a source of confusion. As mentioned by Rouhani & Sohal more than twenty years ago, up to 84 different flow pattern labels have been suggested in the literature.

As air/water flow patterns differ depending on the pipe slope, distinctions are therefore usually made between flow patterns in vertical, sloping and horizontal pipeline flows.

<u>Vertical flow patterns</u>, which are generally more axisymmetric when compared with horizontal flows, can be described as follows (see Figure 4.1):

- *Bubble flow* – the air is distributed in the water as spherical or spherical cap bubbles which are small with respect to conduit diameter. This flow pattern occurs when a relatively small quantity of air is mixed with a moderate flow of water.
- *Plug flow* – occurs as the air flow increases. The transition from bubble flow to plug flow occurs when the bubble diameter is about one-half the conduit diameter.
- *Slug flow* – as the air flow increases further, a regular train of very large bubbles occurs. Each of these slug bubbles occupies almost the whole pipe cross section except for a thin liquid layer on the wall and their length is several times the pipe diameter.
- *Froth flow* – as the airflow increases, the slug breaks up into a turbulent disordered pattern of air and water. This flow pattern is often referred to as churn flow or churn turbulent flow.
- *Annular* – for relatively high air flow rates with low water flow, annular flow occurs. The water flows as a film on the wall of the pipe while the air moves through the central portion of the pipe.
- *Spray flows* – for very large air flow rates the annular film is stripped from the pipe walls and is carried in the air as entrained droplets. This is sometimes referred to as annular mist flow.

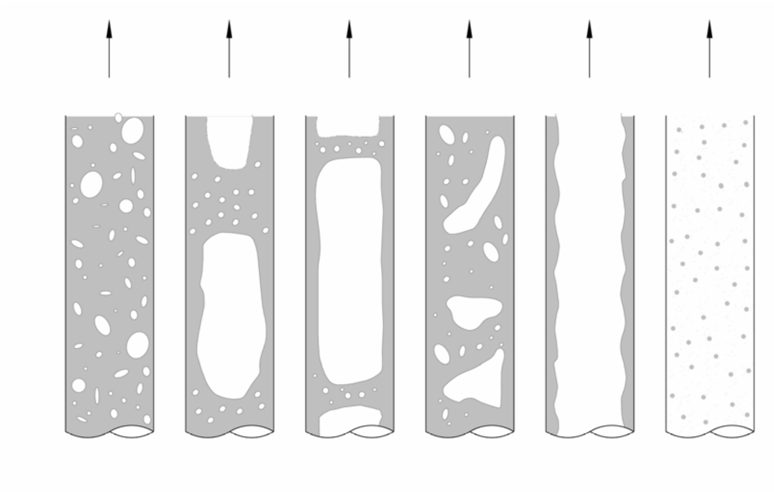

Figure 4.1 Vertical flow patterns (air is represented in white; water in grey)

For flow regimes in inclined pipes, the patterns (Sloping flow patterns) have been found to be the same as in vertical flows except for the limitation or total suppression of the froth flow regime.

In general, most of the flow regimes in horizontal or slightly inclined gravity pipes (Horizontal flow patterns – see Figure 4.2) show a non-symmetrical pattern, which is due to the effects of gravity on fluids with different densities. This generates stratification in the vertical direction, which means that the liquid flow has a tendency to occupy the lower part of the pipe and force the air or vapour to the upper parts:

- *Bubble flow* – the air forms in bubbles at the upper surface of the pipe. The bubble and water velocities are about equal. If the bubbles are dispersed through the water, the flow is termed froth flow. Bubble flow pattern occurs at relatively large liquid flow rates, with little air flow.
- *Plug flow* – for increased air flow rates, the air bubbles coalesce forming an intermittent flow pattern in which air pockets will develop. These pockets or plugs are entrapped in the main water flow and are transported alternately with the water flow along the top of the pipe.
- *Stratified smooth flow* – a distinct horizontal interface separates the air and water flows. This flow pattern is usually observed at relatively low rates of air and water flow.
- *Stratified wavy flow* – as the air flow rate is increased, surface waves appear on the stratified flow interface. The smooth interface will become rippled and wavy.
- *Slug flow* – Wave amplitudes are large enough to seal the conduit. The wave forms a frothy slug where it touches the roof of the conduit. The slug travels with a higher velocity than the average liquid velocity.
- *Annular flow* – for high air flow rates, the water flows as a film on the wall of the pipe (the annular zone) while the air flows in a high-speed core down the central portion of the pipe.
- *Spray flow* – for very great air flow rates the annular film is stripped from the pipe walls and is carried in the air as entrained droplets.

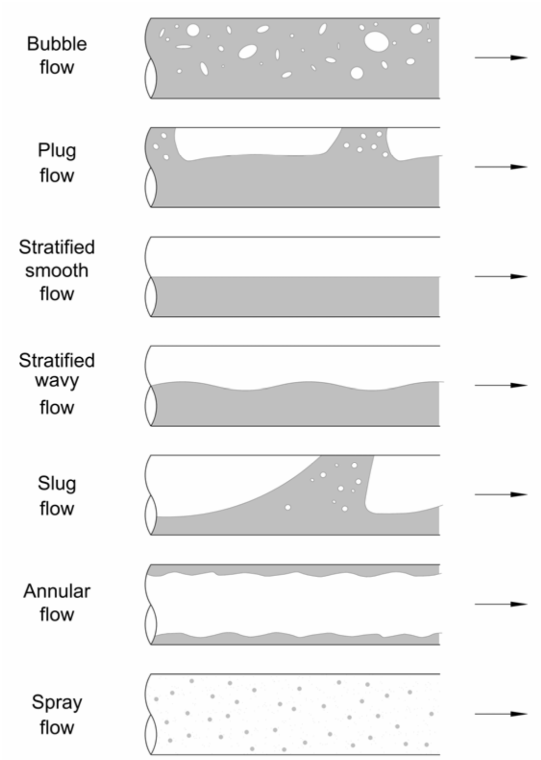

Figure 4.2 Horizontal flow patterns (air is represented in white; water in grey)

Many authors have provided flow pattern maps for the estimation of the onset of these different flow patterns. The transition from one flow pattern to another is a function of a number of different variables, including:

- the gas and liquid mass flow rates
- the properties of the fluids
- the pipe diameter and angle of inclination to the horizontal.

For illustration purposes, Appendix A provides some examples of flow pattern maps based on the relationship between the superficial velocities of the gas and the liquid. The superficial velocity is defined as the fluid velocity (either liquid or gas) multiplied by its volume fraction.

In engineering applications, where maximising the capacity for discharge or transport of water is the main objective, the flow patterns most commonly encountered are those associated with lower air flow rates, namely bubble flow and plug flow and, for higher flow rates, slug flow.

4.2 MOVEMENT OF AIR IN PIPELINES

The following description of air-water movement is given by Kobus (1991) in a monograph on air entrainment in free surface flow. It has been reproduced here to provide a summary of the general conditions concerning the movement of air in pipes.

"The (air) transport capacity of the water depends primarily upon the ratio between water velocity and bubble rise velocity. In stagnant water the transport capacity is zero and the air bubbles will rise to the surface due to their buoyancy and escape. In slow flowing water the entrained air bubbles are displaced by the water flow and the flow field may be changed drastically by the air bubbles …….In closed conduit flows the transport capacity is additionally dependent upon the orientation of the flow with respect to the direction of the buoyancy force. The transport capacity is a maximum in vertically upward flow and a minimum for vertically downward flow."

An interesting illustration of the movement of air in pipelines can be made by considering the case of an instrument well known to civil engineers: the spirit level. A spirit level is essentially a water-filled tube with an air bubble that is disturbed by small movements of the tube. When the spirit level is in a horizontal position, the air bubble is stationary and, due to its buoyancy, sits at the top of the pipe. The pressure and buoyancy forces are in equilibrium. Movement of the spirit level disturbs this equilibrium because a component of the buoyancy force is generated in the upward direction caused by the tilting and local flow velocity of the liquid. This forces the bubble to move upwards (note that a slight curvature is introduced in the pipe to prevent the bubble from moving out of range).

Although an analogy can be made with a spirit level, air movement in pipelines is far more complex not only because the amount of air present can vary along a pipeline but because the shape and the behaviour of air bubbles/pockets are strongly influenced by the amount of air present, the flow conditions (namely the flow velocity) and the pipe slope.

A distinction needs to be made between full-bore pipes and part-full pipes as the flow patterns in the two types of flow are quite dissimilar. Due to variations in operational flow rate, pump stoppages and start-ups, conditions in pipelines can easily shift from full-bore to part-full and vice versa, as illustrated in Figure 7.2 (Chapter 7). These two types of flow condition are described separately in the following sections.

4.2.1 Full-bore conditions

There are three full-bore flow patterns that are of distinct interest in the design of pipeline systems:

For relatively low rates of air moving with the water flow

- bubble flow
- plug flow (air pocket movement)

For higher rates of air

- slug flow, where the air/water flow pattern is intermittent.

Bubbles and air pockets can occur in a number of situations where air is present in a pipeline for reasons mentioned in Chapter 2, whereas slug flow can occur as a result of stoppages and during filling and emptying operations.

Air pocket movement as opposed to bubble movement is of particular interest for engineering applications, given that bubbles will tend to coalesce into air pockets and these present generally more critical conditions for the design and operation of pipelines.

Recent experimental research carried out at HR Wallingford on air pocket movement in pipes set at downward slopes between 0^{o} and 22.5^{o} (Escarameia *et al*, 2005) showed that a range of air pocket shapes could be present in the pipes depending on a number of factors. The distinction between air pockets in very mild slopes and in steeper slopes was apparent (see Figure 4.3). Air pockets were found to be very thin and elongated for pipes set at horizontal or near horizontal slopes but took a wedge-like shape for steeper downward slopes (see Figures 4.4 and 4.5).

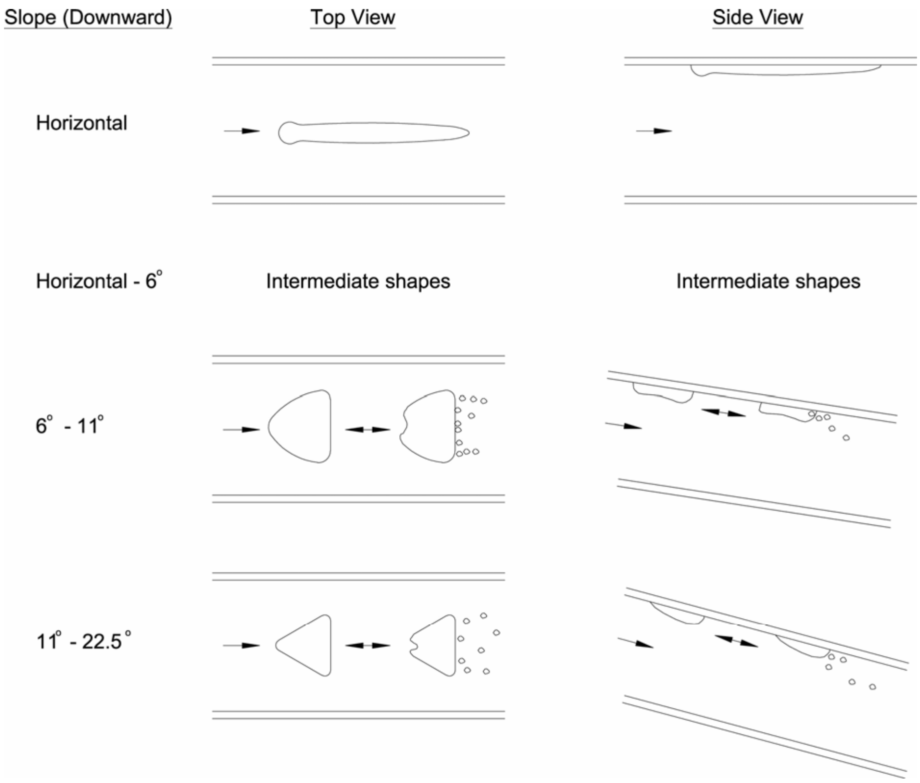

Figure 4.3 Schematic air pocket shapes in pipes: variation with pipe slope (from Escarameia *et al*, 2005)

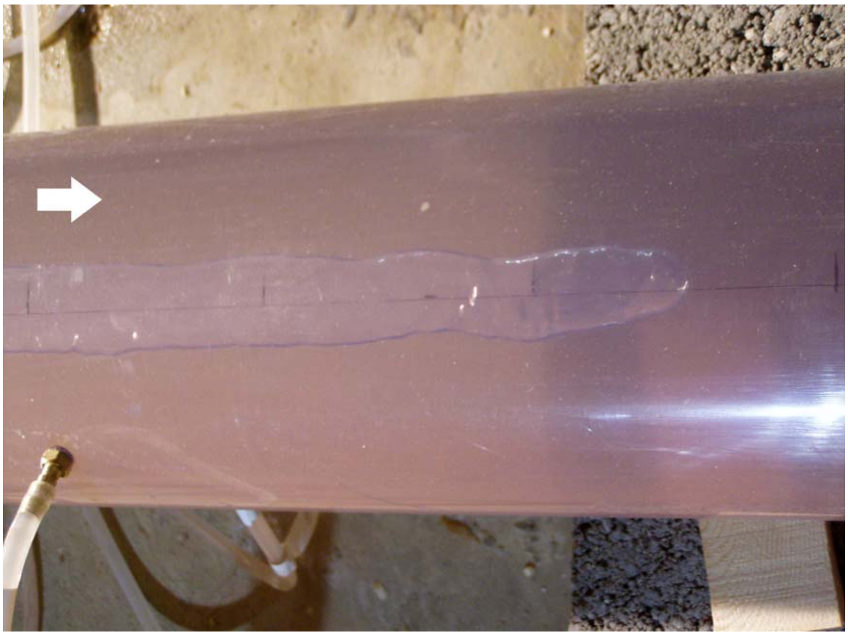

Figure 4.4 Elongated air pocket in horizontal pipe (HR Wallingford study, 2005)

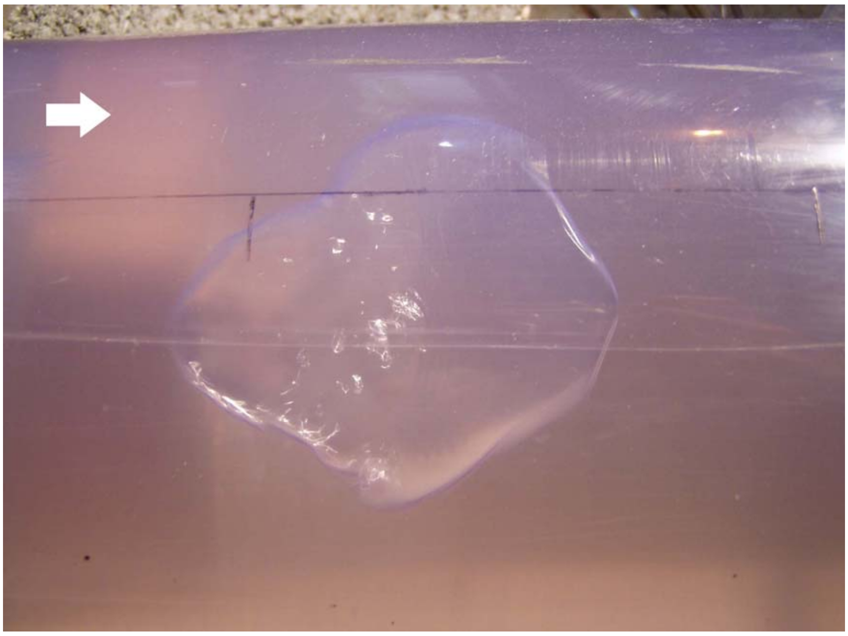

Figure 4.5 Wedge-shape air pocket typical of pipes at steeper slopes; view from top (HR Wallingford study, 2005)

Appendix B provides some experimentally collected information on air pocket length and width and how these dimensions change with increase in the air pocket volume in horizontal and downward sloping pipes. The behaviour of air pockets in horizontal and “near horizontal” pipes was found to be very different.

The mechanisms of air movement in pipes of varying slope have been studied by a number of researchers including Kalinske & Robertson (1943), Kent (1952), Wallis (1969), Wisner *et al* (1975), Mosevoll (1976), Bendiksen (1984) and Ervine (1998) to mention but a few. Useful summaries of work in this field can be found in Little (2002) and Lauchlan *et al* (2005).

4.2.2 Part-full flow conditions

When pipes are flowing part-full, hydraulic jumps sometimes form in downward sloping pipes. The rate of air removal by the pumping action of the hydraulic jump (air entrainment) is one of the important issues associated with air in pipelines. Several researchers have worked on this topic, namely Chanson & Qiao (1994), Kalinske & Robertson (1943) and Escarameia *et al* (2005). Lauchlan *et al* (2005) provides an overview of published literature.

It is generally accepted that the violent action of the hydraulic jump is used only to break up the large air pocket upstream into small bubbles, which the flow rate is capable of carrying. If the flow rate is still insufficient to carry these small bubbles through, the churning action of the jump will have no effect on the amount of air the system can remove. The maximum churning rate will be reached when the depth of flow under the air pocket has reached normal depth for that discharge and slope.

Figure 4.6 gives an illustration of the flow patterns in a hydraulic jump in a downward sloping circular pipe. With regard to the jump length, two lengths can be identified:

- Jump front length (JFL), which is defined as the length of the steep face of the jump; and
- Overall jump length (OJL).

Values for these two lengths normalised by the pipe diameter are given in Chapter 6.

Through an experimental study in 150mm diameter pipes, Escarameia *et al* (2005) confirmed the observations of previous researchers (for example Kalinske & Bliss,1943) who reported the following phenomenon at hydraulic jumps. The air is entrained by the jump in the form of bubbles, typically 3 to 5mm in diameter; a proportion of these bubbles is carried downstream by the flow but a certain amount coalesces as they move downstream, increasing in size. Due to this increase in size and therefore in buoyancy, the bubbles rise to the top of the pipe where they coalesce further into air pockets of several tens of millimetres in size. These pockets then move upstream towards the front of the hydraulic jump and the air is engulfed back into the air cavity upstream of the jump. This phenomenon appears to be periodic: the average duration of a complete cycle measured in the HR Wallingford tests varied between 7 and 40 seconds, with maximum durations of almost 2 minutes.

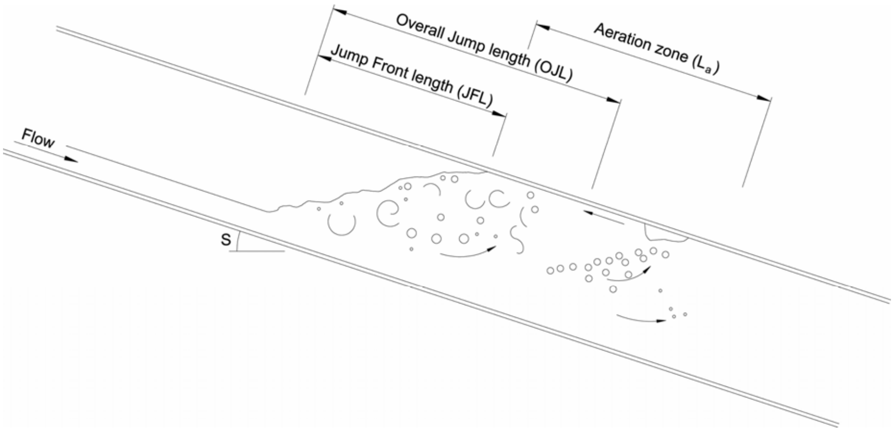

Figure 4.6 Schematic of hydraulic jump in a circular downward sloping pipe

Chapter 7 provides further information on design of pipelines under part-full flow conditions.

5. Hydraulic transients

5.1 BACKGROUND

Pressure transients in pipeline systems are caused by the interruption to fluid flow arising from operational changes, affecting the various boundary conditions which dictate behaviour. These can include starting/stopping of pumps – either by routine action or power failure, changes to valve settings, changes in power demand, action of reciprocating pumps and vibration of impellers or guide vanes in pumps etc.

There is a wealth of literature available addressing the problem of fluid transients or ‘waterhammer’, the most notable source reference probably being the work of Wylie & Streeter (1978). Many hydraulics textbooks provide a useful elementary overview of the background theory (e.g. Nalluri & Featherstone, 2001) for the non-specialist civil engineer. The works of Thorley (1979, 1991) provide, in the case of the former, guidelines for computational formulations and in the latter a broader descriptive background with practical case studies. Anderson (2000) provides a useful historical overview of the subject.

The effects of entrapped or entrained air on surge pressures experienced by a pipeline can be either beneficial or detrimental, the outcome being dependent on the air pocket volume, distribution and location, the characteristics of the pipeline concerned and the nature and cause of the transient. By way of illustration, Figure 5.1 shows the effect on transient pressures arising from pump shut down of air pockets (of volume V_{air}=0.015m^3 and V_{air}=0.700m^3) compared with that without air present (V_{air}=0m^3), see Burrows & Qiu (1996).

