Air in Pipelines

A Literature Review

C S Lauchlan
M Escarameia
R W P May
R Burrows
C Gahan

Report SR 649
Rev 2.0
April 2005

HR Wallingford

Document Information

Project	Guidance manual for prevention of air problems in water pipelines
Report title	Air in Pipelines - A Literature Review
Client	DTI
Client Representative	Mr M Roe
Project No.	MAS0440
Report No.	SR649
Doc. ref.	SR649-Air in Pipelines Lit review rev 2.0 doc
Project Manager	Manuela Escarameia
Project Sponsor	Phil Besley

Document History

Date	Revision	Prepared	Approved	Authorised	Notes
02/02/04	0.0	CSL			
24/02/04	0.1	MME&CSL			
17/03/04	0.2	MME			
22/07/04	1.0	CSL	MME	PB	Interim version
11/04//05	2.0	MME	MME	PB	Final

Prepared Manuela Escarameia (for Christine Lauchlan)

Approved Manuela Escarameia

Authorised Phillip Besley

Summary

Air in Pipelines

A Literature Review

C S Lauchlan
M Escarameia
RWP May
R Burrows
C Gahan

Report SR649
April 2005

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 cost can be incurred in providing air valves and chambers, and in deepening trenches so as to provide the minimum gradients that are thought necessary to enable air bubbles and pockets to move towards the valves.

This report is the first output of a research study commissioned by the Department of Trade and Industry (DTI), to be carried out between October 2003 and November 2005. The study is aimed at producing a guidance manual for designers and operators of pipelines in order to reduce the number and cost of problems caused by air in water and wastewater pipelines. The detailed objectives of the study can be summarised as follows:

- To collect and review existing knowledge and experience relating to air problems in pipelines.
- To carry out targeted experimental and numerical studies to obtain information necessary for the preparation of the guidance manual.
- To combine information from the knowledge review with results from the experimental and numerical studies to produce practical design guidelines for use in the manual.
- To produce a guidance manual for designers and operators of water and wastewater pipelines on how to avoid or eliminate problems due to air.

This report summarises the findings of a review of published data and practical experience relating to the movement and effects of air in water and wastewater pipelines. Available information on the use, sizing and location of air valves is also reviewed. A first version of this report was published in July 2004 and later amendments were introduced in the current, final, version. The conclusions of this review had implications for the design of test facilities for studying air bubble or pocket movement in pipelines, which were taken into account in the experimental work carried out in the latter half of 2004.

Contents

Contents continued

Contents continued

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.

This report is the first output of a research study commissioned by the Department of Trade and Industry (DTI), to be carried out between October 2003 and November 2005. The study is aimed at producing a guidance manual for designers and operators of pipelines in order to reduce the number and cost of problems caused by air in water and wastewater pipelines. The detailed objectives of the study can be summarised as follows:

- To collect and review existing knowledge and experience relating to air problems in pipelines.
- To carry out targeted experimental and numerical studies to obtain information necessary for the preparation of the guidance manual.
- To combine information from the knowledge review with results from the experimental and numerical studies to produce practical design guidelines for use in the manual.
- To produce a guidance manual for designers and operators of water and wastewater pipelines on how to avoid or eliminate problems due to air.

A Steering Group was formed for the project involving the following partners:

- Black & Veatch Consulting (BVCs)
- CIRIA
- Dean & Dyball
- MWH
- Ove Arup & Partners
- Thames Water Utilities
- United Utilities
- University of Cambridge, BP Institute for Multiphase Flow
- University of Liverpool, Department of Civil Engineering.

The present report summarises the findings of a review of published data relating to the effects of air in water and wastewater pipelines. It also includes information on practical aspects and experience provided by the project partners. Following the Introduction in Chapter 1, Chapters 2 and 3 explain briefly why air can be a problem in pipelines and how it enters pipe systems. A description of air/water patterns in pipes is given in Chapter 4 and Chapter 5 presents a review of research on the mechanisms of air movement. Different available criteria for the movement of air bubble/pockets are presented and discussed in Chapter 6. Chapter 7 deals with air removal by means of valves, including a description of the various types of air valve and criteria for selection. The effect of air in pressure transients is discussed in Chapter 8 and information from practical experience on pipeline design to avoid air problems is given in Chapter 9. The conclusions of this literature review and their implication on the next stage of the project are presented in Chapter 10.

2. Why is air a problem?

The collection of published information and discussions with practitioners have revealed the following issues related to the presence of air in pipelines:

- Air pockets reduce the effective pipe cross section, which results in a reduction in pipe capacity.
- The bulk properties of the fluid (a mixture of air and water) are changed. This concerns mainly the density and the elasticity.
- 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.
- Air accumulation in a system may lead to disruption of the flow and 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.
- Air can cause difficulties in filter operation. The surges produced by varying air pressure make it difficult to maintain good filter operations. Also, bubbles can become trapped in the sand filters reducing their efficiency.
- The presence of air can reduce 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 a loss of priming.
- In ferrous pipelines the presence of air enhances corrosion by making more oxygen available for the process.
- Sealing, a transition from part-full to pipe full flow, can cause vibrations of the structure and surging of the flow can accompany it.
- Air can produce false readings on measuring devices.
- Cooling water systems have additives in the water for anticorrosion and this increases foaming of the water.

In addition:

- Transported air will be released at the discharge location. This raises environmental concerns including: foaming, particularly in conjunction with algal activity; visual, the appearance of the water can be very aerated (i.e. white water); and odour, from wastewater/sewerage.
- Air is associated with buoyancy effects for underwater pipelines, such as outfalls.

3. How air enters pipe systems

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.