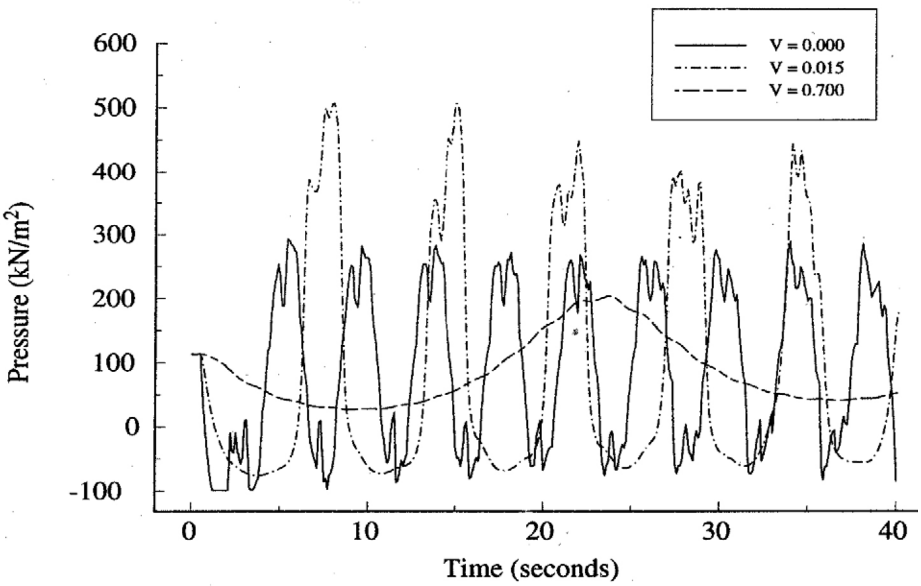

Figure 5.1 Effect on pressure transients of air pockets of various volumes

The existence of entrained air bubbles within the fluid, together with the presence of pockets of air complicates the analysis of the transient pressures and makes it increasingly difficult to predict the true effects on surge pressures, as reported early in the standard references (Wylie & Streeter, 1978) and subsequently elucidated in numerous scientific contributions, some of which are cited herein.

Under low pressures the phenomenon of gas release, or cavitation, creates vapour cavities. When swept with the flow to locations of higher pressure or subject to the high pressures of a transient pressure wave, vapour cavities can collapse suddenly, creating further ‘impact’ pressure rise and potentially causing severe damage to the pipeline. In normal pipeline design, cavitation risk is to be avoided as far as is possible or practicable. The work of Burrows & Qui (1995) highlighted that the presence of air pockets can be further detrimental to pipelines subject to un-suppressed pressure transients and localised cavitation, such that substantial underestimation of the peak pressures might result.

In contrast to the above adverse effects of air, the speed of travel of an induced (transient) pressure wave can be greatly reduced and its amplitude dampened if gas bubbles are distributed evenly throughout the liquid (Wylie & Streeter, 1978) as the amount of free air present will increase the elasticity of the fluid. The gas will only be evenly dispersed, however, if the velocity of the liquid is moderate. Moreover, if the velocity of the liquid does not remain constant or moderate, pockets of air will form. Additionally, the air can accumulate into intermittent columns of gas and liquid when the liquid is flowing more rapidly (Martin, 1976) and in these circumstances a more detailed analysis of the then multi-phase flow (water and air-filled voids) may be called for. This occurrence, generally characterised by high gas fraction, is common in fuel lines associated with oil/gas wells and delivery pipelines and industrial pipe systems (Falk & Gudmundsson, 2000, Fujii & Akagawa, 2000).

5.2 REVIEW OF MODELLING APPROACHES

The practical standard for the modelling of ‘waterhammer’ is a one-dimensional analysis of the flow, where the underlying equations of motion (continuity and momentum) are expressed in terms of changes over finite intervals in space (Δx) along the pipeline and time (Δt). The resulting finite difference equations can then be configured for solution by the so-called Method of Characteristics (MOC), derivations being widely available (Wiley & Streeter 1978, Thorley 1979, 1991, Nalluri & Featherstone 2001).

For the single fluid problem, this approach is normally acceptable for predictive design though refinements can improve the simulation of experimental observations in terms of shape of the pressure peaks, the frequency of the oscillations and the rate of decay.

When air is entrained such that the gas void fraction is significant and two-phase motion occurs between the water and air in bubbles, pockets and/or voids, it may become necessary to introduce multi-phase modelling. This can be introduced at different levels (Falk & Gudmundsson, 2000, Fujii & Akagawa, 2000, Huygens et al, 1998 and Lee et al, 2003) ranging from a two-fluid (two component) model which satisfies the equations of motion (conservation equations) in each fluid concurrently, to a homogeneous flow model, which assumes the same velocities in each phase, effectively requiring input of mean parameters (i.e. density and pressure wave speed) into the normal formulation. Falk reports that the modified MOC gives a good picture of the pressure waves but is unable to predict void waves, a proposition also concluded by Huygens.

Returning to the potential adverse effect of air variously mooted as the cause of underestimation of observed peak pressures by standard (MOC based) problem synthesis. Various attempts at explanation have been put forward, mostly supported by reference to associated modelling studies. Lee’s work (1994), attempting to explain the underestimation of observed peak pressures using standard waterhammer theory, was established on a numerical model based on variable wave speeds arising from the release/absorption of gas as the pressures change. Whilst the presumption of diffusion of gas volume (time delayed release/re-absorption in Lee’s model) during the transient is apparently at odds with the view of Huygens et al (1998), the results demonstrated that the peak pressure could be significantly higher than predicted by the standard (fixed wave speed) theory.

Given the potential range of issues relating to the level of sophistication to be adopted and related assumptions to be made, a need for guidelines has been recognised. Brunone (1999) and Baker & Ramos (2000) report EU sponsored studies towards European standards for transient analysis software, intended to guide practitioners to the appropriate level of modelling complexity consistent with the problem to be tackled. Attempt has been made to utilise formal 'Design of Experiments' methodology (Stewardson et al, 2000) to characterise behaviour and provide predictive modelling on the basis of multi-regression from simulations of a specific transient problem with a degree of success. However, the study fell some way short of providing any general (predictive) guidance for typical, and potentially complex, systems. The unlikelihood is increased substantially if air presence is to be accommodated since Lee and Pejovic (1996) have earlier demonstrated the absence of underlying laws of similarity, which might be expected to underpin the validity of regression outcomes based on dimensional analysis etc.

In respect of the structural integrity of the pipeline, the implications of the hydrodynamic variations to potential structural response and fatigue damage should also be addressed, especially in respect of suitable forms of pipe restraint. Recent contributions by Kajaste (1998) and Rashid & Mattos (1998a, 1998b, 1999) address elasto-plastic pipe behaviour, cumulative damage and lifetime estimation as well as structural failure based on coupled and uncoupled modelling. Jang & Aral (2003) further investigate the increased risks of pipe corrosion damage from collapsing vapour bubbles as a result of pressure transients.

In the light of the many and varied factors associated with waterhammer in pipelines, the recommendation of Baker & Ramos (2000) that competent transient modelling contractors be employed to do the detailed investigations, such that due consideration can be given to all the potential modelling issues, would therefore appear to be sound advice.

5.3 PRACTICAL CONSIDERATIONS

Specific issues related to the impact of air in respect of the propagation of transient pressures in the pipeline flow are considered in the following sequence:

(i) Air columns (e.g. rapid filling problems)

(ii) Air vessels

(iii) Reflux (Check) valves

(iv) Air valves

(v) Air pockets

Air columns

Air columns taking up the entire pipe cross-section may form during the rapid filling of a pipeline, partial drainage of a rising main or as a result of tidal drawdown of a marine outfall following topographical profile. The air column might be located adjacent to a closed valve at the end of the pipeline or may separate two water columns at the high point of an undulating profile. Several investigators have reported that peak transient pressures can be larger than those arising in the absence of the air-filled void (i.e. with the pipeline full of water when the transient is initiated).

For large air voids occupying the full pipe cross section significant dynamic amplification of the original driving pressures can be expected. With well defined (and spatially limited) air/water interfaces, which may extend over multiple spatial (Δx) increments, a simplified rigid column analysis may be sufficient, but customised modelling routines are likely to be called for and preliminary reference to the works cited above is suggested prior to commissioning the work.

Air vessels

Air vessels, sometimes referred to as surge vessels, are standard devices employed for surge suppression on pipelines subject to pressure transients. They function by translating the energy of the pressure wave into a much slower mass oscillation, decreasing the pressure wave amplitudes in the process. Detailed account of their properties can be found from most transient flow references, some practical considerations recently being offered by Verhoeven et al (1998) and Tan & Zhou (2003), the latter pointing out the potential benefits of installing multiple vessels. Ngoh & Lee (1998) investigated the influence of entrained air in the flow on the function of air vessels with largely inconsequential outcome given the inherent effectiveness of the vessels in surge suppression.

The surge suppressing capability of air vessels should not be compromised by entrained air. The possibility of continuous accumulation of additional air into the vessel from migrating air bubbles or pockets in the pipeline may be considered, although this is unlikely to occur with standard surge vessel connection arrangements. In any case, dissolution of air would almost certainly be the dominant effect, requiring measures such as compression equipment to top up the air volume, or membrane separation of the air and water. Inadequate design or inappropriate operation of the vessels can result in air entering the line from the vessel, and this could therefore be another potential source of air in pipelines. Suitable design and operation of vessels will eliminate this risk.

Reflux (check) valves

Check valves are routinely installed downstream of pump units to prevent backflow and draining of the pipeline/rising-main when the pumps are inoperative. The sudden closure of these valves upon pump shutdown can exacerbate the basic flow transient, resulting in 'gate slam' potentially coupled with cavity formation (cavitation).

Modelling of check-valve dynamics may be necessary to fully address the problem of transients in pipelines without surge suppression measures installed (i.e. air vessels, air valves, high pump inertia etc). There is evidence that the presence of entrained air and/or local air pockets can increase positive pressure peaks.

The risk and effects of check valve slam should in general be considered during transient analyses. There are no direct guidelines on what constitutes an acceptable slam pressure however, and unfortunately it is often difficult to obtain dynamic characteristics of valves from manufacturers.

Air valves

Air valves, whilst being crucial for the evacuation of large build-ups of air within pipeline systems, are recognised to create also operational problems, not least in respect of potential impact on surge pressures. Hunt (2004) has recently offered practical guidelines for air valve installation and De Martino et al (2000) have investigated the transients propagated by air valves. Lee TS (1999), using his variable wave speed modelling approach to address air entrainment, has presented a rigorous treatment of air valve (with associated air pocket) dynamics and confirms the increased risk of higher positive peak pressures. Additional to these studies, work of Martin and Lee (2000) examine the effects of entrapped air following expulsion through orifices of varying diameter, creating a situation analogous to air valve operation, concluding that the maximum pressures achievable as the air is expelled can exceed those of both an entrapped air cavity and pure water hammer, and suggest optimum orifice sizes for the control of the shock wave. On the basis of experimental data, De Martino et al (2000) comment on the most favourable design in terms of shock wave control via the installation of air valves. It is to be noted that excessive air release capacity can result in very high 'impact loading' as the last of the air is evacuated. It is difficult to obtain reliable information on shock loads that can be withstood by air valves.

Air valves require regular maintenance, and when neglected, can deteriorate to the point where they are no longer able to fulfil their function. This raises a specific concern where air valves are designed as part of the surge protection system. In such cases, the surge analysis should include a consideration of the effect of failure of the critical air valves, and if this is found to result in potential damage to the pipeline, alternative surge mitigation measures should be considered.

It can be concluded that air valves offer an essential function of bleeding the internal build-up of air so as to prevent hydraulic constriction in pipeline delivery. They can also provide a secondary benefit in preventing cavitation during negative pressure surge by drawing in air, whilst potentially worsening the scale of positive pressure peaks. Modelling software can be so configured to adequately represent their effect on the loading from transients. The installation of air valves is not a viable solution in all situations, however, especially in underwater pipelines and in wastewater (sewerage) applications where solids and debris can severely affect operation of the valves and their seatings. The use of air valves for surge mitigation is also not advisable in pipelines conveying potable water where there is a risk that they may allow ingress of ground water into the pipeline.

Air pockets

The presence of air in pockets in proximity to check valves (Jonsson, 1985) and air valves (see above) have been shown to potentially increase surge pressure peaks. In the absence of air valves on all summits of undulating pipeline profiles, the presence of air pockets, even if migratory, is inevitable, with potential impact on resulting surge. In support for explicit consideration of potential 'air pocket' formation in modelling studies, Larsen and Burrows (1992) compared actual observed transient effects in several real Danish sewerage (rising-main) pipelines with the output of a numerical model. The comparisons drawn therein highlighted the combined effects of both cavitation and air pockets on the transient pressures and it was found that only by the inclusion of the air pockets along high points within the numerical model could the observed peak pressures be reasonably well matched. Subsequently, it has been shown from these same case study data sets that, whilst a large air cavity acts as an effective accumulator and suppresses the maximum pressure excursions, following pump shut-down for example, it seems that small pocket volumes, or volume split between multiple pockets, can substantially exacerbate the peak pressure experienced (Burrows and Qui, 1995).

Burrows (2003) further cites a real case study where a rising main suffers from repeated fractures over a period of several years. The study found that following standard analysis of the pressures within the system (then being subject to cavitation arising from operation without the benefit of an originally installed air vessel for surge suppression), it was determined that the synthesised pressures would not have been solely responsible for the repeated failure of the pipe. Following initial MOC-based computer simulation of the transient pressures using WHPS (after Larsen, 1992) and additional work by Burrows and Qiu (1996), it was concluded that the presence of small pockets of air could have had a potentially profound effect on the levels of surge pressure experienced by an abrupt interruption of flow arising from routine pump shutdown. It was contended that this could have serious implications for hydraulic systems where surge analysis has not accounted for air accumulation.

In the light of these findings and the fact that air pocket accumulations might be feasible under some conditions in most pipeline systems, a series of numerical experiments has recently been conducted at the University of Liverpool based on case study pipelines. A summary of this work is presented in Appendix C.

From the results obtained, potential peak pressure magnification due to air pockets by an enhancement factor of up to 2.6 over the outcome of a normal (MOC) transient modelling analysis has been observed. Allowing such a factor would provide the cautious designer with a suitably conservative prediction of the pressures that could potentially be present in a pipeline system, under transient conditions, if precautionary surge suppression ancillaries are omitted from the design. However, if it were found that these figures result in an excessively expensive system a more rigorous analysis would be recommended.

5.4 DISCUSSION

Air accumulations in a pipeline are both unintentional and unavoidable and, in most cases, will be unquantifiable. As a consequence, the potential influence upon pressure transients is rarely, if ever, given consideration, either at the design stage or in any operational planning investigation. Situations where severe transients may occur include system malfunction or temporary operation during maintenance or repair. In poorly designed installations, such occurrences may regularly follow normal pump start or shutdown.

The outcome of limited numerical studies (see Appendix C) has shown that the presence of single air pockets of a critical (small) size, at potentially many locations (but especially so in the upstream section of a pipeline), can result in significant exacerbation of peak transient pressures, as well as triggering also a cavitation risk. Pressure magnification as high as a factor of 2.6 has been observed in the numerical experiments conducted at University of Liverpool and figures as high as 9 have been observed by others in the modeling community. Earlier work (Burrows & Qiu, 1995) also found that, for pipelines with multi-summits, a distribution of the air void between each of the high points also exacerbated the pressures.

The risk can be avoided completely where suitably designed air vessels, or other surge suppression, are deployed within the pipeline design. It has been demonstrated that small volumes of air at specific locations can enhance surge pressures. It follows, therefore, that undersized or inappropriately operated vessels can actually result in higher extreme surge pressures than might be expected without surge protection, for example if the vessel is operated with inadequate air volume.

In surge analysis, the assumption of dissolved or entrained air permits the use of a variable wave speed approach in which wave speed varies with local pressure, depending on an assumed proportion of free air. The consequence of this assumption is usually that surge pressure oscillations are mitigated, and surge protection requirements may be relaxed. Surge analysts commonly make use of this effect, but consideration should always be given to the validity of the assumption. It may be difficult to justify relying on free air in a clean water pumping system where the water has been standing in reservoirs for some time. Consider for example a pumping station delivering water from a desalination plant.

The dilemma facing the practitioner and designer of systems not afforded such protection, therefore, is the question of whether the modelling study is sufficiently reliable and realistic for these radical findings to be adopted. Clear evidence exists of peak pressures observed in the field exceeding conventional model predictions, as discussed in the review earlier. Yet, omission of such allowances for the adverse effects of air pockets on peak pressures would be expected to subsume the normal factors of safety in design (i.e. the ratio ultimate stress: working stress) such that widespread structural failure might be expected. Conversely, it could be that in reality pipelines entrapping air rarely possess accumulations that prove critical (i.e. small pockets, possibly at only several finite locations). Intuitively, and on the contrary, a widespread distribution of accumulations of varying size might be expected to offer effective damping, either directly by pressure wave energy absorption or by the destructive interference effect of the multiple reflections created.

In the absence of better information in respect of the true extent of air accumulations in pipelines, and perhaps more openness in the report of pipeline failures, no firm guidance can be given here. Therefore, the decision on the allowance to be made for flow capacity losses and the possibility of pipeline damage that may occur due to air entrapment rests on the overall level of engineering prudence to be adopted. Judgement should be drawn from best available knowledge and could be supported by detailed analysis such as described above where it is thought that there could be very sensitive problems. It is generally best to design in such a way as to avoid as far as possible the possibility of accumulation of air in the first place.

6. Performance criteria

6.1 OVERVIEW OF CURRENT PRACTICE

There appears to be an agreement among practitioners that the current published information is insufficient and confusing (and sometimes even flawed) with regard to the design of pipelines to prevent air problems. The areas that are normally considered in design are listed below together with brief summaries of the practical information available. Much of the traditional guidance on air management is concerned with location and specification of air valves and the AWWA manual M51 is widely used. A critical discussion of current design guidance, its limitations and implications to pipeline schemes is given in Chapter 7.

Pipeline profile

With regard to the pipeline profile, pipelines will typically follow the ground profile but with some requirements for minimum cover and minimum pipe gradient. Some practice manuals have suggested that, in near level terrain, pipes should be laid with a saw tooth profile with minimum slopes of 1:250 (downward in the direction of flow) and 1:500 (upward in the direction of flow). The slope of 1:500 has been suggested as the shallowest gradient that can be constructed without risk of a backfall. Some designers, however, are using flatter slopes in some cases and avoiding the requirement for installation of air valves, particularly in areas where maintenance and access are difficult. It should also be noted that the specification of either option - saw tooth profiles and very mild slopes – has cost implications and that setting pipelines to a very shallow gradient is not always easy to achieve in practice. Pipe gradient will be chosen to suit specific project needs. Chapter 7 gives further elaboration.

Hydraulic considerations

Design pipe full flow velocities for pumping mains typically are in the range of 1 to 2m/s, based on economic analysis of whole life costs. The requirement for a minimum downward slope is linked with the need to prevent pipes flowing more than 2/3 full during priming or re-priming, to allow air to pass upstream to an open air valve. Some designers have adopted half-full pipe as the condition to achieve the above and this might be preferable, particularly for small pipe sizes. Information on critical velocities for movement of air in pipelines can be sourced from a number of publications but is often contradictory and therefore confusing (see Little, 2002, and Lauchlan *et al* 2005). A useful practical reference is provided by Mosevoll (1976) who proposes the following equations: $V/(gD)^{0.5} = 0.6$ for S< 20 degrees and $V/(gD)^{0.5} = 0.45 + 0.4(\sin S)^{0.5}$ for S between 20 and 40 degrees. In these relationships V is the mean pipe velocity, g is the acceleration due to gravity, D is the pipe diameter and S is the pipe slope angle.

Spacing and location of air valves

Different air valve manufacturers offer their own recommendations on air valve spacing, typically in the range 500m to 800m. Chapter 7 elaborates on air valve location.

Some practitioners locate air valves exactly at the high points but there is some awareness that the air can collect slightly downstream of this point, thus rendering the valve ineffective. Recommendations from some air valve manufacturers indicate that it is advantageous to position air valves a few metres downstream of apex points formed by the proximity of the pipeline to the hydraulic grade line.

6.2 RECOMMENDATIONS FOR DESIGN

The recommendations provided in this section are applicable to single sections or reaches of pipe as opposed to the whole length of the pipeline. They are a result, to a large extent, of work recently conducted at HR Wallingford, UK, on the movement of air in pipelines (see Lauchlan *et al*, 2005 and Escarameia *et al*, 2005).

This section provides information on three distinct types of flow velocity that are useful to consider in the design of pipelines:

- The minimum velocity of the liquid (typically water) that is required to completely shift an air pocket from a section of pipe. This is termed Critical Velocity, V.
- The velocity of the liquid that is required to sustain an air pocket in a stable location in a section of pipe. This is termed Hovering Velocity, V_h.
- The velocity of travel of air pockets in liquid flows in pipes. This is termed here Air Pocket Velocity, V_p.

Both the Critical Velocity and the Hovering Velocity are defined as the mean pipe velocity in a section of pipe unaffected by the presence of air pockets, i.e. where water fills all of the pipe cross-section. Information is also provided on hydraulic jumps and on the effect of air pockets on energy losses.

Critical velocity for air pocket movement

The critical velocity for air pocket movement, V, is the velocity required to completely remove an air pocket from a section of pipe. The study by HR Wallingford, combined with previous investigations, found that this critical velocity is dependent upon the downward slope of the pipe. It was also apparent that there is a dependency on the size of the air pocket. For upward sloping pipes experimental evidence suggests that air pockets rise without the need for any flow velocity due predominantly to the effects of buoyancy. This has been experimentally established for smooth-walled pipes of 100 and 150mm diameter set at very mild slopes. It is possible, however, in real pipelines at very mild slopes, where air pockets can be very elongated (see Figure 4.3) that these may be held at joints and thereby resist movement.

The critical velocity, measured in a cross-section free from air pockets, for a range of downward slopes can be predicted by:

$$V/(gD)^{0.5} = a + 0.56\,(\sin S)^{0.5} \qquad (6.1)$$

where *a* equals:

0.45	for	$n < 0.06$
0.50	for	$0.06 \leq n < 0.12$
0.57	for	$0.12 \leq n < 0.30$
0.61	for	$0.30 \leq n < 2$

In the above equation V is the minimum mean pipe velocity required for movement of an air pocket with size defined by the parameter $n = 4V_{air} / (\pi D^3)$ in a downward pipe of slope angle S and diameter D. V_{air} is the volume of the air pocket. It is recommended to increase the critical velocity given by Equation (6.1) by using a safety factor S_f; a value of 1.1 is suggested.

This equation was developed based on a range of air pocket sizes and the maximum values of critical velocity associated with each of the air pocket classes were used in the development of the equation. It can therefore be said that the equation was based on an envelope to the data. However, no safety factor was applied and, for engineering applications consideration of a safety factor, S_f, is advisable.

The applicability of the above equation is as follows:

- Downward slopes from 0 to 22.5 degrees (1/2.4). There is experimental evidence from other researchers (see Escarameia *et al*, 2005) that this relationship may be valid for slopes up to 40 degrees (1/1.2). Beyond this slope, the critical flow velocity may start to decrease with the slope, as found by some researchers. Estimates of critical velocity in this region can be obtained based on Figure D.1, Appendix D.

- Air pockets with sizes in the range defined by n=0.0002 to 2 in a 150mm diameter pipe. This corresponded to air pocket volumes of 0.5ml to 5 litres. For larger air pockets, the required critical velocity for pocket movement may not increase significantly. It is thus suggested that taking a=0.61 for larger pocket sizes above 5 litres (in 150mm diameter pipe) may be reasonable, until further work is carried out in this field.

- Tests were performed in a single pipe diameter of 0.150m. There is evidence from previous research (as discussed in Lauchlan *et al*, 2005) that scale effects due to surface tension can be neglected if pipes of this size are used. Therefore, extending the results to larger pipe diameters appears to be legitimate. However, published information refers to bubbles in stationary flows and the behaviour of air pockets is likely to be affected by the air/water aspect ratio, i.e. the cross-sectional area occupied by the air pocket divided by the whole cross-sectional area. Although not confirmed experimentally or otherwise, in larger diameter pipes the smaller curvature of the pipe walls may be conducive to generating shallower air pockets, which would be associated with lower aspect ratios when compared with air pockets in smaller diameter pipes. Critical velocities required to move such air pockets would be relatively smaller than those predicted by Equation (6.1). In view of the uncertainty in this area, it appears reasonable to suggest that Equation (6.1) can be used with confidence for pipe diameters of up to 1m. For this size, the required velocity for air pocket movement in a horizontal pipe as predicted by this equation for large air pockets is 1.9m/s (excluding any safety factors). For larger pipe sizes Equation (6.1) indicates that very large velocity values, well in excess of 2m/s, would be required to move air pockets but current experience suggests that lower velocities may suffice. In Appendix E a possible approach for the application of Equation (6.1) to pipes with diameter in excess of 1m is presented. It should be emphasized that this is suggested as one possible way to overcome the lack of theoretical or experimental support with regard to scaling up results.

Figure 6.1 illustrates the variation of the critical velocity with downward slope for a pipe of 0.150m diameter and Figure 6.2 shows the assumed variation with pipe diameter for a horizontal pipe. A line corresponding to typical pumping velocities in the UK (1.2m/s) is also presented in Figure 6.2 – see 7.3.2.1. In both graphs values were calculated using Equation (6.1) with no added safety factor.

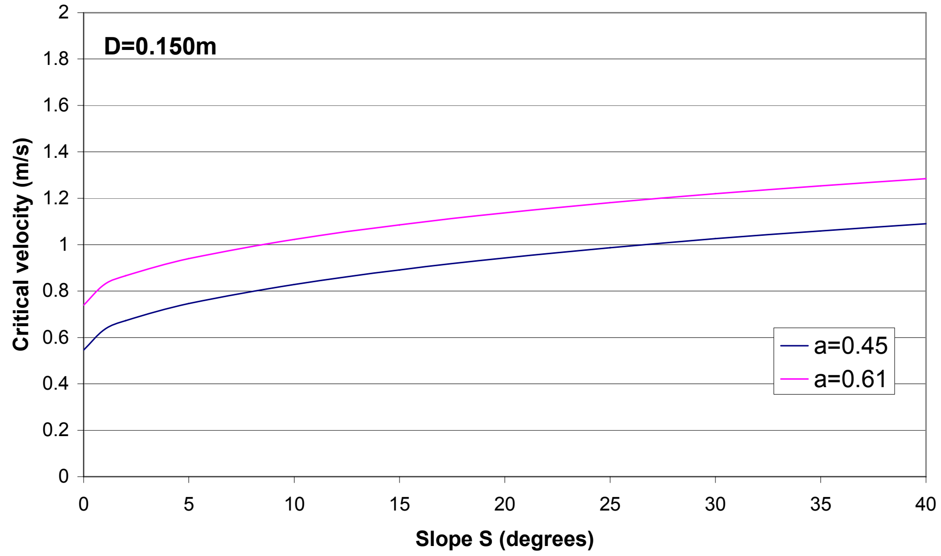

Figure 6.1 Variation of critical velocity with pipe slope for a pipe diameter of 0.150m (no allowance for safety factor)

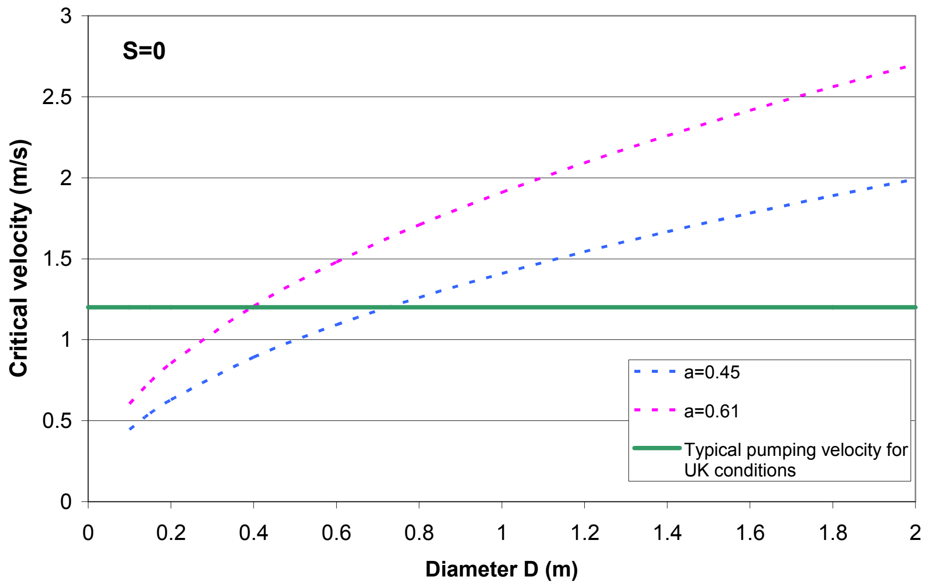

Figure 6.2 Variation of critical velocity with pipe diameter for horizontal pipe (no allowance for safety factor)

Important Note: There is substantial uncertainty regarding predicted critical velocities for pipes above 1m in diameter (see discussion earlier in this section and Appendix E).

Air pocket velocity

The speed at which an air pocket is transported by the flow, Air Pocket Velocity V_p, can be of interest for the estimation of the time required to remove a certain amount of air from a section of pipeline.

For air pockets varying between 0.5ml and 5 litres in volume (in a 150mm diameter pipe), air pocket velocities of the order of 0.02 to 0.6 m/s can be expected in downward sloping pipes (slopes between 0 and 22.5 degrees). An exponential decline of the ratio air pocket velocity/critical flow velocity with increasing slope was found in the HR Wallingford study (Escarameia *et al*, 2005), implying that expelling the same volume of air from a steep pipe will take longer than from a pipe at a milder slope. For the same pipe diameter, the time required to move an air pocket in a pipe at 11 degrees can be 15 times greater than in a horizontal pipe.

Hovering velocity

The flow velocity of the liquid that is required to sustain an air pocket in a stable location in a section of pipe is termed here Hovering Velocity, V_h. Similarly to the critical flow velocity, the hovering velocity is defined based on a cross-section upstream of the air pocket, where the whole pipe cross-section is filled with water.

Experimental data obtained during the HR Wallingford study in downward pipes with slopes ranging between 0.8 degrees and 22.5 degrees showed that values of the hovering velocity, V_h, could be related to the critical flow velocity, V, by the following expression:

$$V_h = \beta V \qquad (6.2)$$

where β can be taken on average as 0.90. Although this coefficient is suggested as a constant for design purposes, slightly lower values were found the flatter the pipe slope (0.85 for slope of 0.8 degrees compared with 0.93 for slope of 22.5 degrees). This indicates that air pockets may be more stable under flatter slopes, as a larger increase in velocity is required to make them move when compared with steeper slopes where a smaller increase in velocity will suffice.

Figure 6.3, which is based on the HR Wallingford work, illustrates how the critical velocity for air pocket movement is thought to vary with pipe slope, from upward sloping pipes (negative x-axis), through horizontal to downward sloping pipes (positive x-axis). In this graph, dashed lines were drawn around the flatter slopes to indicate a zone of uncertainty. This uncertainty is a result of difficulties in achieving high accuracy when establishing horizontal or near horizontal slopes in the relatively short length of pipe (compared with real pipeline schemes) that was available in the test section. The accuracy when setting the horizontal slope was ±0.036 degrees (which corresponds to $(\sin S)^{0.5} = \pm 0.025$). In order to clear air pockets from downward sloping pipes, the required flow velocities need to be on or above the red line and air pockets are unlikely to move upwards if velocities do not drop below the blue line (hovering conditions). As mentioned earlier in this Section, there is experimental evidence suggesting that in upward sloping pipes air pockets do not require any flow velocity to initiate movement.

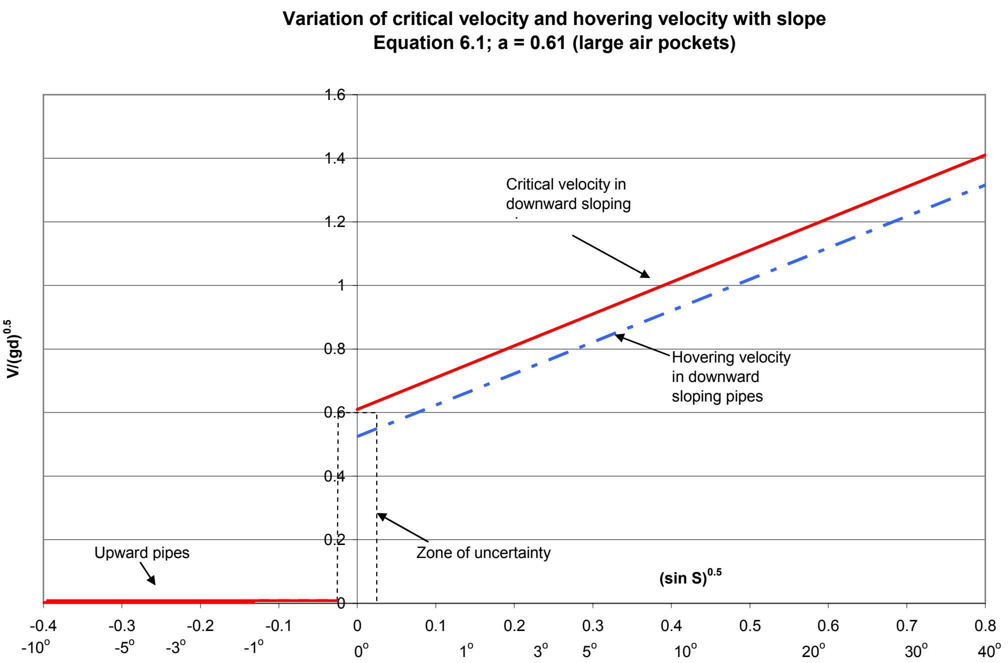

Figure 6.3 General variation of critical velocity with pipe slope

Hydraulic jumps in downward sloping circular pipes

The formation of a hydraulic jump in a circular pipe is a mechanism by which air can be both entrained and removed from the pipe system. Figure 4.6 shows a schematic diagram of a hydraulic jump in a downward sloping pipe. For the test conditions covered in the HR Wallingford study (Froude numbers ranging between 1.3 and 3.0 – see definition given by Equation 6.4), the ratio Overall Jump Length/Diameter varied between 2 and 11 and the ratio Jump Front Length/Diameter varied between 1.3 and 5.

The following expression, developed from the HR Wallingford study from tests at slopes from 0 to 22.7 degrees can be used to estimate the rate of air entrainment by a hydraulic jump in a circular pipe:

$$Q_{air} = 0.0025(Fr - 1)^{1.8}\ Q \qquad (6.3)$$

where Q is the water flow rate, Q_{air} is the air flow rate and Fr is the flow Froude number defined as

$$Fr = QB^{0.5}/(A^{1.5}g^{0.5}) \qquad (6.4)$$

where B is the surface width of the flow upstream of the hydraulic jump and A is the flow area in that section; g is the acceleration due to gravity.

Equation (6.3) is applicable to the situation where the conditions downstream of the hydraulic jump are pipe full.

Other equations are available in the literature, namely those suggested by Rabben, Rajaratnan and Wisner and described by Chanson & Qiao (1994) but when compared with the HR Wallingford equation they show a significantly higher rate of expulsion of air. This can be attributed to factors such as different pipe cross-sectional shape (rectangular rather than circular) and downstream exit conditions (open–channel as opposed to pipe-full). Kalinske & Robertson (1943) suggested a relationship which predicts a higher rate of air expulsion than the HR Wallingford equation. Kalinske & Robertson's data relate to pipe slopes from 0% to 30% but applies only where all the entrained air is carried forward and discharged:

$$Q_{air} = 0.0066\left(Fr - 1\right)^{1.4}\ Q \tag{6.5}$$

When a hydraulic jump forms in a pipe it may be important to position the jump so that significant volumes of air are not entrained and swept into regions where air could accumulate as large pockets. A study detailed by Mosevoll (1976) used experimental tests to develop an expression for the "aeration zone" in a hydraulic jump in a circular pipe. The aeration zone, shown in Figure 4.6, was defined as the length downstream of the front of the hydraulic jump for which large air bubbles and pockets are present in the flow. The aeration zone was defined as:

$$L_a = 4\frac{Fr_1 U_2 \left(1 - (\sin S)^{0.5}\right)}{\cos S} D \tag{6.6}$$

where Fr_1 is the upstream flow Froude number defined based as $U_1/g^{0.5}R_1^{0.5}$ (note that this definition differs from the usual definition given by Equation 6.4), U_1 is the flow velocity upstream of the hydraulic jump, R_1 is the hydraulic radius upstream of the hydraulic jump (defined as the ratio of the cross-sectional area and the wetted perimeter), U_2 is the flow velocity downstream of the hydraulic jump, S is the pipe slope, D is the pipe diameter and the numerical coefficient has dimensions of s/m. This equation can be used to estimate the distance downstream of a hydraulic jump for which large pockets of air may accumulate. This allows the designer to choose configurations that prevent air pockets in steep sections from being carried into flatter slopes.

Effect of air pockets on hydraulic head losses

For preliminary design purposes, and when lacking more accurate information, experimental results indicate that the passage of air pockets in small diameter pipes can increase the hydraulic gradient in a straight section of downward sloping pipe by about 30% when compared with similar conditions associated with water alone. This finding is based on test data for air pockets varying between 6ml and 5 litres in volume in a 150mm diameter smooth-walled pipe. Although there have been cases where the presence of air was found to be responsible for head losses in excess of 30% above those assumed in design, there is need for further investigation in this area. As for other parameters, there is some uncertainty as to the effect of air pockets on the hydraulic gradient in larger diameter pipes and caution is recommended.

For the specific case of slimed sewer pipes, the hydraulic roughness coefficient of the pipe can be estimated using the following equation (from Forty *et a*l, 2004) which was derived from extensive field measurements in rising mains:

$$k_s = \alpha V^{-2.34} \tag{6.7}$$

where k_s is the hydraulic roughness coefficient in mm (for use in the Colebrook-White equation), V is the flow velocity in m/s and α is a coefficient based on the pipe condition. This coefficient takes the following values: α = 0.446 for average conditions, and 0.054 and 3.66 as lower and upper bound values respectively. It is quite possible that the results of the field measurements may have been affected by the presence of air and this is reflected in the upper and lower bound values. It is therefore recommended that an increase in hydraulic gradient be considered only for pipe sections where air pockets have been identified as a particular problem.

Pipelines with saw tooth profiles are prone to air accumulation at high points and also the generation of hydraulic jumps either by design or accident. In these situations where part-full sections exist, head losses should be considered separately.

6.3 KNOWLEDGE LIMITS

The movement of air pockets in flowing water inside pipes is a topic insufficiently understood at present and therefore design recommendations will necessarily rely on the limited (and disjointed) information available as well as on a number of assumptions.

The study led by HR Wallingford in 2004 clarified some of the issues that are important for achieving sound design solutions, namely how to estimate the critical velocity of the flow that will move air pockets along a downward sloping pipe (see Section 6.2). The analysis carried out on the experimental data obtained from that study was based on relating a Froude-like parameter, which incorporates the critical flow velocity and the pipe diameter, to the pipe slope. This is in line with the work of most researchers and is substantiated by dimensional analysis. Dimensional analysis (e.g. Bendiksen 1984; Falvey 1980; Wisner et al 1975) has shown that the critical velocity to move an air bubble/pocket is a function of the Froude number (which represents gravity and buoyancy related effects), the Reynolds number (which represents viscosity effects), surface tension and pipe slope:

$$V = f\,(Fr, Re, \sigma, S) \qquad (6.8)$$

In most civil engineering applications, the flow of water (or sewage) in pipes will be fully turbulent and viscosity will play a relatively minor role compared with other forces such as buoyancy and gravity. The dependency on the Reynolds number is therefore often neglected. Similarly, the effects of surface tension are, for simplicity, neglected and the critical velocity for a given pipe slope has been taken by several researchers as proportional to $(gD)^{0.5}$, where g is acceleration due to gravity and D is the pipe diameter. There is experimental evidence to support the assumption that both viscosity and surface tension effects are minor but this is still a simplification. For a comprehensive description of the behaviour of air pockets in flowing water these parameters would, in principle, need to be drawn in but further research is still required in this area.

Having accepted that a partial description of the phenomenon is sufficient for engineering applications, most formulae suggested by the various researchers relate the critical velocity of the flow, V, with the pipe diameter D and slope S, as well as with the acceleration due to gravity. It should be noted however that many authors' work (including the recent HR Wallingford work) was carried out using a single pipe diameter and therefore dependence on D could not be established from their experiments. Conclusions regarding the absence of scale effects (due to surface tension) in larger diameter pipes have been drawn from work involving pipes of various but fairly small diameters, which are at the lower range of sizes typically used in civil engineering. There is a good reason for this: the requirements for experimental work on pipes with diameter above 400mm are normally economically prohibitive and field work is equally difficult, with the added problem of increased uncertainty in results. This poses the question of how to extrapolate results to large pipe diameters, of the order of metres rather than hundreds of millimetres. The applicability of the recommended Equation (6.1) to pipe diameters above say, 1m is debatable (see Appendix E) and a matter for further research.

7. Application and guidance

7.1 INTRODUCTION

7.1.1 Scope

This chapter summarises sources of air, the effects of air and methods to limit and control air in pipeline systems. It sets out accepted guidelines for choosing air valve locations and gives criteria for refining these choices, with reference to the design equations extracted from the test programme carried out at HR Wallingford.

The chapter is intended to provide information and support for an expert discipline but not to be prescriptive or to propose an expert system.

Examples are given in the following chapter, where a summary of issues to be addressed for design is also presented.

7.1.2 Background

Behaviour of air in pipelines is complex and not well understood. Processes are random and turbulent. Common sense, engineering skill and judgement, open and enquiring minds are required.

Much of the data available prior to the HR Wallingford study relates to small diameter pipes or to pipe slopes steeper than about 10 degrees, equivalent to a gradient of about 1 on 6. Data on utility size pipelines at horizontal and near horizontal gradients, representing much of the pipeline population, are sparse. Guidelines for positioning air valves suggested that quite close spacings should be considered. Criteria were not clear and indeed in many situations, such as underwater pipelines and sea outfalls, air valves are not practicable at all.

Recent developments in privatisation of the water utilities and procurement techniques have increased the drive to simplify and reduce construction costs and to reduce dependence on regular preventative maintenance. Pipelines considered range from major water and effluent transfer schemes to large cooling water and desalination intake and reject streams, small sewerage and water supply schemes and within pumping and process facilities. Management of air is common to all.

Pumping downhill presents a typical problem; pipelines with intermittent and variable flow, as is common in sewerage schemes, may drain between pumping cycles, several times per day. The volume associated with the fill and emptying cycle may well mean that in a long pipeline attenuation occurs in which flows downstream of a high point never reach full flow capacity: this may affect self cleansing velocities and need pump well sizes and operating regimes to be addressed.