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. Temperature increases can also promote the release of air, as the vapour pressure of water increases with temperature (at 15°C this is 1.70kN/m^2 whereas at 30°C it is 4.24kN/m^2). This means that at 30°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°C. This can be an important consideration for pipeline design in hot climates or 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°C and 21°C, with 15°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°C to 35°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 and Swaffield, 1998, titled “Fluid Mechanics”) and are not covered in this review.

In addition to air coming out of solution, there are several ways in which air can be found in pipelines. These are listed below:

- Entrainment at the inflow location such as a drop chamber, inlet or intake.
- Entrainment at the outflow location. For instance, sea outfalls may operate under varying tidal levels and the outlet may be located above the sea level.
- Entrainment due to vortices at an inlet or intake.
- Turbulence in shafts.
- Hydraulic jump. The flow within a pipe system may change from gravity to surcharged flow and under these conditions a hydraulic jump may form.
- Direct pumping. Direct pumping of air into a system may be carried out to reduce cavitation pressures.
- Pumps. There may be insufficient submergence on the pump or vortices may form at the inlet causing air to be entrained into the system.
- Filling or emptying of lines. Air transport can occur during filling and emptying of pipelines. The air movement along the pipeline can be slow during filling and can become trapped at high points in the system.
- Gas formation through biological activity.
- At sections under negative pressure air can leak in at joints and fittings.
- Negative pressures at the inlet to the pipe.

4. Air/Water flows

4.1 DESCRIPTION OF AIR/WATER PATTERNS

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 and Sohal (1983) provide reviews of the different possible flow patterns. A summary of typical flow patterns and their definitions are given below. It should be noted that the terminology used herein may differ from that used in some publications. As mentioned by Rouhani and Sohal (1983), up to 84 different flow pattern labels have been suggested in the literature.

4.1.1 Vertical flow patterns

Vertical flow patterns, which are generally more axisymmetric when compared with horizontal flows (See Section 4.1.3), can be described as follows:

- *Bubble flow* – the air is distributed in the water as spherical or spherical cap bubbles which are small with respect to the conduit diameter. This flow pattern occurs when a relatively small quantity of air is mixed with a moderate flow rate 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 occupy almost the whole pipe cross section except for a thin liquid layer on the wall and their length is several times the pipe diameter.

- *Churn 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 froth 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 great airflow 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.

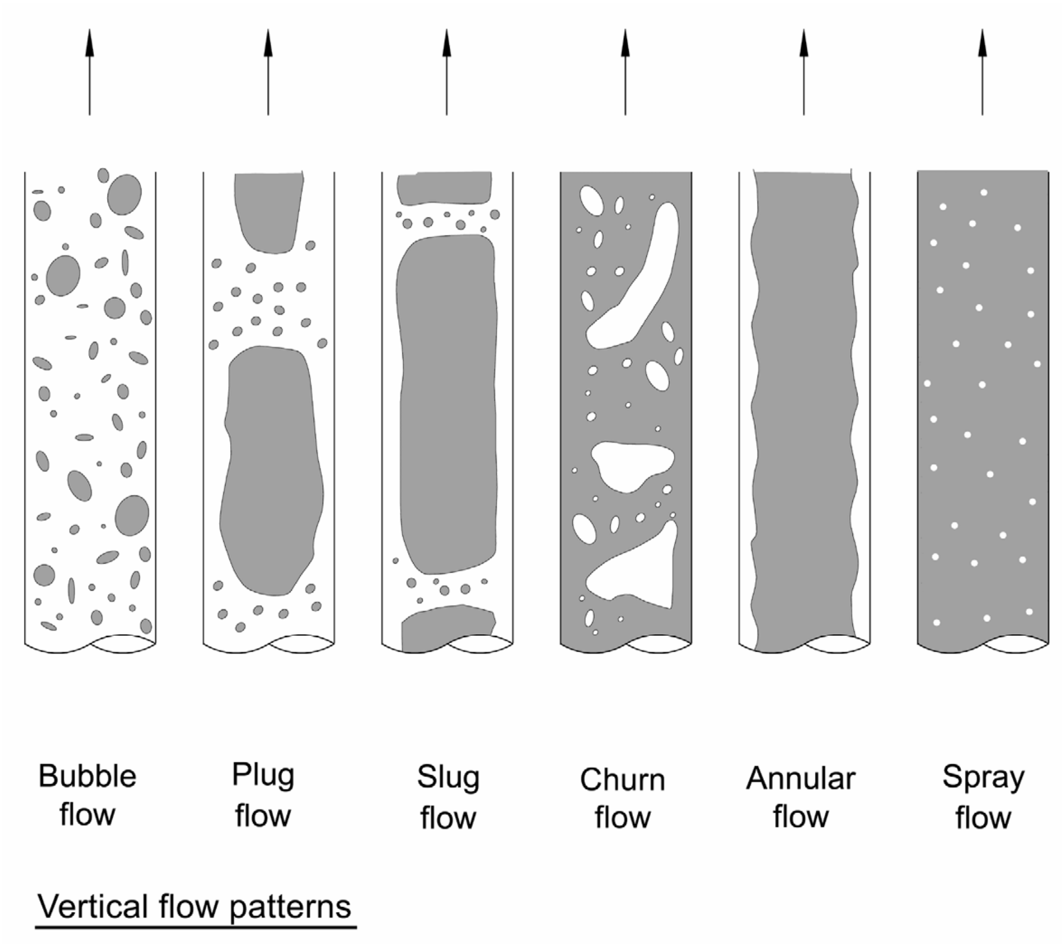

Figure 1 Vertical flow patterns

4.1.2 *Sloping flow patterns*

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

4.1.3 *Horizontal flow patterns*

In general, most of the flow regimes in horizontal gravity pipes show a non-symmetrical pattern which is due to the effects of gravity on fluids with different densities. This generates a tendency for 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 though 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 airflow 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 airflow 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 airflow 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 airflow rates the annular film is stripped from the pipe walls and is carried in the air as entrained droplets.

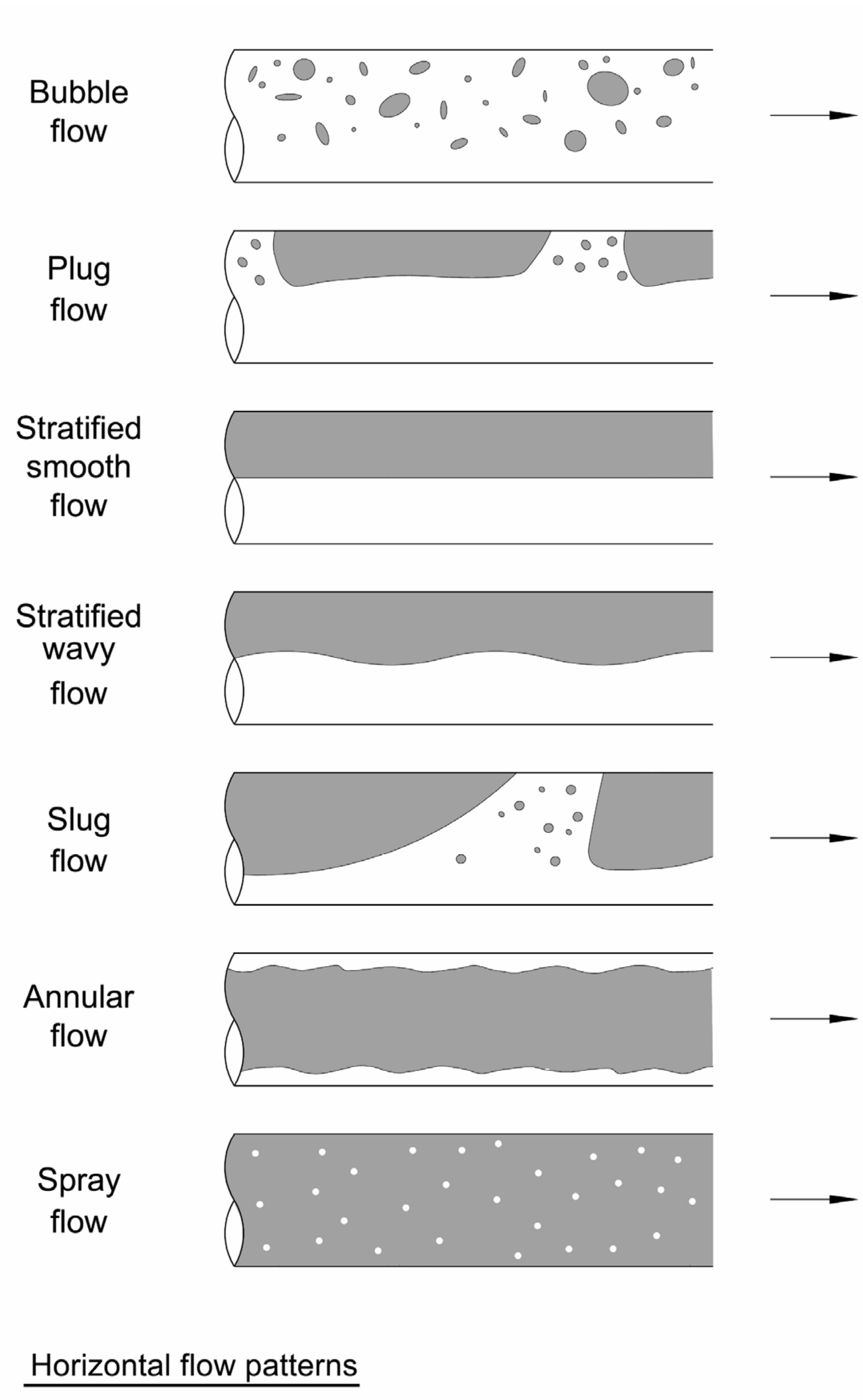

Figure 2 Horizontal flow patterns

4.2 PREDICTION OF AIR/WATER REGIMES

Hansen (1986) undertook a study of two-phase flow regimes in both vertical and horizontal pipes. He found that different flow regimes did arise for the vertical and horizontal directions. For horizontal or near horizontal pipes the flow is more complex than for vertical pipes because of the asymmetry introduced by the gravitational forces.

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.

A model for determining flow regime transitions in two-phase gas-liquid flow was developed by Taitel and 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 3 shows the generalised flow regime map based on the model.

The authors studied the effect of small degrees of inclination of the pipe on the flow transitions. It was found that for downward inclinations much higher gas and liquid flow rates were required 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 and 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°. Generalised flow pattern maps for inclined pipes based on Barnea et al (1980) are shown in Figures 4 and 5.

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. A comparison of vertical flow pattern maps of Ishii and Mishima (1980) with those of Dukler and Taitel (1977) is shown in Figure 6. They give an indication of the likely flow regime for vertical pipes. Figure 7 is a generalised flow pattern map for vertical flow, based on Dukler and Taitel (1977).