Flow downhill can frequently result in open channel flow - a simple plot of ground profile, pipe profile and hydraulic energy level for the range of operating conditions will show hydraulic control points and where open channel flow could occur. A hydraulic jump may (depending on pipe slope) occur at the change from open channel to full pipe (surcharged) flow.

Construction, operation and maintenance, specifically filling and emptying pipelines, also need to be addressed in considering the air problem.

In sea outfalls the tide level will also vary, resulting in a wide range of hydraulic energy levels and typically a “tidal” section in which part full (open channel) flow occurs with a hydraulic jump at the change to full flow. In addition to the effects air has on hydraulic capacity and transients (pressure surges), for underwater pipelines air reduces underwater weight and affects pipe stability, particularly for lightweight pipes. Foaming onshore and at offshore discharges is a further concern.

7.1.3 Sources of air

Sources of air are outlined in Chapter 2 and are elaborated below. Examples (Lescovitch, 1972 and others) include:

- air not being purged on pipe filling;
- entry at pump start if not released at the pump manifold or before the non return valve;
- vortex entrainment at intakes;
- pipe joints, pump glands;
- hydraulic jumps at the end of sections with open channel flow (common in gravity and downhill sections of pumped pipelines);
- entrainment at drops into pools and downstream of gates;
- release as internal pressure drops (but see comments above);
- intake during transient events (for example pump failure);
- intake through open air valves on sections running at atmospheric pressure (open channel flow on near level or downgrade sections).

7.1.4 Effects of air

Air bubbles rise in still water at a velocity of about 0.2 to 0.25 m/s. Small air bubbles with diameters of a few millimetres will be carried forward with water flow more readily than air pockets. This document refers to transport of air pockets from tests in 150mm diameter pipe carried out with volumes up to 5 litres as distinct from air bubbles with diameters of a few millimeters and volumes of the order of millilitres.

A key point demonstrated in the HR Wallingford study is that, at near horizontal slopes, air pockets became very long and thin, with large volume pockets occupying a very small percentage of cross sectional area but over a long distance. This and the instability of long pockets affect the velocity required to move air pockets down slope and, to a lesser extent, the upward slope at which they will begin to move in real schemes.

Air pockets reduce the effective pipe cross-section. The energy losses which can result at a series of high points are cumulative and can lead to serious loss of carrying capacity, particularly in gravity pipelines. Air pockets can also cause instability of flow and can affect transient (surge) pressures: although large air pockets may reduce transient pressures, small air pockets may have the opposite effect (as discussed in Chapter 5). Similarly, small amounts of air may reduce the friction loss because the wetted perimeter is reduced by a greater proportion than the area of flow. Air can therefore affect perceived pipe roughness.

A well designed system will therefore aim to prevent entry of air. In the event that air does enter the system the pipe size and profile should be designed so that, where possible, air is carried along the pipe - or rise back against the flow - and escape at air release points. The full range of flows and hydraulic conditions needs to be considered.

Figures 7.1 to 7.3 show the effects of air pockets, where EGL denotes Energy Grade Line.

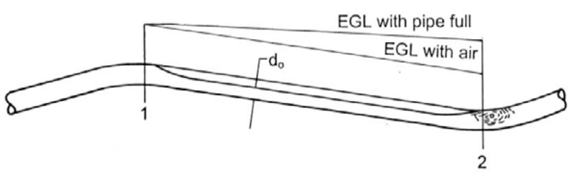

Figure 7.1 Air pocket in pipe with mild slope. Normal depth (d_o) > critical depth (d_{cr}) - after Edmunds (1979)

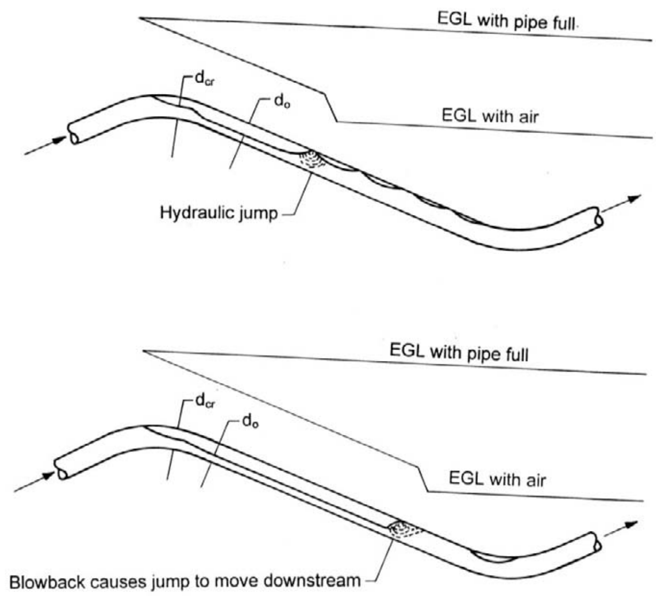

Figure 7.2 Air pocket in pipe with steep slope. Normal depth (d_o) < critical depth (d_{cr}) - after Edmunds (1979)

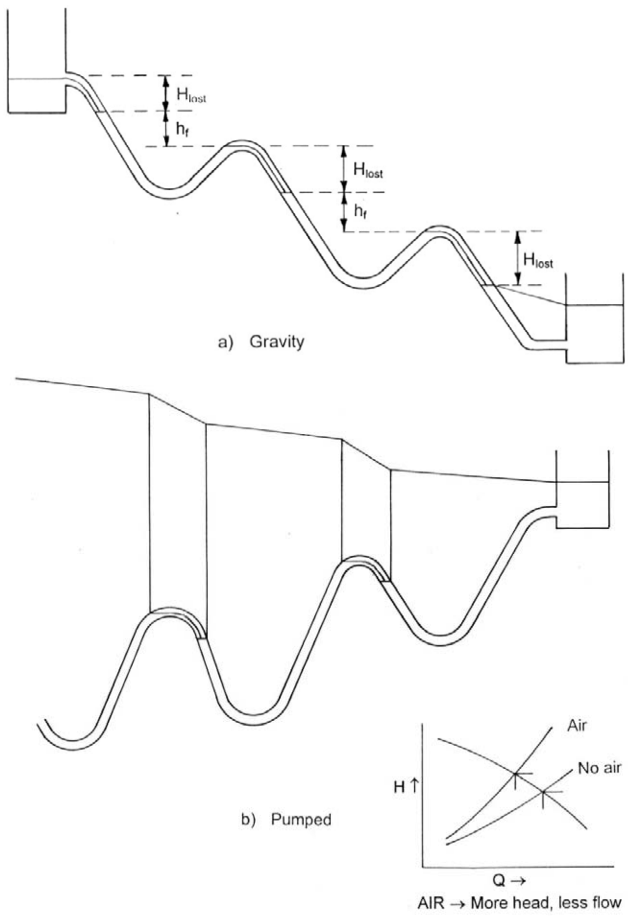

Figure 7.3 Cumulative energy losses (H_{lost} denotes total energy lost and h_f denotes friction loss)

Pipeline rupture tends to be more destructive in the presence of air. On fracture of a pipeline without air, the internal pressure is rapidly dissipated as water is expelled from the pipeline. This is not the case where a significant quantity of air is present, and the pressure differential across the break remains high for some time, potentially resulting in an explosive tearing of the pipeline.

In pressure testing of pipelines, or in flow measurement, the presence of air can distort the results.

The discharge of air from pipelines, particularly from sewage lines can result in the release of objectionable odours to atmosphere. Where this could be a problem, the fitting of odour control devices should be considered. During venting, air valves can be unacceptably noisy, and care should be taken to ensure that the noise levels are consistent with the location. High discharges can result in noise levels exceeding 85dBA at 1m. Even quite low noise levels can generate complaints. In particular, animals can be frightened by the intermittent hissing of the small orifice in double orifice air release valves. Sudden noisy discharges can cause distress to passers by. An assessment of the acceptable noise level for each location should be carried out and silencers should be considered if noise levels could be a nuisance.

7.1.5 Problems

For air to be a problem under normal flow conditions:

- there must be a source of air (for example at poorly designed intakes and pumps)
- the air must separate or come out of solution (typically as internal pressure reduces along a pumped system) and
- air must accumulate and not be moved along the pipe (which is a function of pipe gradient, diameter and velocity).

Several actions, described in the following sections, can be taken to minimise the potential problems caused by the presence of air in pipelines and a summary is given in Figure 7.4.

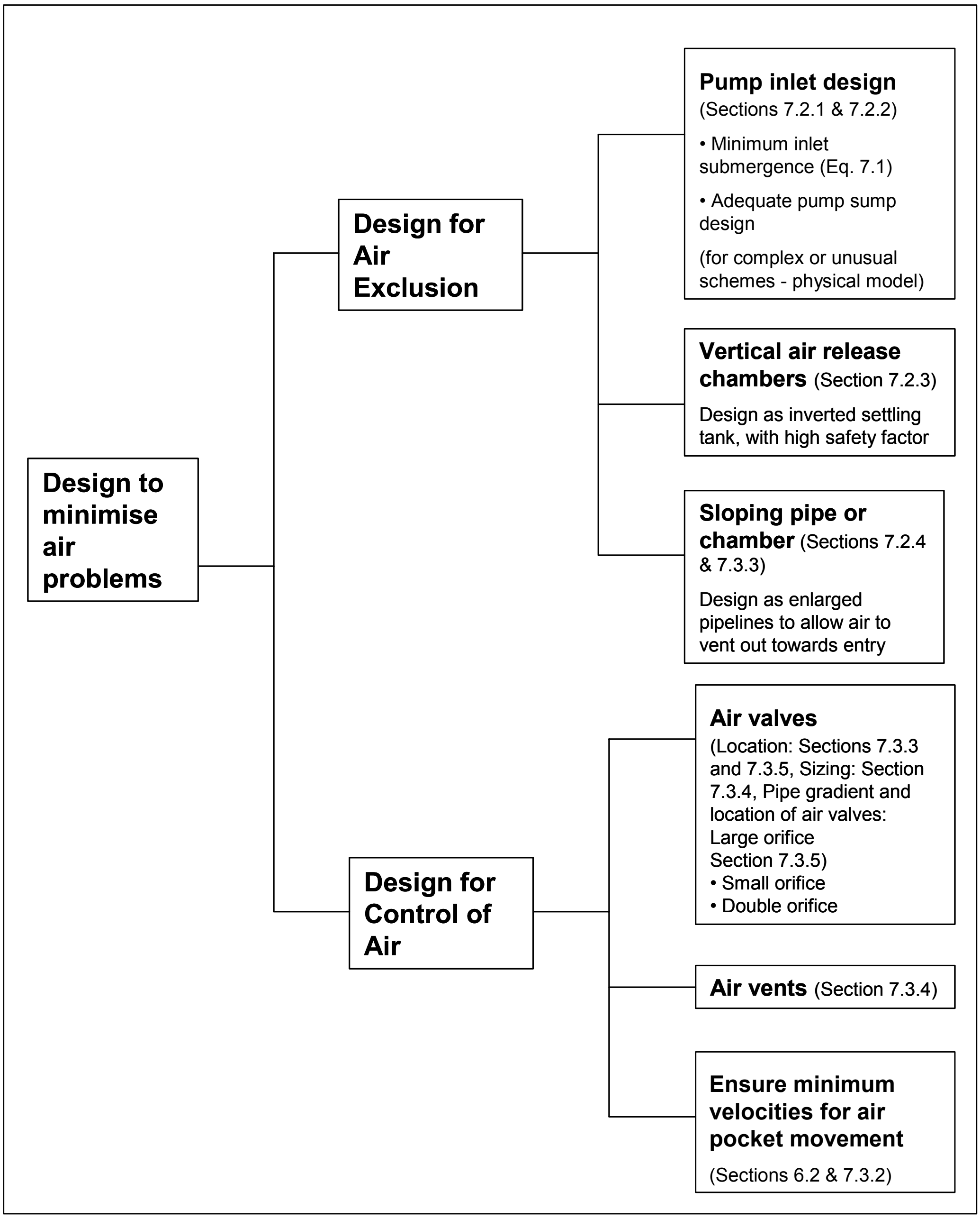

Figure 7.4 Flowchart for minimising impact of air in pipelines

7.2 AIR EXCLUSION

7.2.1 Pump inlet design

Air is generally excluded from pumping mains by providing a suitable pump intake arrangement. This is achieved by means of appropriate sump design and adequate intake submergence. Intake submergence is usually designed in order to limit vortex swirl and gross air entrainment, primarily motivated by the need to protect the pumps from mechanical damage. The criteria usually applied are therefore slightly more conservative than would be required merely to prevent air entering a system. Consequently, the criteria given below should be sufficient to avoid gross entrainment of air due to inadequate submergence. However, in cases where pumping stations have unusual arrangements, particularly if asymmetrical geometries are present and/or large flow rates are involved, the prediction of flow patterns and vorticity becomes difficult or critical and commissioning a physical model study is recommended.

7.2.2 Vertical chamber - inlet submergence

A conservative rule for minimum submergence to prevent air entrainment and excessive vorticity at an intake from a chamber is given by the following equation (ANSI/NI, 1998):

$$S_u / D = 1.0 + 2.3\,Fr \qquad (7.1)$$

where S_u = submergence below lowest water level
D = pipe diameter (or bellmouth diameter at lip)
Fr = Froude number = $V/(gD)^{0.5}$
V = mean velocity through the pipe (or bellmouth).

With a horizontal pipe exit (pipe from wall of chamber) S_u is measured from the pipe axis. With a vertical exit (pipe vertically down from floor of chamber), S_u is measured from entry to the pipe or bellmouth (see Figure 7.5).

However, it should be noted that the criteria given in the literature generally assume that a suitable pump sump arrangement is provided. Poorly designed sumps can promote vorticity and air entrainment. The hydraulic design of pump sumps is beyond the scope of this document.

For a gravity main, the submergence criterion can generally be relaxed depending on the acceptability of air entry into the pipeline, but should not be less than 1.5 times D.

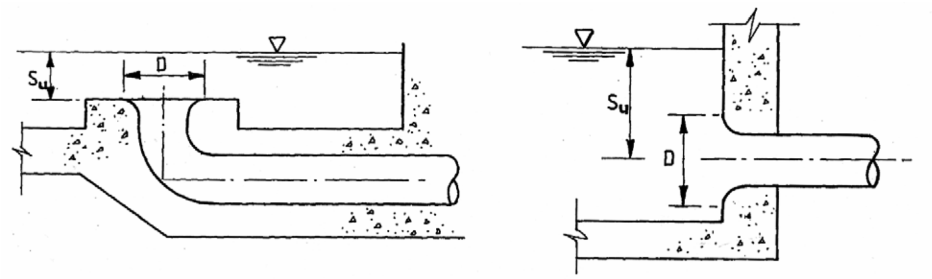

Figure 7.5 Submergence at chamber exit

For inlet chambers to sea outfalls, the submergence will need to be checked for the full range of tide levels and effluent flows and pipe roughness values. Charts of submergence against flow can be plotted to indicate the critical case. Effectiveness of bellmouth entry can also be investigated.

7.2.3 Vertical chamber - air release

Air entrained at entry to a chamber, for example where effluent drops to a free water surface, will typically be carried forward as small bubbles towards the exit. Small bubbles can be stabilised by organic material such as mucopolysaccarides or proteins to form objectionable foam at the chamber, the point of discharge or both. The effluent or receiving water may include silt and other material which colours and makes the foam unsightly and draws public attention.

Chambers to release air bubbles require careful design and bubble behaviour is not compatible with scale modelling. A basic concept is to dimension the chamber as an inverted settling tank such that horizontal velocity gives the air bubbles time to rise above the outlet level. A factor of safety of at least two would be required on length but will depend on detail design which is outside the scope of this document. This can result in a long chamber. Proprietary designs with baffle walls and perforated plates may be used to limit chamber size where design information and calibration with prototypes are appropriate.

7.2.4 Sloping chamber – air release

This concept is described later in this chapter (Section 7.3.3) and accepts a free water surface within the pipeline which then has to extend far enough at a diameter large enough to allow air to vent back up the slope towards the entry.

7.2.5 Choice

Choice will depend on costs and elements specific to the project. For an outfall, selection of pipe slope and diameter to allow air to vent back to the entry ("sloping chamber") can be a simple and cost effective option, particularly where environmental concerns require the foreshore and surf zone to be crossed by tunnelling or directional drilling.

7.3 CONTROL OF AIR IN PIPELINES

7.3.1 Air valves

7.3.1.1 Air valve types

Three main air valve types, single large orifice, single small orifice and double orifice, are summarised briefly below. Specialist air valves are not included here and are described in manufacturers' data.

- **Large orifice air valves** are designed for air release on filling and for air entry on draindown or pipe burst. Large orifice air valves will not release air under pressure.
- **Small orifice air valves** are for release of smaller quantities of air which may accumulate under pressure during normal operation.
- **Double orifice air valves** combine both large and small orifice functions and are used where large quantities of air release or entry are required – during pipe filling or emptying – and where small quantities of air may accumulate during normal operation.

Air valves require a minimum pressure to seal - typically about 4m or, for low head valve types, about 2m (depending on manufacturer's advice). Where the pressure may be less than the manufacturer's minimum recommended value, a vent pipe can be fitted but its design must allow for the full range of operating conditions and pipe roughness values. This may require a jockey pipe parallel to and above the pipeline and extending slightly higher than the maximum operating energy level, including transients.

Air valve capacity is governed by the valve orifice size and differential pressure. Large orifice size is not necessarily the same as the valve flange size or connecting pipework size.

Sonic velocity imposes a limit on valve capacity and occurs in the valve when the ratio of inlet to outlet pressure is more than 1.9 (or outlet/inlet pressure ratio is less than 0.53). Taking atmospheric pressure externally at 1 bar (14.8 psi, 101kPa) and ignoring secondary losses, there will be no increase in flow when the internal pressure falls below 0.53 bar absolute (7.8psia or -7psig). Typically the maximum differential pressure for design of the air valve will be limited to about 0.33 bar (5psi) to limit noise, or to a lower limit fixed by the subatmospheric pressure allowed by the pipe structure (buckling taking into account ovality and burial or other support).

7.3.1.2 Air valve variations

Several other types of air valve are used for a variety of purposes, such as surge alleviation or control of slam pressures. Such devices are often provided by manufacturers as 'add-on' features to standard designs. However, these special types of air valve often introduce problems of their own, again highlighting the need to address the various problems associated with air in pipelines in a consistent and collaborative way.

Devices which may be used for specific purposes include:

- *Vented non-return valves:* These devices operate as normal during air inflow, but operate with a constricted outlet during air outflow, resulting in a much reduced outflow coefficient. Vented NRVs are frequently used to minimise the potential for generation of secondary shock pressures following air valve slam. The disadvantage of these devices is that, while large quantities of air may be introduced into the line in a relatively short time during a pump stop event, the same mass of air will take much longer to be expelled, due to the limited outflow capacity. If the system is restarted before the air is fully expelled, the air may be forced on down the line, instead of being expelled from the air valve.

- *Outflow check valves:* These devices operate as normal during air inflow, but have total restriction on air outflow. They are principally used to limit local pressure drop to just below atmospheric by opening to admit air, but the air cannot be expelled from the air valve, and is moved on downstream when the system is restarted.
- *Inflow check valves:* These devices operate as normal under pressure (any air that is present is vented as normal), but they do not admit air when pipeline pressure falls below atmospheric. They are used where air valves are required for venting, but where it is considered necessary to prevent air entering the pipeline during transient conditions, in order to avoid the problem of air valve slam altogether. The main concern about these devices is associated with the draining of adjacent sections of pipe: they may require manual vents in order to drain sections of main properly. Also, in order to cater for mal-operation (attempted drainage without manual venting), or pipe bursts occurring below the level of the inflow check valve, the probability and consequences of severe suction pressure in the main should be considered.

7.3.1.3 Air valve locations

Traditional advice for water pipelines (AWWA M51, 2001) is that

a) air valves should be *installed* in pipelines:
   i) at high points relative to level to allow air release on pipe filling and air entry on pipe emptying (for maintenance or in the event of pipe burst);
   ii) at high points relative to the hydraulic gradient and
   iii) on the downslope side of line valves to allow air release and entry on pipe filling and emptying and

b) air valves should be *considered* in pipelines:
   i) where the gradient steepens significantly in a pipeline falling in the direction of flow (eg before crossing below roads or rivers), where the air transport capacity is reduced;
   ii) where the gradient flattens significantly in a pipeline rising in the flow direction of flow;
   iii) at intervals of 400m to 800m along long ascending, descending or horizontal sections of pipeline and

c) air valves should be *installed*
   i) upstream of Venturi meters;
   ii) on the discharge side of deep well and vertical turbine pumps (special considerations required) and
   iii) on the high point on siphons to allow air release on priming (with shut off or non return valve to maintain subatmospheric pressure during operation).

The above implies, simplistically, air valves at high points topographically which is obvious and relative to the hydraulic gradient which is not so obvious - and at special locations which are not covered in this document.

Item a) ii) above requires a large orifice air valve at each end of a section parallel to the hydraulic energy line and at the change of gradient on a section approaching and then moving away from the hydraulic energy line. Logic for defining high points relative to the hydraulic gradient is not clearly set out in texts commonly referenced. They represent sections of minimum gauge pressure and where the energy line can form a free surface, depending on the range of flow and uncertainty in pipe roughness, particularly if the energy line is close to the pipe soffit and open channel flow could occur. Also air in solution will come out as the pressure drops and will take considerable time to re-dissolve (Lescovitch, 1972, Edmunds, 1979): this can be expected at locations in pipelines which run at subatmospheric pressure (Thorn & Kenyon, 1954) but for gravity pipelines and pumped pipelines air on entry to the system would typically be at atmospheric pressure and would not otherwise be expected to come out of solution. However, air entrained by pumps or at hydraulic jumps in greater quantity than normal could be released as the pipeline gauge pressure reduces. Air could be conveyed forward along a section of pipe where the physical gradient is less than the hydraulic gradient and be released where the physical gradient steepens to become greater than the hydraulic gradient, allowing part-full flow to occur. If this does occur, the required hydraulic gradient would become steeper in the part-full section, approximately matching the pipe's physical gradient along the section of pipe where part-full flow occurs. This will lead to a consequent reduction in the flow through the pipeline.

Accordingly it could be argued that item a) ii) is good practice in general but could be transferred to group b) and considered for individual projects – for example possibly not installing the additional air valves on long pipelines well (say 5 to 15m) below the lowest hydraulic energy line and where air will already have passed a number of air valves and had reasonable chance of being vented.

Location of air valves should also take account that changes of pipe gradient may become high points under certain hydraulic conditions, for example as the hydraulic gradient increases and drops during pipe drain down or pipe burst. This condition may not necessarily require an air valve – for example if it is infrequent and structural design of the pipeline permits sub-atmospheric pressure.

An equivalent situation may occur during pipe filling: if the flow rate is too fast air may not be vented and may be trapped at local humps and bumps in the profile. This may have a pernicious effect on sewage pipelines pumping downhill, where the pipe may fill and empty several times per day. On large pipelines air may be trapped permanently at high points and on near horizontal gradients where tight laying tolerances are not practicable.

The above guidelines may also result in additional air valves at quite close spacings. Criteria for deciding where the additional air valves should be considered are typically not given: the intention of this document is to provide basic information to facilitate this choice. Prescriptive guidelines are not given and the intention is that the designer should satisfy himself as to applicability of the information given.

It should also be noted that, as a rule, air valve manufacturers do not guarantee leak free operation of the valves at low internal pressure. The internal pressure required to ensure a seal is typically quoted as being about 0.2 bar (gauge), although some air valves are rated for pressures as low as 0.1 bar (gauge). The situation is especially problematic for undulating sewage mains that contain air valves that may be either open or closed during normal operation, depending on flow rate.

7.3.1.4 Sizing air valves

AWWA M51 gives generic information and outlines procedures for sizing air valves. Manufacturers' data should be consulted and the basis for the data should be reviewed, as these are often extrapolated from tests carried out with small diameters. In calculating air valve capacity and differential pressure, allowance should be made for fittings, connections and isolating valves. Required capacity depends on pipe size and on filling and emptying rates, including pipe burst. Clusters may be fitted where one valve is not enough.

7.3.1.5 Further guidance

Further guidance in AWWA M51 is as follows:

1. Fill slowly, 0.3m/s velocity.
2. Size air valves to limit the air pressure on release during filling.
3. Lay the pipeline to set gradients (rather than to a fixed cover); install air valves at high points and if the terrain is flat, at regular intervals.
4. Flush the system at moderate velocities, 0.6 to 1.2m/s, and low pressure to move air to air release points.

5. Install air valves upstream of control valves.
6. Use double air valves where possible.
7. Review air valve locations, sizes and detail in the light of transients (surge) analysis; check for additional, less obvious locations; alternative valve locations and pipe profiles; confirm valve selection, connection and detail.

7.3.2 Air pocket movement velocity

Air pockets will tend to agglomerate at the pipe soffit. Air normally is expected to be transported along pipes sloping upward in the direction of flow. The test series in the HR Wallingford study included flows at upward slopes of about 1 and 2 degrees (slope about 1/60 and 1/30) and found zero flow was needed to transport air pockets up these slopes. Further tests were performed at very mild slopes (1/3000) which showed similar results. However, on real pipelines with discontinuities and uneven slopes, a minimum gradient would seem more likely (see Section 6.2) - but is not quantified and may have little practical consequence.

Under typical operating conditions air pockets may be transported forward down shallow slopes but will not be transported down steep slopes. There is a critical downward slope at which air pockets will be trapped, the value depending principally on pipe diameter and flow. Figure 7.6 illustrates the principle where air may collect on convex profile, sloping downward in the direction of flow.

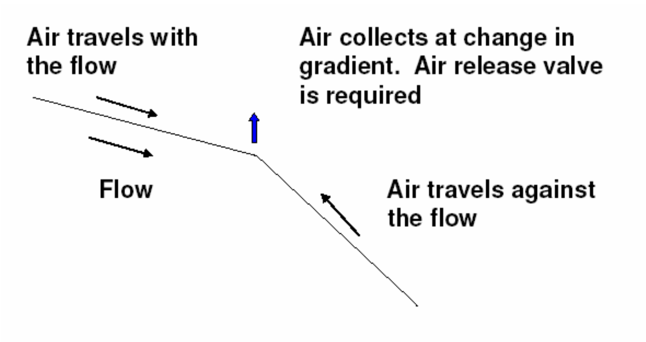

Figure 7.6 Critical slope for air transport

Equation (6.1) in Chapter 6 gives a general non-dimensional relationship for the velocity to move air pockets forward in the direction of flow on a downward sloping pipe. Coefficients are given for a range of air pocket sizes.

Assessment of test data indicates that the clearing velocity will not increase significantly for pocket sizes larger than those investigated - which is consistent with results from other research.

These tests indicate clearly that the velocity to move air pockets increases with increasing slope. They also indicate that, even along horizontal pipelines, a minimum velocity is necessary to move air pockets. This is consistent with equations developed by a number of other researchers. It does not support relationships inferred by some researchers - that the curve passes through the origin (that air pockets on level and near level pipelines will move at very low flows).

Comparison with relationships derived from a wide range of sources is given by Escarameia *et al* (2005) and Little (2002).

The HR Wallingford tests also indicated that air pockets would hover (neither move forward nor backward) at a slightly lower velocity than that required to move the pockets forward. This and the scatter of results indicate a velocity band in which air pockets may move forward, move backward or be static. Above the upper bound, air will be transported forward down the slope: below the lower bound air will rise up the slope against the flow. The band is narrower at steeper slopes and wider at flatter slopes. Logically the lower bound should eventually pass through or near the origin, implying a wide band width of flow at which air pockets may rise, be carried forward or hover on near horizontal slopes. These observations suggest a possible overlap with the results of other researchers and may result from difficulties with measurement and moving the long thin unstable air pockets that occur on near horizontal pipes.

The upper range of constants “a” in Equation (6.1) gives results which are consistent with the velocity $V = 0.56\ (gD)^{0.5}$ at which an air pocket will enter as a defined front in a horizontal pipe that is emptying (Benjamin, 1968). This velocity defines a limiting value above which air will be swept clear from a pipeline. The value of 0.56 is also consistent with test data by Kent (1952).

To determine the velocity required to move air forward down slope, the use of the HR Wallingford Equation (6.1) is recommended.

It is also recommended that movement of both small and large air pockets should be considered when assessing whether air pockets will be carried downstream.

Test data are on pipes up to about 200mm diameter and may give conservative results for larger pipe sizes (see discussion in Section 6.2).

7.3.2.1 Implications

The chart in Figure 6.2 (Chapter 6) includes a line at 1.2 m/s which is a typical optimum velocity resulting from economic whole life analysis of pumped pipelines in the UK and some other countries. In the Middle East and other areas where power costs are low, the optimum velocity may be higher, say 1.8 m/s and cooling water systems, where available energy level is higher due to the process requirements, may operate at even higher velocities, say 3 m/s.

The chart shows that, for a typical flow velocity of 1.2 m/s, air will be swept clear from small diameter pipelines but for pipes larger than about 400mm diameter large air pockets will not be carried forward. It implies that large diameter pipes may be permanently intruded with air or velocities may be overestimated by Equation 6.1 (see discussion in Section 6.2).

7.3.3 Air trap – sloping pipe or chamber

Equation (6.1) indicates conditions of pipe slope, flow and diameter under which air will be carried forward.

It can therefore also be used to choose a pipe slope or diameter, or both, needed to prevent air pockets being carried forward – in essence, if required, to control forward movement of air. The aeration zone of the hydraulic jump should not then extend into an area where air can be carried forward – and the pipeline upstream should be vented to allow for the range of flows and hydraulic conditions which will occur.

Equation (6.6) gives the length of the aeration zone at a hydraulic jump in a sloping pipe – refer to Figure 7.7.

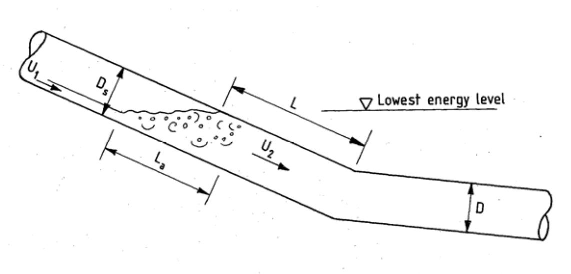

Figure 7.7 Length of aeration zone

Recommendations (Mosevoll, 1976) are that the pipe should continue downstream of the jump at the same slope and diameter for twice the aeration zone length (at least $L > L_a$ and preferably $L = 2L_a$) and where this approach is used as a sloping chamber to limit air entry at the landward end of an outfall; the pipe full flow velocity should be no more than 0.5 m/s and its diameter D_s should be at least 1.5 times the pipe diameter leaving the sloping chamber (this would give flow velocity about half that in the pipeline).

For reasons usually related to the ground profile, some sections of pipe may be designed to run part-full and to allow the formation of a hydraulic jump with an air gap large enough to allow ventilation back to a chamber at the pipe inlet. Recommended design parameters for this situation are, with D denoting pipe diameter:

- Maximum flow depth ≤ 0.6D, typically 0.5D for D<200mm
- Froude number typically above 1.3 in the supercritical section and below 0.7 in the subcritical section.

7.3.3.1 Quantity of air entrained at hydraulic jump

Air volume at a high point will depend on the liquid flow, the pipe profile and the quantity of air entering the system. Air will be entrained at hydraulic jumps which will tend to clear air pockets – for example, pockets remaining after pipe filling - provided that the rate entering is less than the removal rate and that air will be carried forward.

Tests, made as part of the HR Wallingford study, to investigate the rate of entrainment at hydraulic jumps found that, at low flow velocities or with large initial air volume upstream of the jump, air could not be removed. In several tests the right conditions were met and the relationship given in Equation (6.3) was obtained. This is lower than the relationship found by Kalinske & Robertson (1942), Equation (6.5), which applies to horizontal pipes.

These relationships can be used to estimate the amount of air entrained at a hydraulic jump and hence the time to clear an air pocket or to estimate the volume of air at unvented high points in the pipe profile.

7.3.4 Air vents - size of tee to trap air

Air vents typically are sited on tees. Access for maintenance may determine tee size on large diameter pipelines. Tees otherwise are recommended to be full size up to 350mm internal diameter and at least 0.35 times internal diameter on larger diameter pipelines (Mosevoll, 1976, Van Vuuren, 2004). The vent pipe is recommended to be at least 50mm diameter (Mosevoll, 1976) but is suggested here that it should be linked to air flow capacity and to the potential for blockage and for unstable venting flow.

Other recommendations are for tees to be full size up to a maximum of 800mm diameter and to have a height of at least 150mm above pipe crown (van Vuuren, 1994).

The use of relatively large diameter Tees as described above is recommended for reliable and efficient operation of the air valve, as this provides a buffer storage of air for expulsion through the air valve.

7.3.5 Pipe gradient and location of air valves

The above is intended to assist with selection of air valve locations and pipe gradients. It presents a summary of traditional guidelines and indicates that conditions particular to each project should be considered. It suggests that large diameter pipelines should be laid to gradient rather than cover. This will also allow drainage between washouts and access for inspection as well as a regular soffit line allowing air pocket movement. Where there is enough driving energy to prime a pipeline, air valves may possibly be omitted from small diameter pipelines – which can be laid to cover rather than to gradients. Similarly on small diameter mains, where velocity will be sufficient to sweep air forward, air valves may not be needed and on distribution mains with service tapping points on top of pipe, air valves are not normally fitted.

The relationships found do not provide a basis for a generic rule for a minimum gradient rising to or falling from air valves. If air in service or small amounts of water on drain down cannot be tolerated, very flat gradients should be avoided as they cannot be achieved accurately in practice and the pipeline sections may move vertically and horizontally during backfill and long term during operation: a gradient of 1/500 is a typical quoted minimum value, probably based on measurements achievable by spirit level.

On filling, the flow will reach a high point and weir over to the section downstream. Critical flow occurs near the high point but in practice this high point may extend over a length. Open channel flow and hence the majority of the air pocket will occur downstream of the critical point: the air vent therefore should be sited slightly downstream. Typically, detail of the air vent system and local pipe profile should be designed so that, where practicable, the high point and hydraulic control are just upstream of the vent.

In addition, and in order to facilitate maintenance, as far as possible air valves should be sited such that their chambers may be easily located and accessed.

7.4 AIR VALVE MAINTENANCE

Air valve maintenance is arguably the most neglected duty in the operational management of pipelines (Figure 7.8). Inspection of air valves on pipelines that have been in service for many years frequently confirms this, with cases of corroded or otherwise unserviceable air valves and occasionally air valves in chambers that cannot even be located. In situations where air valves have been designed as the primary source of protection against damage from transients, this state of affairs is particularly concerning and suggests that it may be unsafe to propose designs which incorporate air valves as the primary means of surge protection.

Several publications give recommendations for air valve maintenance, and these are invariably more rigorous than the maintenance regimes which are typically applied in practice. Pumping Station Design (Sanks, 1998) has the following to say about air valve maintenance:

… "Some manufacturers recommend an overhaul every 6 months, but failures have occurred with such a schedule. To be safe, count on inspection and/or overhaul at frequent intervals (twice per week to be conservative or once per month for greater risk)."

It is unlikely that pipeline operators comply with even the 'greater risk' regime described here. Nevertheless, such exacting suggestions from the literature highlight the extent of the problem.

As mentioned above, it is the responsibility of designers to ensure that air valve chambers may be easily found and accessed, in order to facilitate and encourage compliance with specified maintenance regimes.

Figure 7.8 Example of neglected air valve

8. Illustrative examples

8.1 SEWERAGE SEA OUTFALL

A key feature of sewerage system hydraulics is that the flow varies diurnally and seasonally and more significantly due to storm events. Flow variations can be quite rapid and the change from gravity flow to surcharged can cause significant damage if air cannot be released under controlled conditions (Zhou et al, 2002).

Sea outfalls in addition discharge typically to a varying tide level. This, coupled with changes in pipe roughness with time, requires a range of hydraulic conditions to be taken into account.

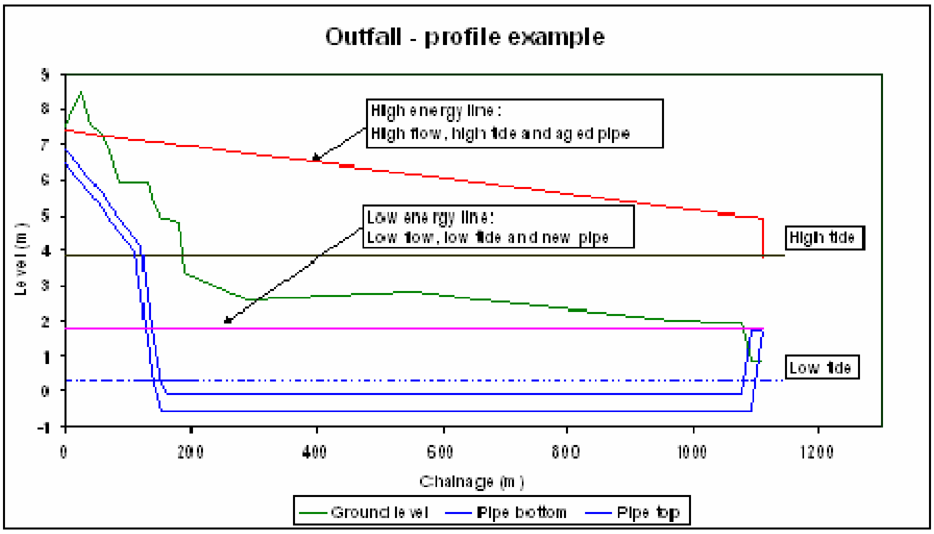

Figure 8.1 Outfall example

Figure 8.1 shows a longitudinal profile and hydraulic energy lines of an outfall across an estuary. The energy required to drive the outfall ranges from a combination of high flow, high roughness (aged pipe) and high tide to low flow, low roughness (new pipe) and low tide. Energy level in the pipe will be controlled by the tide level or by the diffuser exit level if this is above tide level. The first section on land may run part full and a hydraulic jump will occur in the down slope at a position governed by the energy level at the end plus the friction loss along the pipe. The pipe size and slope are chosen so that air pockets generated and entrained by the jump should rise against the flow and not enter the horizontal section of pipe.

Pipe size and slope are also chosen so that open channel flow in the section on land should leave an air gap big enough to allow ventilation back to the chamber at the head works. The maximum flow depth is limited to about 0.6 times pipe diameter, giving an air depth of about 0.4 times pipe diameter. The actual flow depth chosen should allow for laying tolerances and typically may range from about 0.5 times (1/2) diameter for pipes less than say 200mm internal diameter to about 0.67 times (2/3) diameter for large diameter pipes. To help assure ventilation in these sections, pipe diameter and slope should also be targeted to ensure stable flow without significant surface waves: Froude numbers in the open channel section should typically be below about 0.7 or more than about 1.3. Similarly, sudden changes in horizontal direction should be avoided at supercritical flow: where ventilation of open channel sections is important, a suggestion is that horizontal bends should be limited to 22.5 degrees and where larger bends are needed they should be formed from a series of bends not exceeding 22.5 degrees, with straight sections of say 10 diameters length between.

Some small air bubbles can be expected to be carried forward but should not normally accumulate. Provided the system is designed to prevent air pockets being carried forward, air should not be a problem. However, due to construction tolerances and varying flow rates some allowance for small quantities of air at undulations in the as built profile may be prudent. A view can then be taken on the quantity of air to be allowed for in design of underwater pipe weight and in pipe stability calculations. Values quoted in Table 8.1 are based on experience and can be regarded as typical minimum values for both air and hydrodynamic forces. The risks of maximum air fill and maximum hydrodynamic forces occurring at the same time would need review: air content can be assessed based on hydraulics for the pipe profile and on formulae in this document: hydrodynamic forces should be calculated separately for each project. Installation arrangements and stresses also need to be addressed in choosing pipe weight but are outside the scope of this document.

Table 8.1 Air quantity for underwater pipelines

	Gravity	Pumped	Major highpoints
Potable water	10%	15%	20%
Sewage	25%	30%	50%

(Source: Pipelife manual Table A.4.4.1)

8.2 UNDULATING PIPELINE PROFILE WITH INTERMEDIATE HIGH POINTS

Figure 8.2 shows an example of a pipe profile on land, which incorporates some of the typical problems that can appear in pumping main design. The profile rises to a series of intermediate high points and ultimately falls to a level only slightly above the origin. Profiles such as this are difficult for hydraulic design and frequently result from a consideration of horizontal alignment constraints only, without regard to potential difficulties associated with the vertical alignment, which only become evident later when the hydraulic analysis is carried out. However, the problem may also be a consequence of the increasing number of constraints on horizontal alignment, such as environmental and conservational considerations.

If there is a wide range in operating flow rate, the problem is compounded, because the range of possible hydraulic gradients can result in some high points alternating between surcharged and non-surcharged conditions. This represents a particularly exacting environment for air valve operation, particularly in sewage applications. Manufacturers typically do not guarantee air valve seals below about 0.2 bar(g) (i.e. above atmospheric), and air valves which consistently operate at low pressures are prone to leakage, particularly when maintenance is neglected.

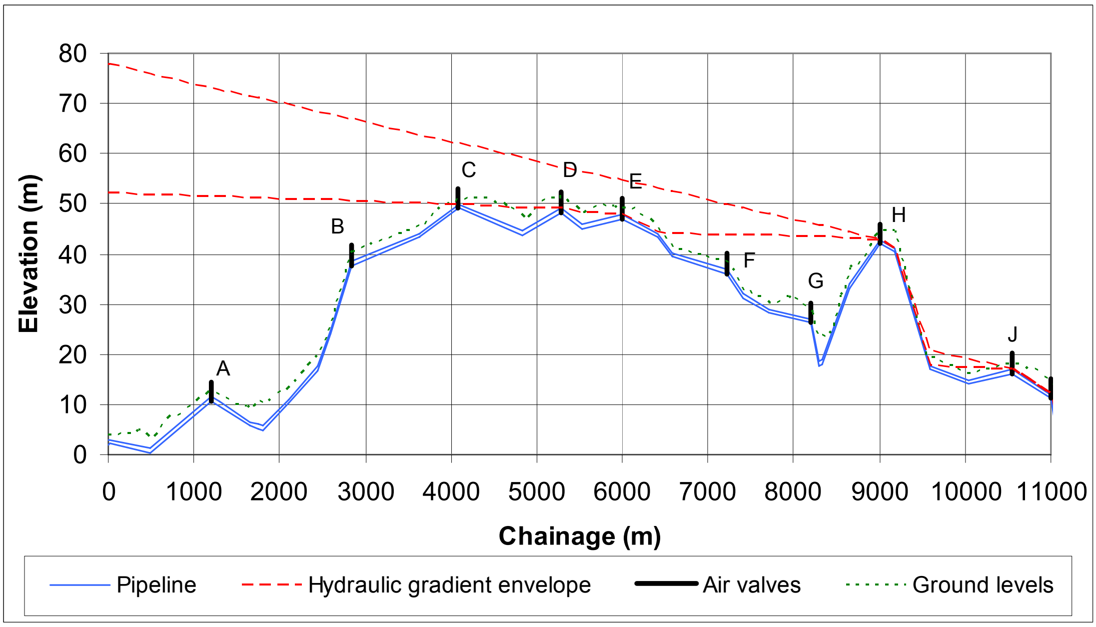

Figure 8.2 Example of undulating pumping main with intermediate high points

In the example in Figure 8.2, hydraulic gradients are shown for maximum and minimum flow rate. At maximum flow rate, there is an unambiguous effective pump discharge point at H, and it is clear that air valves upstream of this location should seal adequately under this flow condition. Air valves at H and J are open, but the minimum operating pressure at air valves upstream of H is about 0.7 bar(g) at E, which would normally be considered satisfactory.