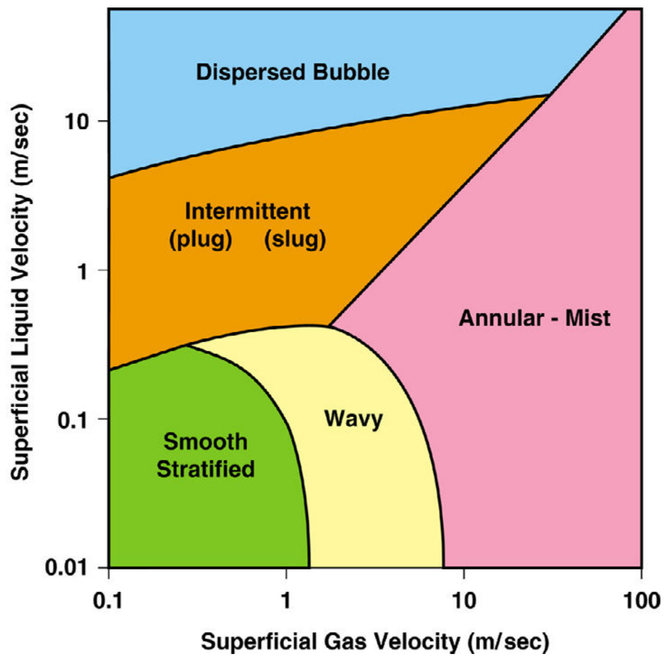

Figure 3 Generalised flow regime map for horizontal two-phase flow (based on Taitel and Dukler, 1976)

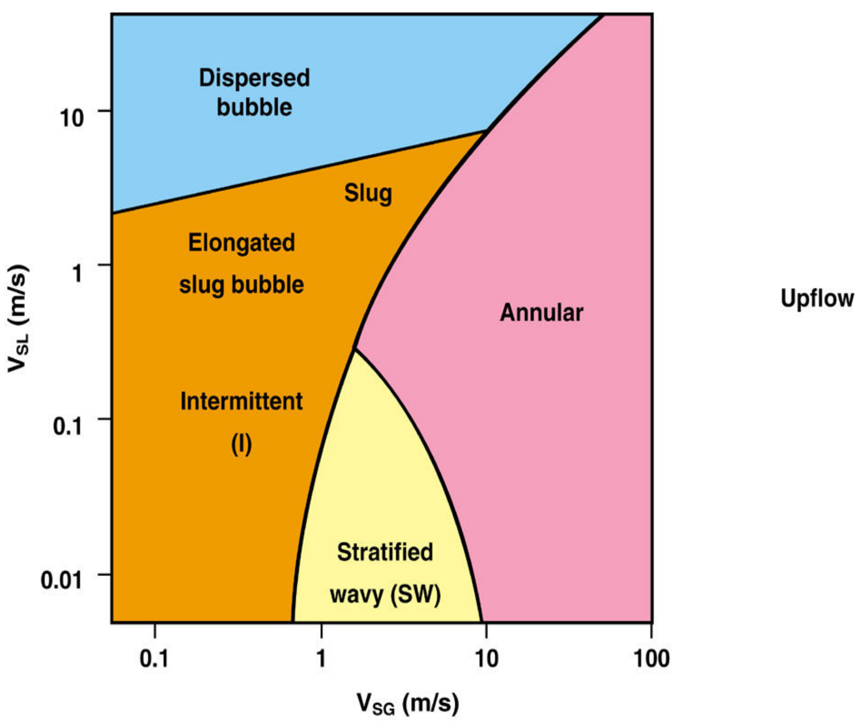

Figure 4 Generalised flow regime map for upward sloping two-phase flow (based on Barnea et al, 1980)

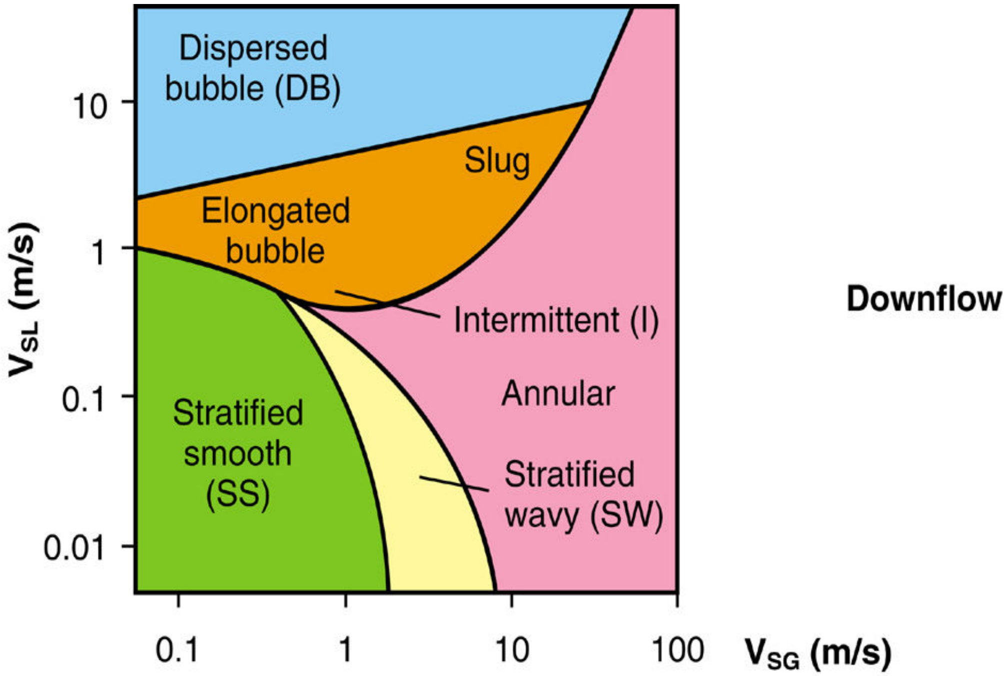

Figure 5 **Generalised flow regime map for downward sloping two-phase flow (based on Barnea et al, 1980)**