At minimum flow rate, the effective pump discharge point is at C, and air valves at C, D, E, H and J are all open. Again, the pressures on the other air valves should be adequate to ensure a complete seal. However, at some intermediate flow rates, the effective pump discharge point is ambiguous, potentially resulting in unstable flow conditions. Furthermore, there is a risk of leakage from air valves at C, D and E, because of insufficient sealing pressure, exacerbated by the unstable flow conditions.

These conditions are undesirable from a hydraulic point of view, and there are several possible options for improving the situation. Occasionally quite minor adjustments to horizontal alignment may improve the vertical profile significantly. In such situations, it is generally best to limit the number of high points as far as possible, and to adjust the levels of high points in order to maintain positive pressures on air valves wherever possible. For example, if the invert level at E could be arranged to be higher than C and D by some accepted safety margin, then an adequate seal would be achieved at C and D.

Other options include the use of orifice plates or reduced diameter on the descending section, although this may not be possible where the flow rate range is wide. In such cases, dynamic control devices such as pressure sustaining valves may be more appropriate. Vents may be used instead of air valves, where hydraulic gradient, topography and environment permit. When using vents, it is important to consider the possibility of discharges resulting from pressure surges during transient conditions.

If flow rate is variable and/or intermittent, the satisfactory behaviour of air valves may be a key element in ensuring stable hydraulic conditions, especially during (partial) priming and emptying as flow rate changes. Maximum depth criteria have been suggested for ensuring stable priming of sections downstream of air valves. These translate into pipe gradient criteria for a given flow and diameter, and are especially important in sections of pipe which run part full, such as those immediately downstream of points C, D, E, H and J.

Undulating pipelines may also require an assessment of the potential for sediment deposition and accumulation. In some cases it may be necessary to implement sediment flushing programs to avoid sediment build-up. This applies especially to undulating pipelines with intermittent pumping. On pump start-up, the surcharged section of pipe from chainage 0 to point C will reach the pumping flow rate almost immediately; by contrast the surcharged section of pipe between H and J will only reach the pumping flow rate once the upstream pipework has partially filled. If this takes more time than the pumping cycle permits, the flow rate between H and J will not reach the pumping flow rate, and self-cleansing velocity may not be achieved.

Air valves should be sized to ensure adequate inflow of air during pipe drain-down. Pipe rupture constitutes a particularly severe case of pipe drain-down, and the consequence of this should be assessed, particularly when dealing with pipes which are not competent to withstand severe sub-atmospheric pressures. Where inflow check valves are proposed for other reasons (such as surge mitigation), the impact of this on pipe drain-down must be carefully considered.

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Appendices

Appendix A Prediction of air/water regimes

Flow pattern maps

A model for determining flow regime transitions in two-phase gas-liquid flow was developed by Taitel & Dukler (1976). The model is based on physical concepts and can be used to provide a generalised flow regime map for horizontal and near-horizontal pipe flows.

The model considered five flow regimes: SS smooth stratified; SW wavy stratified; I intermittent (slug, plug and elongated bubble flow); AD annular with dispersed liquid; and DB dispersed bubble. Intermittent and dispersed bubble flows are the dominant flow regimes likely to be encountered in the pipe flows considered in this study. Figure A.1 shows the generalised flow regime map based on the model. The superficial velocity is defined as the fluid velocity (either liquid or gas) multiplied by its volume fraction.

The authors studied the effect of small degrees of inclination of the pipe on the flow transitions. It was found that the effect of downward inclinations was the need for much higher gas and liquid flow rates to cause a transition from stratified flow to intermittent flow, and the intermittent flow regime region was greatly reduced. Conversely, for flows with a slight upward inclination the model predicts that the intermittent flow regime will take place over a much wider range of flow conditions.

A later paper by Barnea *et al* (1980) describes experimental studies on flow pattern transitions in inclined pipes and compares the results to the model of Taitel & Dukler (1976). From the comparison of the experimental results with the theoretical model it was concluded that the model gave very satisfactory results for horizontal flows and reasonably accurate results for pipes inclined ±10°. Figures A.2 and A.3 show generalised flow pattern maps for inclined pipes based on Barnea *et al* (1980).

It is believed that no such model exists for higher pipe inclination angles or for the vertical flow regimes. However, there are a number of flow regime maps produced by various authors for vertical pipes. Figure A.4 shows a comparison of vertical flow pattern maps of Ishii and Mishima (1980) with those of Dukler & Taitel (1977). They give an indication of the likely flow regime for vertical pipes. Figure A.5 is a generalised flow pattern map for vertical flow, based on Dukler & Taitel (1977).

The graphs are based on the superficial velocity, which is defined as the fluid velocity (either liquid or gas) multiplied by the volume fraction of the fluid. In order to use these flow maps the designer must have an indication of the liquid flow velocity and the gas flow velocity in the pipe. If only the liquid flow velocity is known then the maps can still be used to give an indication of the likely flow conditions. For example, for a horizontal pipe (refer to Figure A.1) with a liquid flow velocity of around 1m/s the likely flow pattern would be intermittent, with plug flow at very low gas flow rates changing to slug flow as the gas velocity increases. For very high gas flow rates the flow pattern changes to annular.

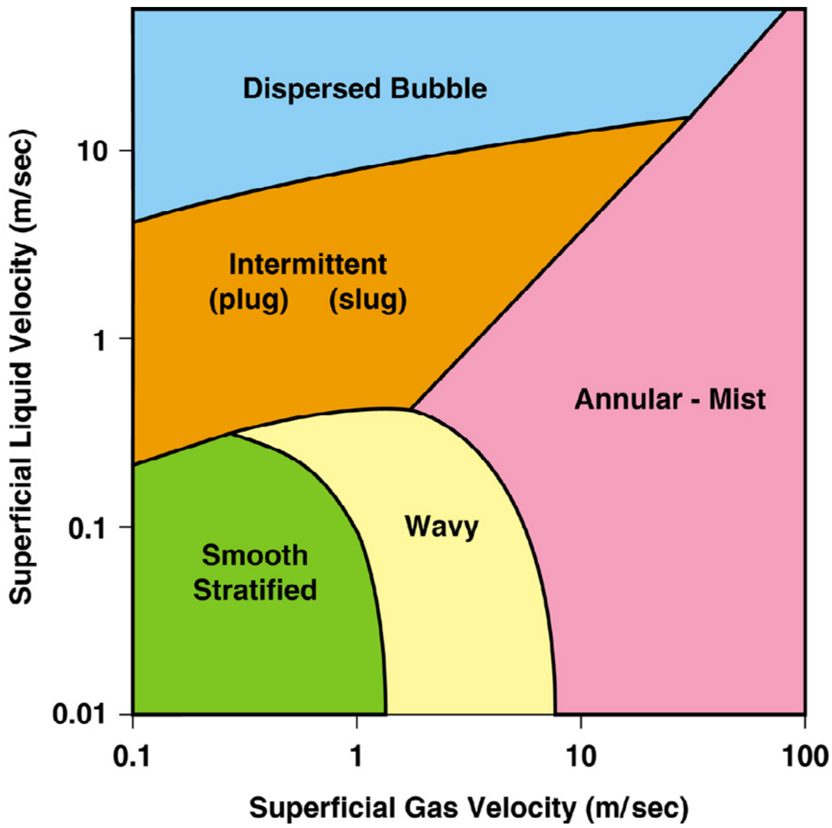

Figure A.1 **Generalised flow regime map for horizontal or near-horizontal two-phase flow (based on Taitel & Dukler, 1976)**

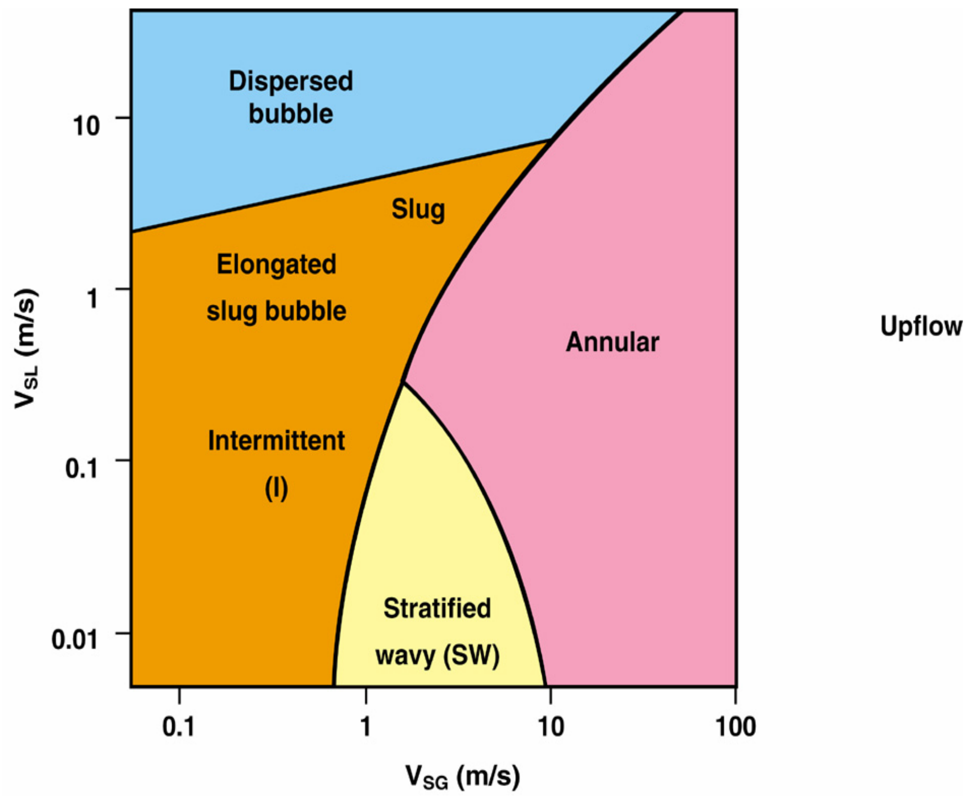

Figure A.2 **Generalised flow regime map for upward sloping two-phase flow (based on Barnea *et al*, 1980)**

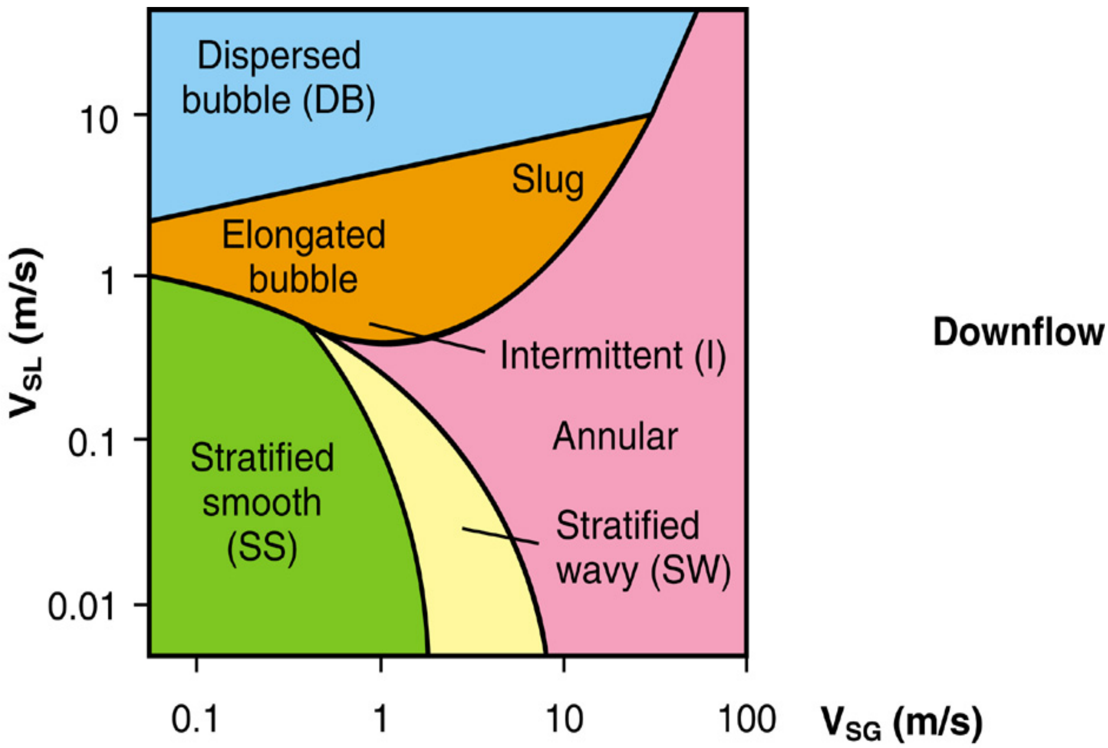

Figure A.3 **Generalised flow regime map for downward sloping two-phase flow (based on Barnea *et al*, 1980)**

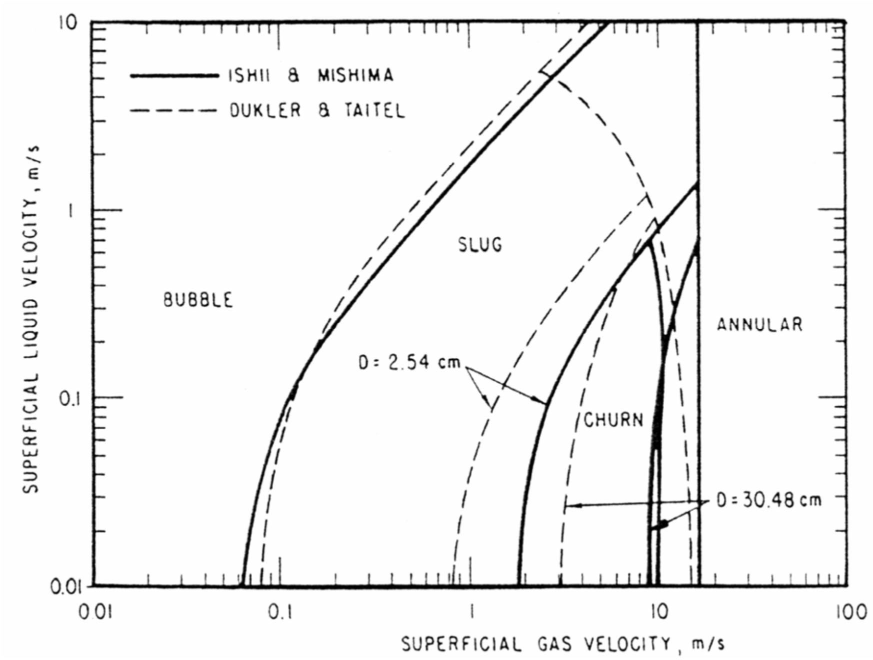

Figure A.4 **Examples of vertical flow pattern maps, showing those of Ishii and Mishima and Dukler & Taitel (taken from Rouhani & Sohal, 1983)**

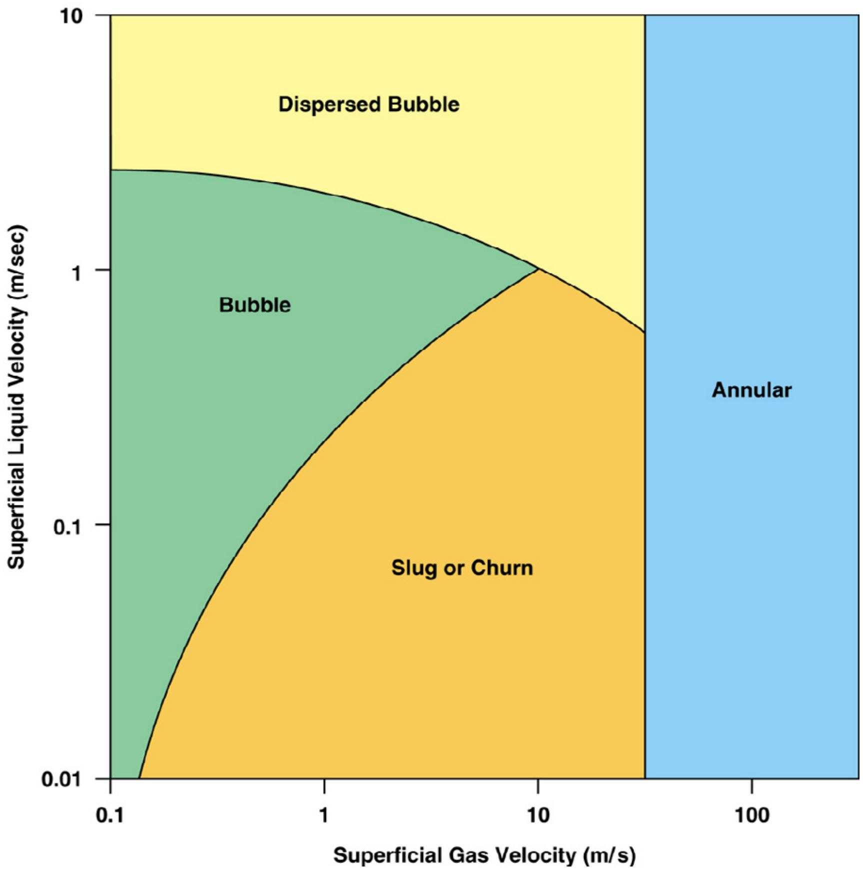

Figure A.5 Generalised flow regime map for vertical two-phase flow (based on Dukler & Taitel, 1977)

A more recent paper by Taitel & Duckler (1987) analyses the hydrodynamics near the discharge of a pipe carrying gas and liquid in horizontal stratified flow. It is shown that for high-viscosity liquids, pipe length may have a considerable effect on the transition from the stratified to non-stratified (annular or intermittent) flow pattern. This leads to a flow-pattern map which contains the pipe length as a parameter for this transition boundary. It was concluded that for low-viscosity fluids the pipe length is unimportant for the stratified-non-stratified transition but for high viscosity liquids the transition can be profoundly influenced.

References:

Barnea D, Shoham O and Taitel Y (1980). Flow pattern transition for gas-liquid flow in horizontal and inclined pipes. International Journal of Muliphase Flow, Pergamon Press, Vol. 6, pp217-225

Dukler AE and Taitel Y (1977). Flow regime transitions for vertical upward gas liquid flow: A preliminary approach through physical modelling. Progress Report No. 1, University of Houston, NUREG-0162

Ishii M and Mishima K (1980). Study of two-fluid model and interfacial area. Argonne National Laboratory, ANL-80-111, NUREG/CR-1873

Taitel Y and Dukler AE (1976). A model for predicting flow regime transition in horizontal and near horizontal liquid flow. AIChE, Journal, Vol. 22, No. 1, pp47-55

Rouhani SZ and Sohal MS (1983). Two-phase flow patterns: a review of research results. Progress in Nuclear Energy, Vol. 11, No. 3 pp219-259.

Appendix B Variation in air pocket dimensions with volume

As part of the experimental work carried out at HR Wallingford (and described in Escarameia *et al*, 2005), the length and width (measured along the perimeter of the pipe) of air pockets were also measured. These air pockets (between 6 ml and 0.6 litres in volume) were injected in the test pipe section under a flow of water. The measurements were taken from the outside of the transparent test pipe using a flexible tape and, although a correction was made for the thickness of the pipe for determination of the air pocket width, the measurements were necessarily limited by the accuracy of the method used. No attempt is made here at generalizing these results, however, the data allowed some interesting conclusions to be drawn with regard to the shape of the air pockets as the volume of air increases. This is illustrated by the graphs in Figures B.1 to B.5, which were obtained from data collected in pipes with downward slopes varying from 0^{o} to 11^{o}:

- Air pockets in horizontal and "near horizontal" pipes have a very distinct behaviour to that of air pockets in steep pipes: as an air pocket in a horizontal or near horizontal pipe increases in volume, the pocket elongates such that the increase in volume is mainly taken up by an increase in length. This is quite apparent in Figure B.1 (horizontal pipe) and B.2 (downward pipe at 0.8^{o} slope or 1/72). The cross-sectional area of the pipe that is taken up by the air pocket remains approximately constant as the air pocket volume increases.

- Air pockets in steep downward pipes (of the order of 2.5^{o} slope or greater) respond to an increase in volume by increasing both the length and width. This can be seen in Figures B.3 to B.5. The cross-sectional area of the pipe that is taken up by the air pocket thus increases with an increase in air pocket volume. Figure B.3 refers to pipe slope of 3.4^{o} but limited data was also collected for slope of 2.5^{o} which showed that at this slope the air pocket behaviour is different from that in horizontal/near horizontal pipes.