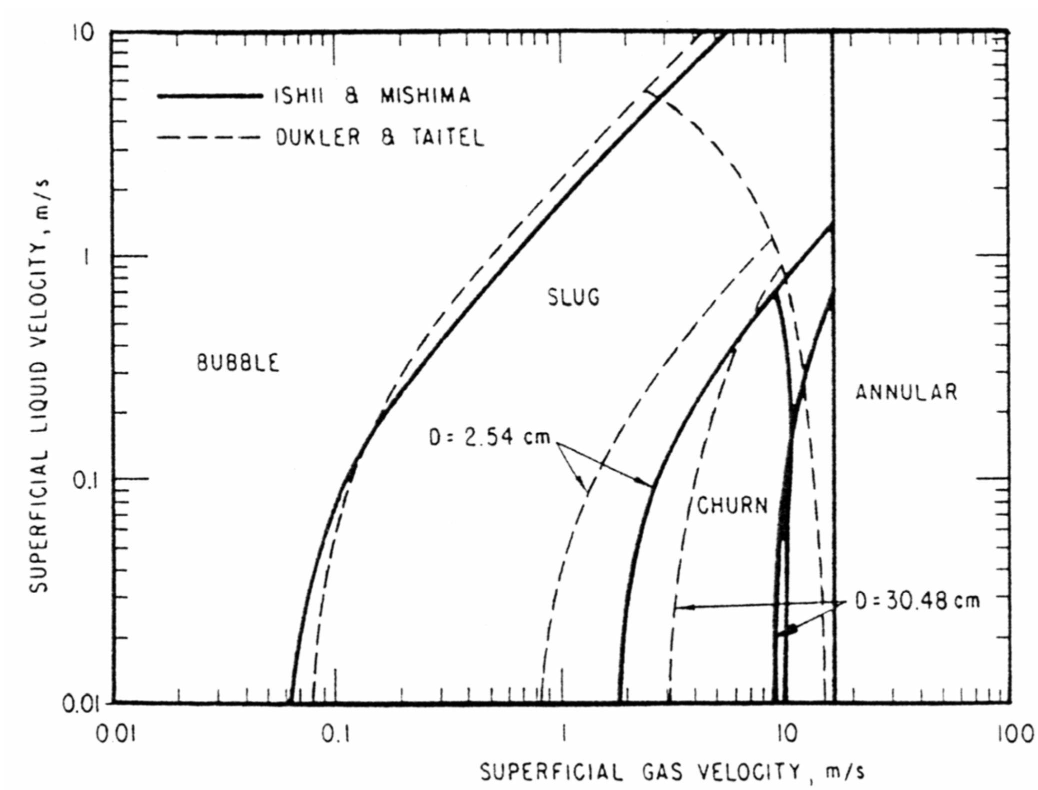

Figure 6 **Examples of vertical flow pattern maps, showing those of Ishii and Mishima and Dukler and Taitel (taken from Rouhani and Sohal, 1983)**

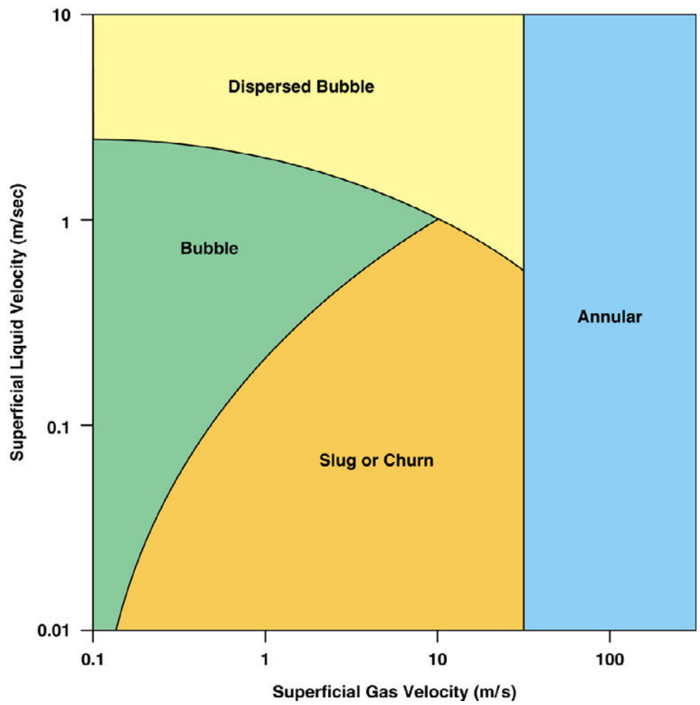

Figure 7 Generalised flow regime map for vertical two-phase flow (based on Taitel and Dukler, 1976)

A more recent paper by Taitel and 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.

5. Mechanisms of air movement

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 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 high speed open channel flows the transport capacity increases with increasing velocity and turbulence intensity of the water flow. 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. If the transport capacity is exceeded in conduit flows, the detrained air will collect at the top of the conduit and form air pockets."

There are three flow patterns that are of distinct interest in the design of pipeline systems: bubble flow and plug flow (air pocket movement) where relatively low rates of air are moving with the water flow; and for higher rates, 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 Section 3; whereas slug flow can for example occur as a result of stoppages, and during filling and emptying operations.

Wisner et al (1975) suggest that the removal of air pockets from a pipeline may take place in the following ways, individually or by both: (1) sweeping, i.e. bodily removal of the whole air pocket; and (2) generation and entrainment. At the downstream end of a large air pocket a hydraulic jump can form and 'generation' refers to the process by which bubbles are created downstream of the hydraulic jump. 'Entrainment' is a term used to describe the movement within the liquid of these newly generated bubbles downstream.

The term "sweeping velocity" denotes the minimum mean velocity required to transport a pocket or a bubble from a water line. The term "clearing velocity" is used to denote the minimum velocity to clear a pocket out of the line without reference to whether removal occurs by sweeping or by generation and entrainment.

In each of the following sections various relevant papers on air-water transport in pipes are reviewed and their key findings presented.

5.1 BUBBLE MOVEMENT IN STATIONARY FLOW

Zukoski, E.E. 1966. Influence of viscosity, surface tension, and inclination angle on motion of long bubbles in closed tubes, J. Fluid Mechanics, Vol. 25, No. 4, p821-837

Zukoski studied experimentally the motion of long bubbles in closed tubes with stationary flow for a range of inclination angles. He studied the effects of viscosity and surface tension along with inclination angle on bubble velocity.

In vertical tubes the velocity of a bubble in large diameter tubes has been shown to be proportional to $(g(D/2))^{1/2}$ where g is the local gravitational acceleration and D is the pipe diameter. However, for sufficiently small pipes, the velocity decreases faster than $(D/2)^{1/2}$, and movement can totally cease for tubes of small enough diameter. For this range of diameters surface tension is important. As the tube size and velocity decrease, the velocity also becomes a function of the viscosity of the fluid involved. Tube diameters of 5 to 178mm were tested. It was found that tube material had no influence on the flow when the diameter was greater than 20mm.

The Reynolds number was defined as $Re = \rho U_o D/(2\mu)$, where ρ and μ are the density and the dynamic viscosity of the non-aerated liquid, D is the pipe diameter, and U_o is a velocity given by $[g(D/2)(\Delta\rho/\rho)]^{1/2}$, where g is acceleration due to gravity and $\Delta\rho$ is the absolute value of the density difference between the non-aerated liquid and the bubble fluid. In the high Reynolds number regime (Re > 100) the conclusion was drawn from the results that the influence of viscosity on bubble propagation rate is small. It was also concluded that the reduction in propagation rate as the surface tension parameter increases is primarily due to surface tension effects (the surface tension parameter is defined as $E_t = \sigma/\Delta\rho g(D/2)^2$, where σ is the surface tension).

In inclined pipes the mechanism of bubble propagation becomes more complex because bubble geometry changes with the inclination angle. From the experimental results it was found that in general, the propagation rate of the bubble increases to a maximum value as the inclination angle decreases from the vertical position to 45 degrees, and a further reduction in angle causes the rate to decrease. In all cases for which the normalised speed was greater than 0.1, steady propagation rates were obtained for inclination angles from 90 degrees to a few degrees. However, for the horizontal position, a steady propagation was only observed if $E_\tau < 0.1$ and none was found for larger values of E_t. If $E_t = 0.01$, D = 0.174m (for fluids at 20°C) which means that for D > 0.174m steady propagation can occur.

The following limitations to the analysis were given:

- Stable bubbles are obtained in relatively large diameter tubes (D > 0.174m) with length-to-diameter ratios in the range 50:1 to 20:1.
- If the length of the flow between the bubble nose and the tube exit is increased indefinitely, then viscous effects will slow the efflux and produce a reduction in bubble propagation rate.

Viana, F., Pardo, R., Yanez, R., Trallero, J.L., Joseph, D.D. 2003. Universal correlation for the rise velocity of long gas bubbles in round pipes, Journal of Fluid Mechanics, vol. 494, pp379-398

This paper discusses the rise velocity of long gas bubbles in stationary fluids in circular pipes. The work predominantly looks at the movement of these bubbles in vertical pipes only. The authors start by reviewing previous work, in particular the various formulations for the prediction of rise velocity for gas bubbles. Additional experiments were performed to extend the results available from previous work. They found correlations for different flow regimes involving the effects of inertia, interfacial tension and viscosity and defined the following parameters R_b (buoyancy Reynolds number) and E (the Eötvös number):

$$R_b = \frac{\left(D^3 g\left(\rho_l - \rho_g\right)\rho_l\right)^{1/2}}{\mu} \tag{1}$$

$$E = \frac{g\rho_l D^2}{\sigma} \tag{2}$$

where D is the pipe diameter, g is the acceleration due to gravity, ρ_l is the liquid density, ρ_g is the gas density, σ is the surface tension and μ is the dynamic viscosity.

Viana et al's results show that for $R_b > 200$ and $E > 40$ the only retarding force on the bubble is inertia and

$$\frac{V}{\sqrt{gD}} = 0.34 \tag{3}$$

where V is the rise velocity.

Assuming $R_b > 200$, if E = 40 then at 20°C, D = 0.173m, which means that for pipe diameters of 0.175m and above only the effects of inertia are important and viscous and interfacial forces can be neglected. Additional relationships for different ranges of R and E are also provided. The relationship given above is similar to that proposed by previous authors such as Dumitrescu (1943) and Davies and Taylor (1950).

Bendiksen (1984) and Alves et al (1993) also give details of air bubble movement in stationary flows. Their results are described later in this report.

5.2 BUBBLE AND PLUG FLOW REGIMES

The movement of bubbles and air pockets in pipes has been an area of active research since the late 1930s. In order for air to move within either stationary or moving water the forces of inertia, buoyancy, drag, viscosity, and surface tension may need to be resolved.

Falvey (1980) states that "if the conduit is horizontal or sloping upward in the direction of flow then all the entrained air will move with the flow. If the conduit slopes downward in the direction of flow, air bubbles can either move upstream or downstream relative to the pipe wall". He comments that for bubble movement you need to consider the relative magnitudes of the buoyant and drag forces upon a stationary bubble in the flow. The bubble will move perpendicular to the pipe axis only when the upstream component of the buoyant force vector equals the drag force component.

This section describes the results of various experimental studies in the literature on the movement of air bubbles though water.

5.2.1 *Vertical* flows

Salih, .M.A. 1980. Entrained air in linearly accelerating water flow, ASCE, Journal of the Hydraulics Division, Vol. 106, HY 10, p1595-1605

The results of experimental tests on bubble motion on vertical accelerating flow found that a gas bubble introduced to a liquid flow of constant velocity gradient will soon move ahead of the liquid flow and attain a terminal value for its velocity slip ratio. The velocity slip ratio is given as:

$$\Delta = \frac{U_b - U_L}{U_L} \tag{4}$$

where U_b is the bubble velocity, and U_L is the liquid velocity. The tests were performed using a rectangular test section, with an accelerating flow area of varying width from 101.6mm to 25.4mm and a depth of 12.7mm.