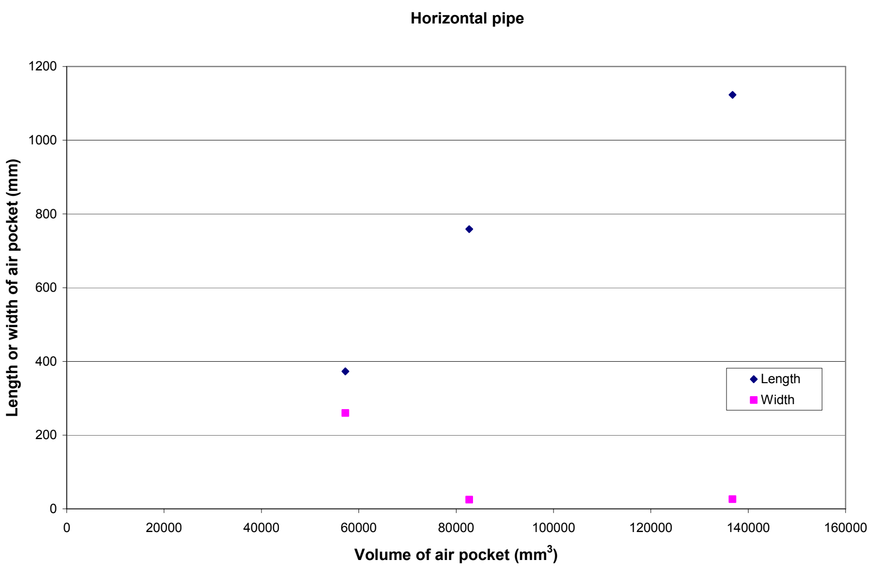

Figure B.1 Horizontal pipes: variation of air pocket length and width with air volume

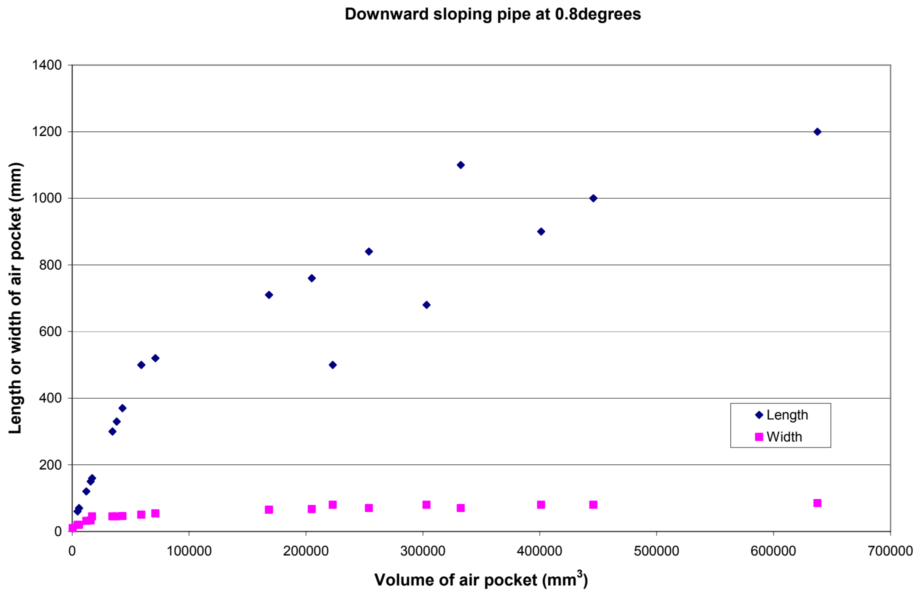

Figure B.2 Pipe at 0.8° downward slope: variation of air pocket length and width with air volume

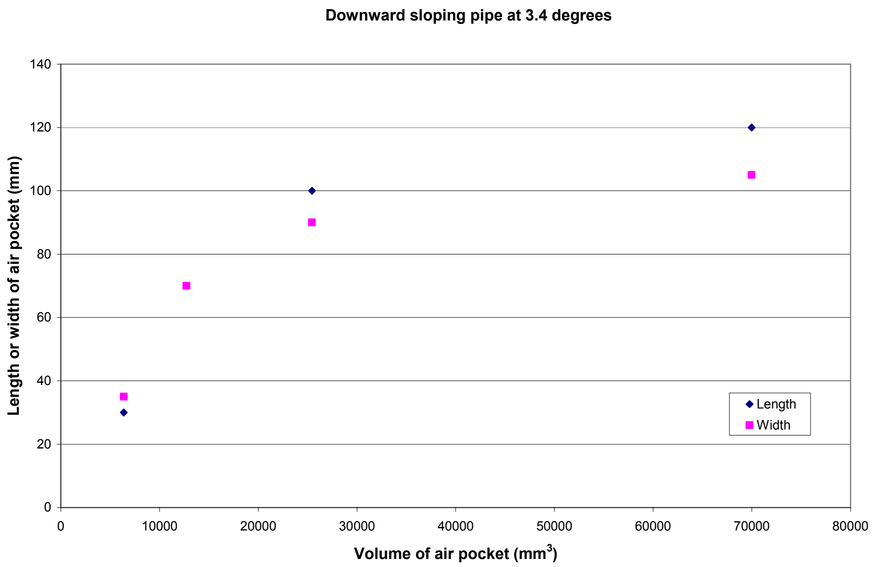

Figure B.3 Pipe at 3.4° downward slope: variation of air pocket length and width with air volume

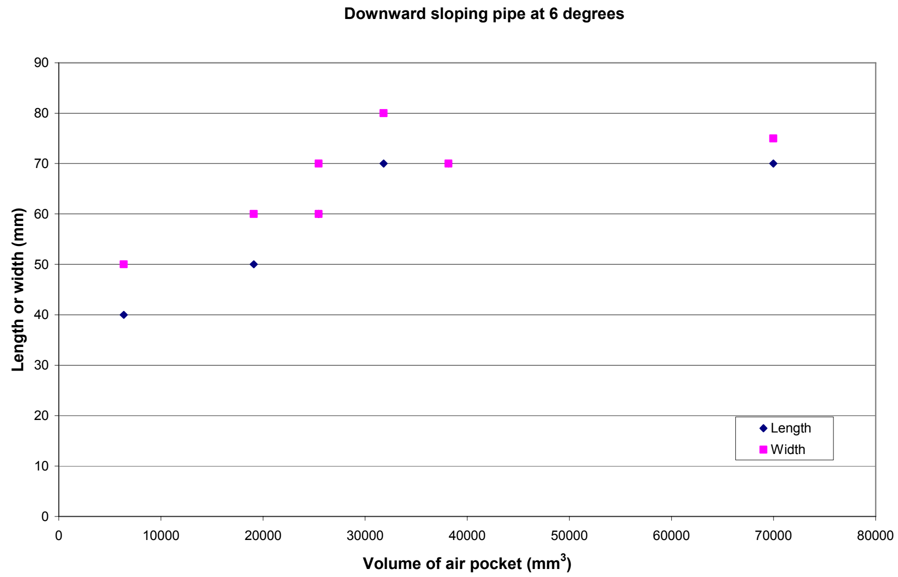

Figure B.4 Pipe at 6° downward slope: variation of air pocket length and width with air volume

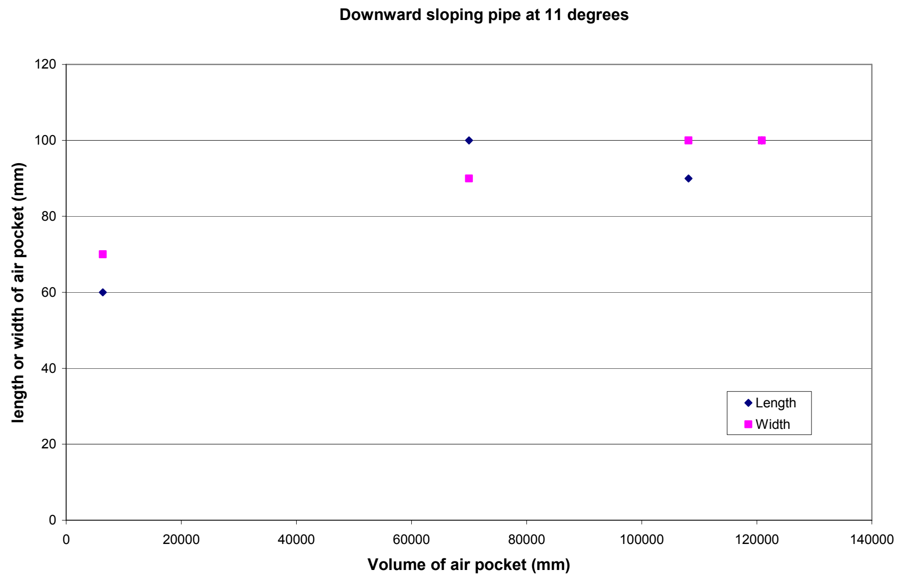

Figure B.5 Pipe at 11° downward slope: variation of air pocket length and width with air volume

Appendix C Hydraulic transient analysis – Case studies

Numerical experiments were recently conducted by research students at the University of Liverpool (Gahan (2004, He (2004)) as part of research commissioned by DTI on “Prevention of air problems in water pipelines”. The work is summarised in more detail in Escarameia et al (2005). The characteristics of real pipelines from which the test cases were drawn are depicted in Figures C.1 and C.2. More technical detail of the modelling application is given in the aforementioned report where, in essence, the pipeline is defined in the form of a number of segments joined at junctions. In the studies, air pockets of various sizes are assumed to be present at one of these junctions during a particular simulation and the size of this pocket varies with pressure during the simulation of the transient, according to the normal polytropic relationship. Calculations are performed using the Method of Characteristics (MOC) whereby the chosen (small) time step (Δt) for the calculations dictates the spatial discretisation (Δx), according to the numerical stability requirement for finite difference techniques. The significance of this is that it is only at each of these subsidiary sections along the pipeline that vapour cavities can be caused to grow, and subsequently collapse, according to the instantaneous pressures encountered. The consequence of this discretised model is that a precise physical representation of the formation and growth of vapour cavities cannot be expected and at best the numerical model can offer an indicative behaviour.

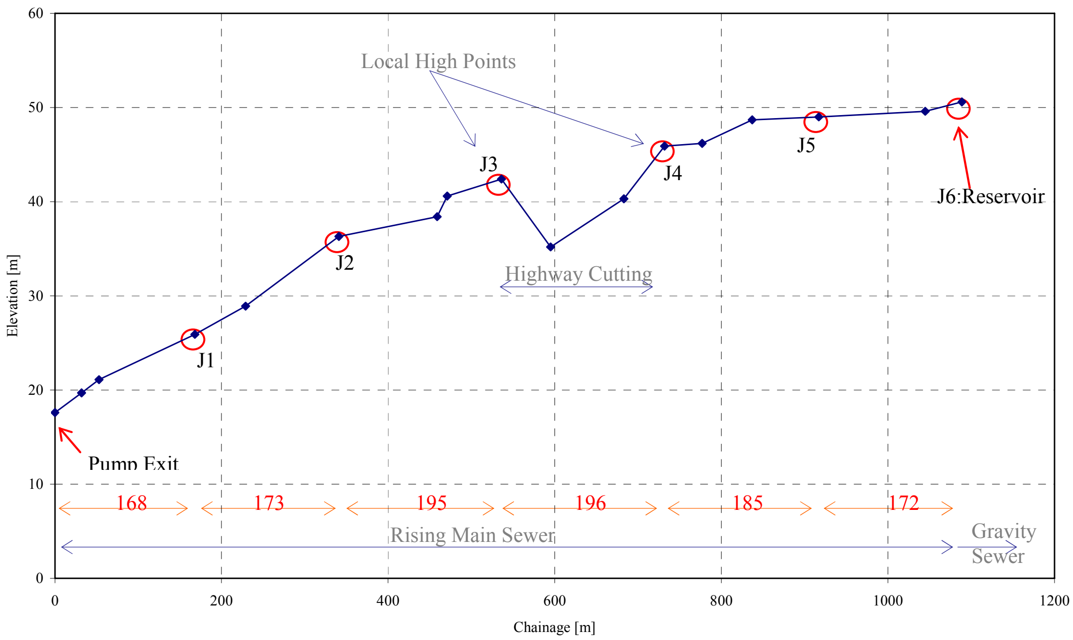

Figure C.1 The UK iron pipeline (CASE 13)

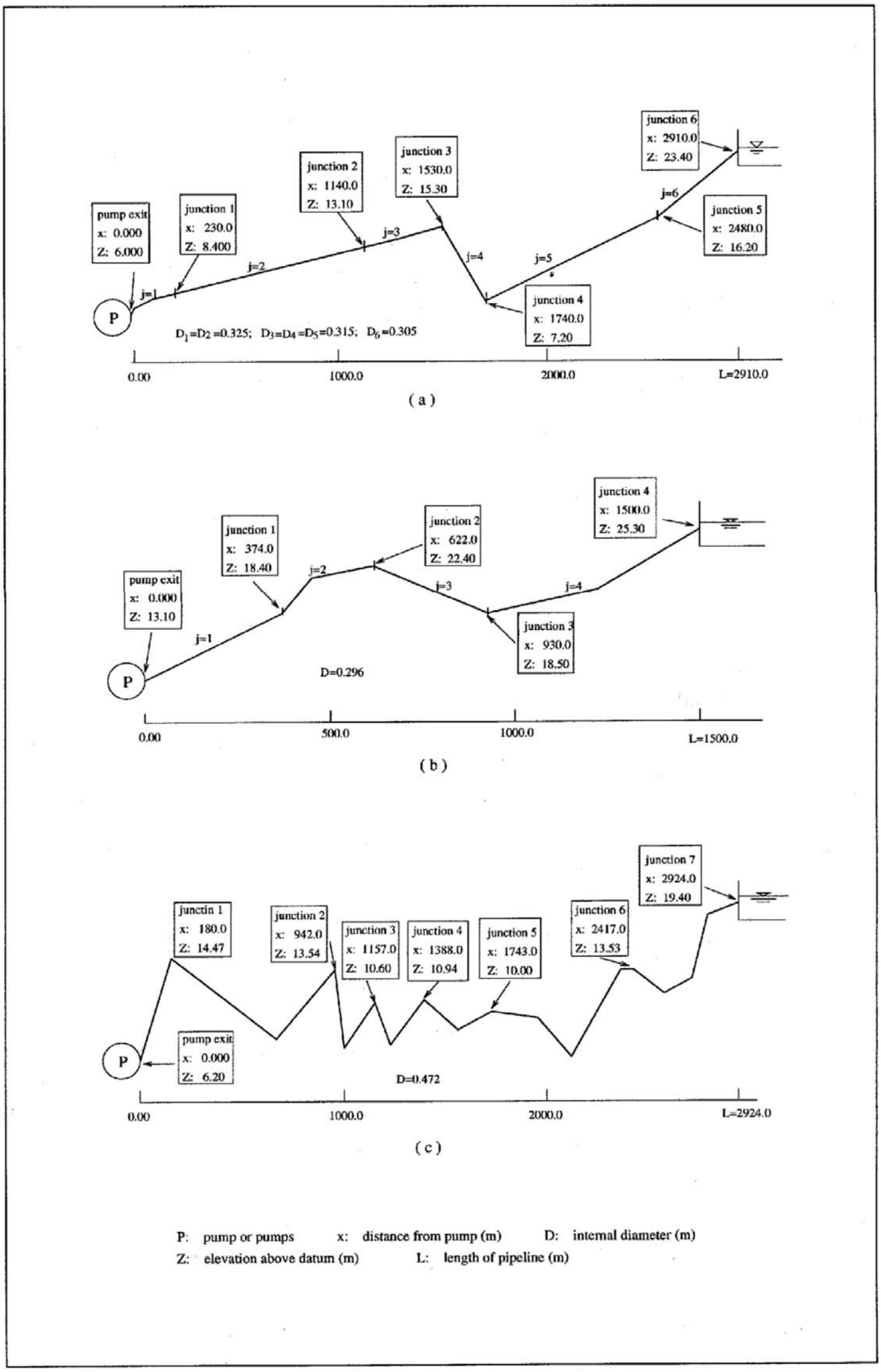

Figure C.2 **The three Danish uPVC pipelines (a – CASE1; b – CASE 2; c – CASE 3)**

The UK pipeline in Figure C.1 is constructed of iron pipe and under normal operation is protected by an air chamber for surge suppression. For the numerical studies, however, the vessel is ignored in the mathematical modelling so as to produce notable pressure transients during pump stop/start and extensive cavitation risk as a result. This has been designated CASE 13, Gahan (2004). A further test case takes the same pipeline but assumes a horizontal profile (at 20m elevation) over most of the length, intended to restrict the cavitation risk (when pressures drop below –10m water column) under the low pressure phase of the transient, this is designated CASE 15. The three Danish pipelines in Figure C.2 were designated CASE 1, CASE 2 and CASE 3, respectively.

In these studies only transients arising from sudden pump stop have been investigated and the procedure was, for each pipeline configuration, to consider single air pockets of different size (in the typical range 0–1.0 m^3) located at each of a series of intermediate 'junctions' along the pipeline in turn. Some typical results are shown in Figures C.3/C.4 and C.5/C.6, the former pair illustrating the time variations and the latter displaying the high and low pressure envelopes superimposed upon the pipeline profile for both CASE 13 and CASE 15.

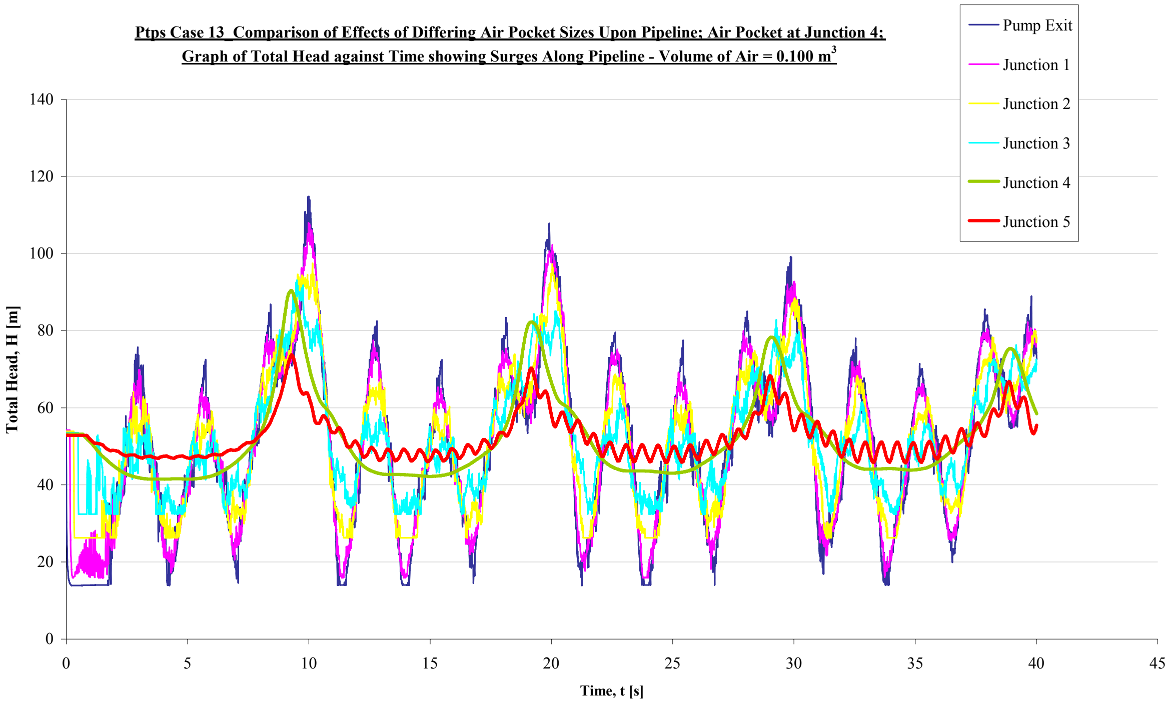

Figure C.3 Pressure surges at various points along pipeline caused by air pocket at a local high point – Case 13

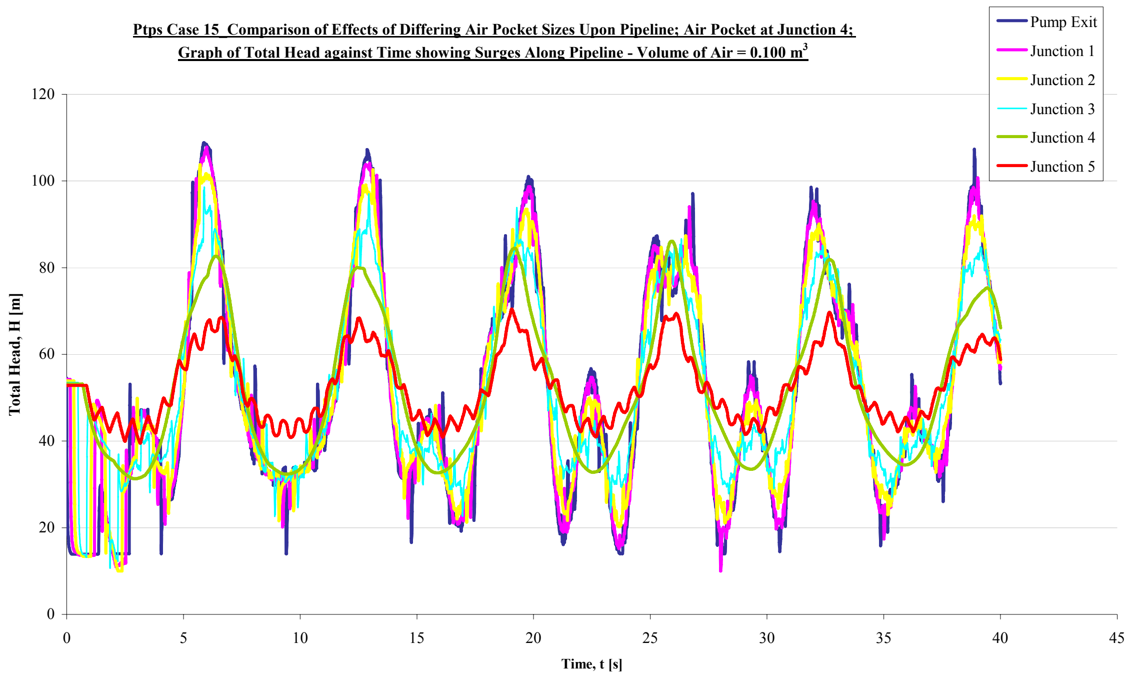

Figure C.4 Pressure surges at various points along pipeline caused by air pocket at a local high point – Case 15