Martin, C.S. 1970. Vertically downward bubbly and slug flow of an air-water mixture in a pipe. Bericht Nr. 511, Institut für Hydromechanik, Der Universität Karlsruhe, Karlsruhe, Germany

Martin studied experimentally the movement of vertically downward pipe flows of air and water. He looked at both bubble and slug flow regimes and the transition from one flow pattern to the other. Relevant findings can be summarised as:

- The distribution of void fraction in bubbly flow is evidently affected by entrance conditions.
- The shape and size of the bubble formation are substantially influenced by the condition of the sump or water supply. The presence of nuclei, dissolved gases, surface active agents, or changes in surface tension altered the character of the air-water mixture.
- The pressure gradient in bubbly flow was not affected by differences in the condition of the water.

The tests were performed using a 140mm diameter clear plastic pipe, with an 8m long test section.

5.2.2 Sloping pipes

Downward slope

Falvey 1980. Air-water flow in hydraulic systems, Bureau of Reclamation, Engineering monograph No. 41

As the bubbles travel downstream in sloping conduits, they tend to form large pockets of air. It has been found that the rise velocity of these pockets is greater in sloping conduits than it is in vertical conduits. For a specific range of discharges, a flow condition can exist whereby bubbles will move downstream and form into pockets that move against the flow in an upstream direction.

Kalinske, A.A. and Bliss, P.H. 1943. Removal of air from pipe lines by flowing water. ASCE, Civil Engineering, Vol. 13, No. 10 pp480-482

This paper provides a discussion of experimental tests of air removal from pipes at various slopes. The tests were performed using 102mm and 152mm diameter transparent pipes. On the downslope a hydraulic jump formed in all but the flattest slopes. It was found that the rate at which the jump entrained the air did not necessarily correspond to the rate at which air was removed from the pocket. Beyond the jump, except for the air bubbles, the pipe flowed full, and the rate at which the air was eventually removed depended on the ability of the water flowing in the pipe beyond the jump to carry the air bubbles along. Except for the higher water flows, the jump pumped air into the water at a higher rate than the flow beyond the jump could handle. The excess air then blew back periodically through the jump. For any pipe size and slope, there was one discharge at which the rate of air entrainment by the jump was equal to the downstream air transport rate.

Results showed that removal of air was controlled by two different hydraulic phenomena. For lower discharges, the air removal was controlled by the flow characteristics beyond the jump. At higher discharges, the air removal was controlled by the hydraulic jump, since the water flow was capable of carrying all the air entrained by the jump and more if available.

It was noted that smaller air bubbles could move more easily than larger ones. However, the smaller ones would gradually coalesce into large bubbles which could not be moved, and these would travel up the pipe and pass back through the jump.

Tests were carried out to ascertain the limiting conditions for bubble movement. It was found that for values of pipe slope greater than approximately 2.5% (or 1.43°) the data follow a straight-line relationship. At smaller slopes the experimental data deviated from this relationship. This occurred when the hydraulic jump at the lower end of the air pocket did not fill the pipe, and thus the process of entraining the air was different. Therefore for slopes less than 2.5% (or 1.43°) higher water discharges are required to initiate air removal.

Kalinske, A.A. and Robertson, J.M. 1943. Closed conduit flow. Transactions of ASCE, vol. 108, pp1435-1447

Experimental tests were performed to study the entrainment of air by a hydraulic jump. A pipe with an internal diameter of 149mm was used and it was set at downward pipe slopes of 0, 0.2, 2, 5, 10, and 30% (or 0, 0.11, 1.14, 2.86, 5.71, 16.7°). The key results are summarised below:

- It was found that air pumped into the flowing water by the jump forms a large pocket beyond the jump which extends to the point where the air leaves the pipeline. For low water flows and especially at the low slopes a single long pocket did not exist, but rather a series of relatively large bubbles was present, which moved downstream.
- For lower flow rates the air pocket did not extend to the end of the pipe and periodically blew back across the jump. Therefore for discharges below the critical value the average rate of air removal from the pipeline was controlled by the flow conditions below the jump and not by the jump itself.
- Values of air entrainment by the hydraulic jump can be estimated from the equation:

$$\frac{Q_{air}}{Q_{water}} = 0.0066(Fr-1)^{1.4} \tag{5}$$

where Fr is the flow Froude number upstream of the jump. This formula was valid for conditions in which the pipeline carried along and discharged all the air the jump entrained. For any value of y_1/D (where y_1 is the upstream flow depth) there was a value of the Froude number below which the pipeline could carry only a part of the air pumped unto the water by the jump. The smaller the slope the lower the critical Froude number (refer to Figure 8).