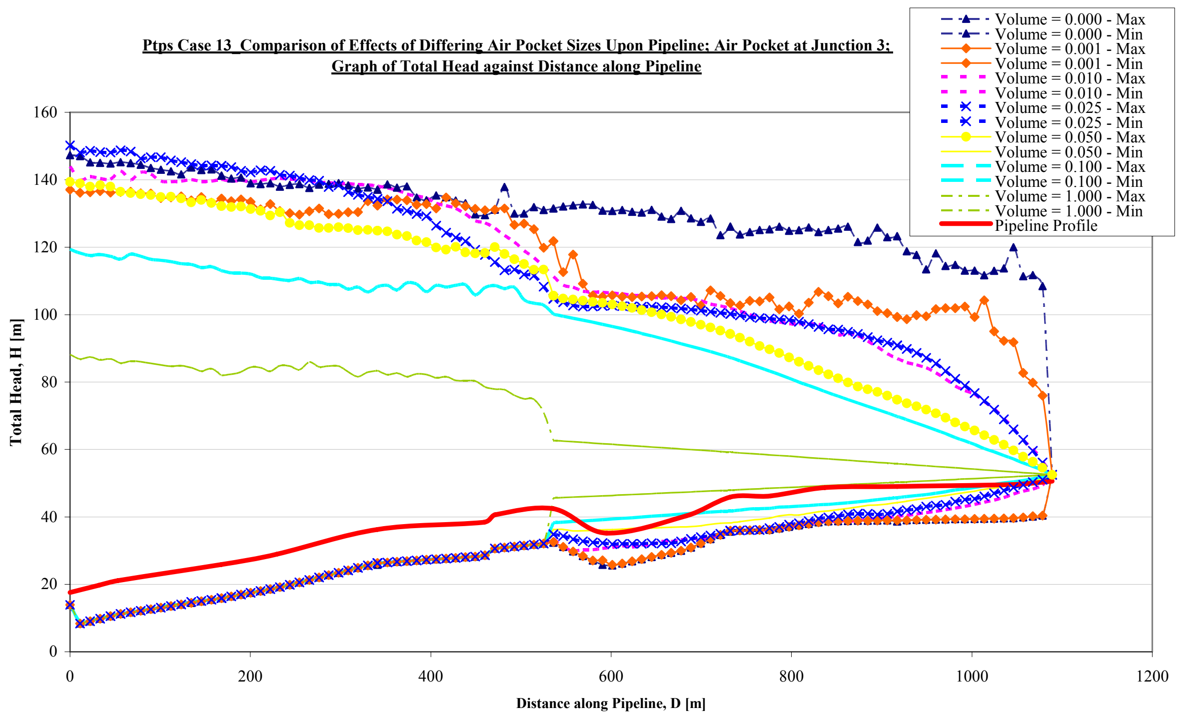

Figure C.5 Comparison of the effects of differing air pocket sizes on pipeline – Case 13

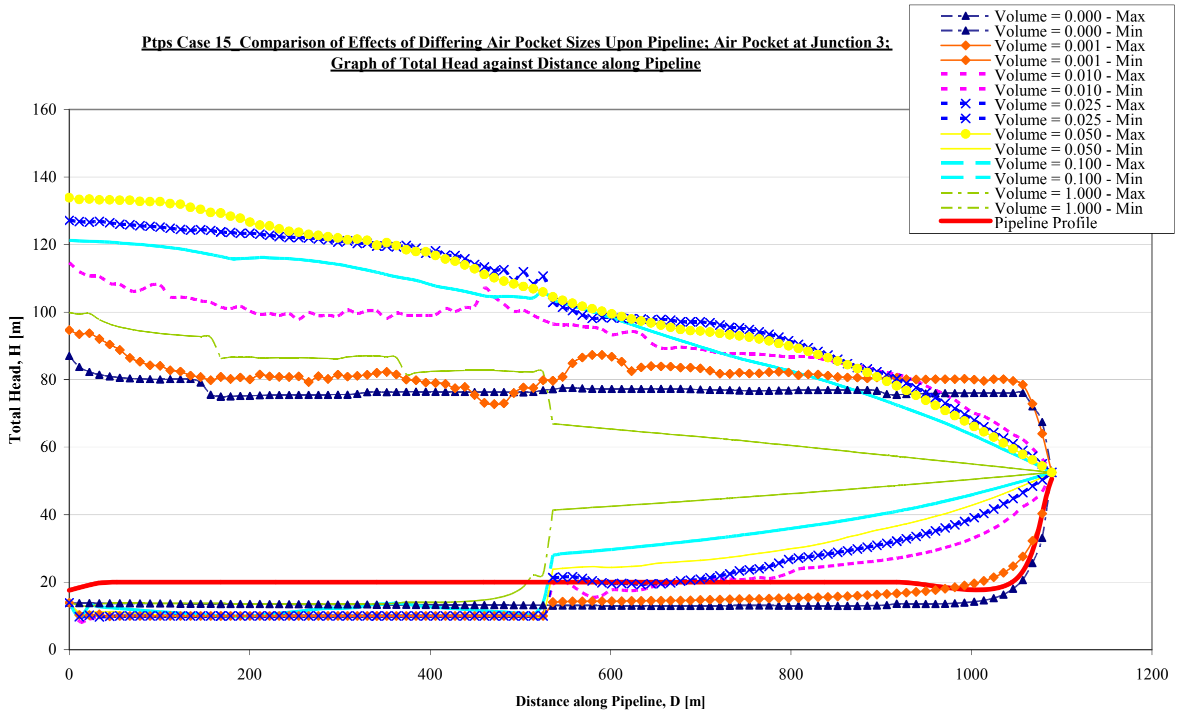

Figure C.6 Comparison of the effects of differing air pocket sizes on pipeline – Case 15

It is apparent from these outputs that in many instances the maximum peak pressures experienced are greater than those for air pocket of volume zero (0.0) which accords to the result of conventional (MOC) surge analysis, ignoring the potential air problem.

Observations arising from the study of the CASE 13 and CASE15 pipelines included:

- The time-plots show characteristic pressure waves and mass oscillations which increase with period as air pocket sizes increase – air pockets acting as partial energy accumulators;
- Small air pockets have the ability to absorb only part of the pressure wave and the majority of the wave will pass through to be reflected by the downstream reservoir. Pressure wave amplitudes have the potential for enhancement under these conditions;
- The results also show that larger air pockets can absorb the transient pressure wave, thereby resulting in a positive effect on the pressure regime within the pipeline system (effectively replicating the behaviour of an air vessel);
- Pressures are of a smaller magnitude further from the pumping station and conversely are larger at the upstream section of a piped system;
- Potentially destructive enhancements of pressures by the presence of air pockets generally have a more significant impact at the upstream/pump end of a pipeline, where pressures are already higher;
- Smaller air pockets produce higher pressures in the pipeline when present at upstream junctions;
- Larger air pockets produce higher pressures in the pipeline when present at downstream junctions;
- Results show that peak pressures can be enhanced due to small air pockets, but there is a limit to the size of pocket to have this effect. This suggests that there is potentially a ‘critical’ air pocket size for any given pipeline configuration;

Conventional wisdom is normally that cavitation should be avoided, such that in the design process surge suppression might then be introduced to eliminate the risk, and in such circumstances the extreme pressure peaks synthesised in the modelling become incidental. It was found in the modelling herein, however, that the interaction of the air pocket with the pressure wave, transmitted as a result of a pump-stop (in CASE 15), might itself trigger the formation of cavitation where this was unexpected.

As a result, in the simulations completed most of the results from numerical experiments are subject to the potential imprecision in the representation of cavity formation, so that neither high accuracy nor systematic behaviour (i.e. with sequential increase in pocket size, for example) should be expected.

Figure C.7 presents a sample of the peak pressure enhancement (over the results from conventional analysis, zero air volume) at pump exit, this time for the simulations for the CASE 2 (see Figure C.2) pipeline. Lines on the plot merely connect the points for ease of visualisation but the lack of systematic variation in the data is likely to arise in part from the above mentioned modelling impression.

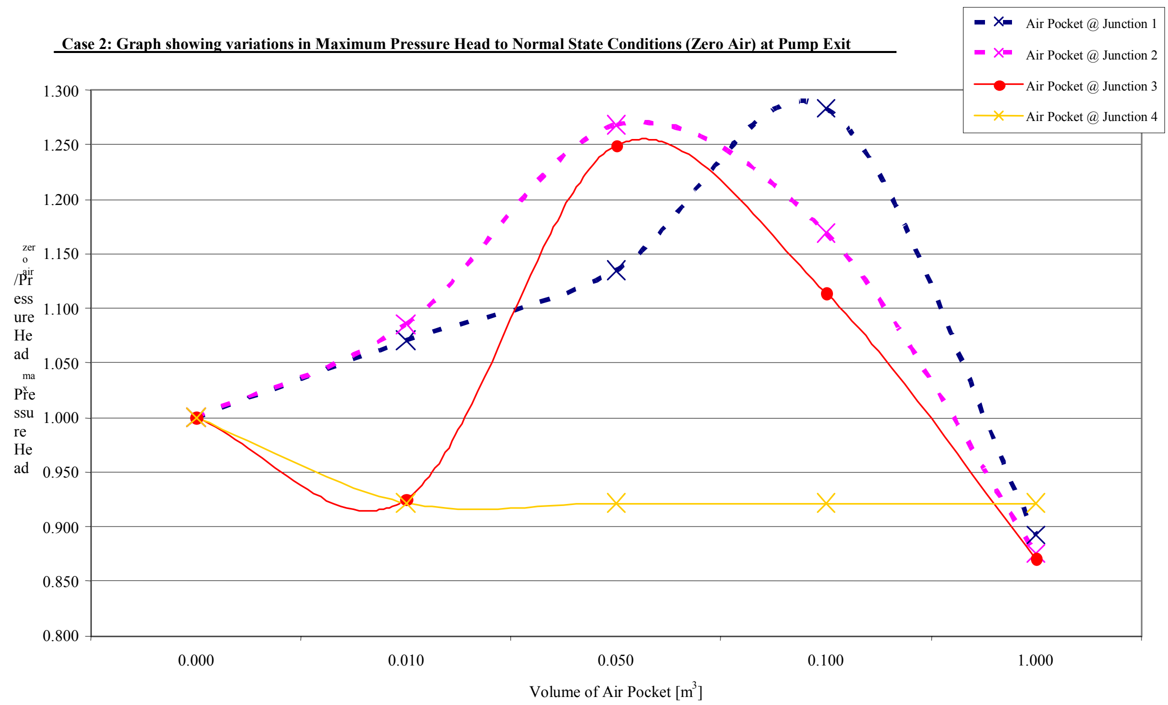

Figure C.7 Example of peak pressure enhancement – Case 2

Table C.1 presents a summary of the worst case peak pressure enhancement arising from the range of air pocket volumes and locations from each of the test cases.

Table C.1 Summary of Peak Pressure Enhancement Factors

Case Study	Approximate Peak Enhancement Factor	Location of Peak Pressure	Air Pocket	
			Size (m³)	Location
CASE 13	1.10	Pump Exit	0.1	Junction 1
CASE 15	2.60	Junction 1	0.01	Junction 1
CASE 1	1.30	Junction 1	0.01	Junction 1
CASE 2	2.00	Junction 1	0.05	Junction 2
CASE 3	2.60	Junction 1	0.05	Junction 2

The outcome of this investigation is, therefore, that significant enhancement in peak pressures can be expected if air pockets of a critical size arise at any given location along the pipeline at the time that a transient is triggered (in these cases by abrupt pump-stop), most critical would appear to be the presence of a small pocket near the upstream end of the pipeline.

It has been mentioned earlier that imprecision must be expected in the outcome of these numerical simulations, which can be sensitive to the fine detail of the numerical discretisation and other aspects of the physical system specification. This is perhaps exemplified by the fact that the scale of enhancement demonstrated here for CASE 13 (1.1 in Table C.1) is somewhat lower than that (~1.6) extracted from Burrows and Qiu (1996). Unfortunately the detailed model specifications from the early study are no longer available so preventing more detailed reconciliation.

References

Burrows R and Qiu, DQ (1996). The effect of air pockets on pressure surge in sewage rising mains. Hydrodynamics, (eds) Chwang, Lee & Leung, Balkema, isbn 90 54 10 860 6, pp1193-1198.

Escarameia M, Dabrowski C, Gahan C and Lauchlan, C (2005). Experimental and numerical studies on movement of air in water pipelines. HR Wallingford Report SR 661, April 2005, UK.

Gahan CM (2004). A review of the problem of air release/collection in water pipelines with in-depth study of the effects of entrapped air on pressure transients. MRes Thesis, Department of Civil Engineering, University of Liverpool, UK

He Y (2004). Computational routines for description of waterhammer in pipelines. MSc (Eng) Thesis, Department of Civil Engineering, University of Liverpool, UK.

Appendix D Additional information on critical velocity for air pocket movement

An envelope of the HR Wallingford results (for the smallest and the highest air pocket classes) without a safety factor is given in Figure D.1 and is compared with work from previous researchers. It should be noted that in this plot the lines attributed to some of the previous researchers do not necessarily represent experimental points but were developed from formulae proposed by these authors or, in some cases, from assessments they carried out on existing data.

It can be seen that for slopes above 40° to 45° degrees, $(\sin S)^{0.5} \geq 0.8$, authors such as Gandenberger predict a decrease in the critical velocities required to move air pockets from downward sloping pipes, which is supported by theoretical work for vertical pipes by Dumitrescu (1943) and Davis & Taylor (1950).

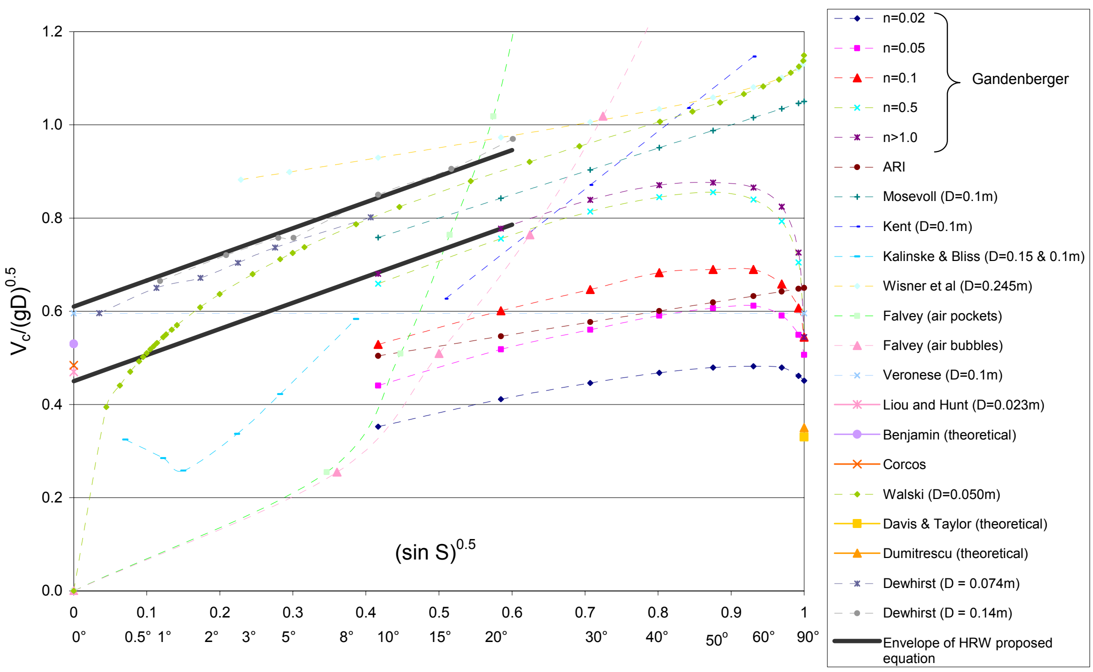

Figure D.1 Comparison of HR Wallingford results (Equation 15 in Escarameia et al, 2005) with published work

References:

Davies RM and Taylor GI (1950). The mechanics of large bubbles rising through liquids in tubes. Proc. Royal Society London, A 200, pp375-390.

Dumitrescu DT (1943). Stomung und einer luftbluse in senkrechten rohr. Z. Angew. Math. Mech. 23(3), pp139-149.

Appendix E Application of Equation 6.1 to larger diameter pipes

This Appendix presents a possible approach to the application to large diameter pipes of the recommended equation for estimation of the critical velocity for movement of air pockets in downward sloping pipes - Equation (6.1). Large diameter pipes are meant here as pipes with D>1m. Refer to the discussion in Section 6.2.

Equation (6.1) shows dependency of the critical velocity on the air pocket volume, which is reflected in the parameter *n*. Practical experience suggests that pipes of large diameter do not suffer more from air problems than smaller diameter pipes, which appears not to be substantiated by predictions of Equation (6.1), where larger pipes would require significantly higher velocities than those currently being used in design. One possible explanation is that the smallest curvature of the pipe soffit may allow an air pocket to extend mainly in length in larger diameter pipes so that it breaks into smaller pockets, thus self imposing a limit in the air pocket volume. This mechanism is likely to take place primarily in pipes at shallow gradients. Therefore, if one assumes, for example, an air pocket of $1m^3$, the following table (Table E.1) illustrates the effect of the diameter on the value of the parameter *a*:

Table E.1 Effect of pipe diameter on the parameter *a* in Equation (6.1) for an air pocket volume of $1m^3$

D (m)	n	a
1	1.27	0.61
2	0.16	0.57
3	0.047	0.45
4	0.020	0.45

As can be seen from Table E.1, if an air pocket is restricted to $1m^3$ volume, the higher values of *a* in Equation (6.1) should not be used. For example, only values of *a* equal to 0.57 should be used for 2m diameter pipes and 0.45 for 3m diameter pipes.

Appendix F List of equations given in the Manual

As a means of providing a quick, convenient reference, this Appendix lists the equations suggested in this Manual (refer to Notation for definition of symbols). Before applying any of these equations, it is essential to refer to the main text and to the discussion and explanations given regarding their limits of applicability.

A table (Table F.1) relating different ways of expressing pipe slope is also given in this Appendix.

Critical velocity for air pocket movement in downward sloping pipes:

$$V/(gD)^{0.5} = a + 0.56\ (\sin S)^{0.5} \qquad (6.1)$$

where *a* equals:

0.45	for	n < 0.06
0.50	for	0.06 ≤ n < 0.12
0.57	for	0.12 ≤ n < 0.30
0.61	for	0.30 ≤ n < 2

Hovering velocity of air pockets in downward sloping pipes:

$$V_h = \beta V \qquad (6.2)$$

where β can be taken on average as 0.90

Air entrained at hydraulic jumps in circular pipes

$$Q_{air} = 0.0025\left(Fr - 1\right)^{1.8} Q \qquad (6.3)$$

Length of aeration zone in hydraulic jumps (see also Figure 4.6):

$$L_a = 4\frac{Fr_1 U_2\left(1 - (\sin S)^{0.5}\right)}{\cos S} D \qquad (6.6)$$

Hydraulic roughness coefficient of slimed rising mains:

$$k_s = \alpha V^{-2.34} \qquad (6.7)$$

Minimum inlet submergence in chambers

$$S_u / D = 1.0 + 2.3\ Fr \qquad (7.1)$$

Table F.1 Pipe slopes

1/x	Degrees	%
0	0	0
1/2000	0.029	0.05
1/1000	0.057	0.1
1/500	0.11	0.2
1/400	0.14	0.25
1/300	0.19	0.33
1/200	0.29	0.5
1/100	0.57	1
1/75	0.76	1.33
1/50	1.1	2
1/25	2.3	4
1/20	2.9	5
1/15	3.8	6.7
1/10	5.7	10
1/5	11	20
1/1	45	100
1/0.58	60	172
-	90	-

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Behaviour of air in pipelines is complex and not fully understood. This manual gives practical information on how to deal with problems arising from the presence of air in pipelines conveying water and wastewater. It will be of interest to all professionals concerned with the design, construction and/or maintenance of such pipelines.

This manual presents issues relating to this specialist subject in a way that will be accessible to individuals with little prior knowledge of this field. More experienced professionals will find useful new information on the potential problems arising from the presence of air and suggestions for reducing or controlling its negative effects.

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