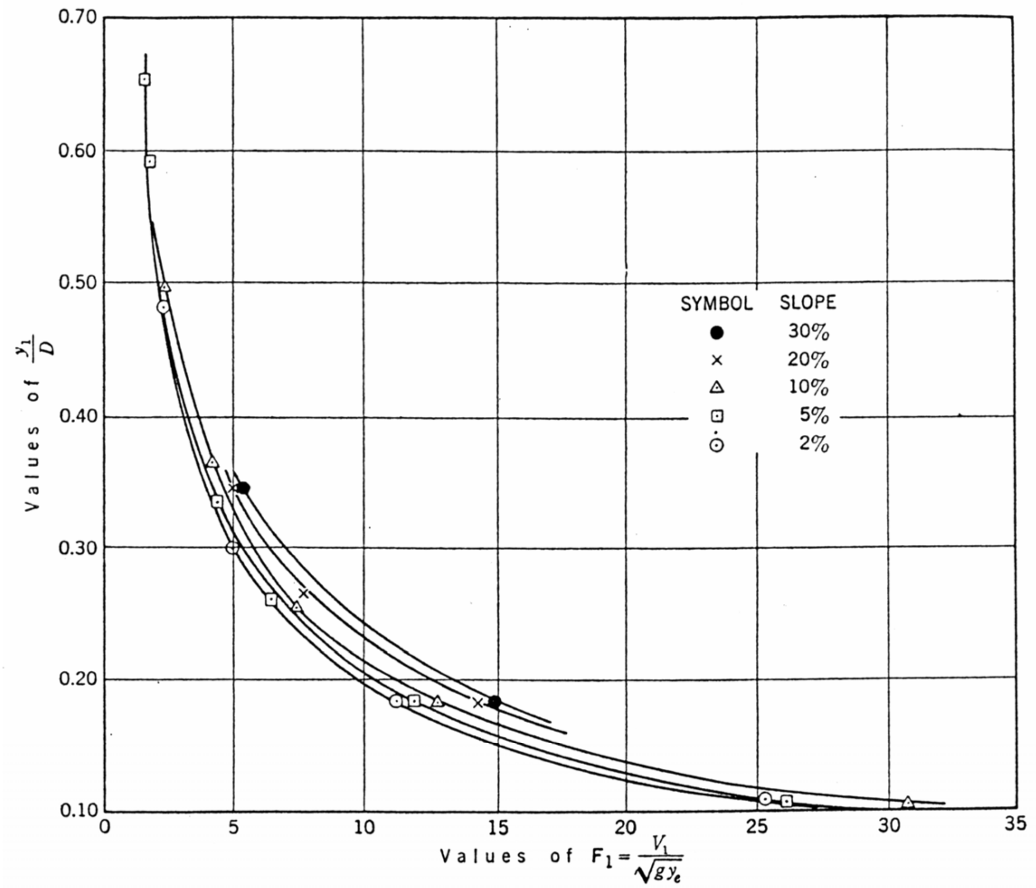

FIG. 14.—EXPERIMENTAL VALUES OF CRITICAL FROUDE NUMBER

Figure 8 Experimental values of critical Froude number (taken from Figure 14, Kalinske and Robertson, 1943)

The authors concluded that above a certain critical condition the rate of air removal from an air pocket in a pipeline will depend on the ability of the hydraulic jump that is formed to entrain air. This critical condition, for any slope of pipe and for any relative depth of flow in the air pocket, depends on the value of the Froude number of the flow ahead of the jump. Below this critical value of Fr the flow beyond the jump will not be able to handle the air entrained by the jump and thus the air removal will not be a function of the jump characteristics but rather on the hydraulic features of the flow beyond the jump.

Gandenberger, W. 1957. Uber die wirtshaftliche und betriebssichere Gestaltung von Fernwasserleitungen, R. Oldenbourg Verlag, Munich, Germany Design of overland water supply pipelines for economy and operational reliability (rough translation by W.A. Mechler, discussion of "Factors influencing flow in large conduits.", Report of the Task Force on Flow in Large Conduits of the Committee on Hydraulic Structures, ASCE, Vol.92, No. HY4, 1966

The author gives a summary and review of work undertaken in Germany by Gandenberger. One of the key aspects of Gandenberger's work is the development of a graph which shows the water velocities for incipient movement of bubbles of different relative sizes from a high point into a downward inclined section of conduit of varying slope. The graph therefore gives the minimum average water velocity required to clear a given volume of air from a peak in the profile of a unit diameter for a certain inclination of the leg through which the water is flowing downward. It was based on experiments on air bubble movement in glass tubes of 45mm, 26mm, and 10.5mm diameter, and in a steel pipe of 100mm diameter having varying inclinations from horizontal to vertical, and with the water flowing upward and downward. More details of the information given by the graph are presented in Chapter 6.

On the movement of bubbles, Gandenberger notes that smaller bubbles tend to stop and adhere to irregularities in the pipe walls at the crown and in recesses at joints and fittings. He believed that in flat and slightly sloped sections smaller bubbles would probably not reach the high points, particularly in large conduits where, because of the relatively flat crown, larger bubbles may pass by without touching smaller ones adhering to the sides. He also observed that the relative low pipe velocities customary during filling are insufficient to remove all air from flat runs.

He also showed that the head loss due to the bubble can be estimated as L sin(a), which is the vertical projection of the bubble, where *L* is the length over which the bubble extends and *a* is the pipe angle.

Summary

- On upward slopes air bubbles tend to coalesce whereas on downward slope they tend to disintegrate to a certain size.
- At high points air is displaced downwards by moving water at the downstream end of the crest and pulled into the descending leg of the pipe. Allowance should be made for this when locating air valves.
- Above a certain minimum velocity air bubbles can move downstream from a crest.
- Entrapped air will contribute to head losses.

Mosvell, G. 1976. Pra 8 Air in outfall pipes, Project committee for the treatment of waste water, (in Norwegian)

This publication provides a review of air problems in outfall pipes. It states that large air pockets will not collect at high points if the flow velocity exceeds a certain threshold value and that pipe angle becomes significant when it is greater than about 20 degrees.

The effluent's capacity to transport air decreases as the downward pipe gradient increases. Under given conditions a large air pocket (up to 70 to 80% air) will collect along the transition between gentle and steep gradient.

Air transport in a horizontal or sloped pipe can be divided into:

- Large bubbles or pockets which move under the pipe soffit.
- Small bubbles (< 1 to 2mm) which hover free in the flow stream.

Further details on critical velocity for bubble movement are discussed in Section 6.

Kent, J.C. 1952. The entrainment of air by water flowing in circular conduits with downgrade slopes. Doctoral thesis, University of California, Berkley, California

Kent studied experimentally the flow of air pockets and bubbles on a downward slope. Pipe slopes from 15 to 75 degrees were tested. He used both a 38mm and 102mm diameter pipe for the tests.

He found that an effective rate of air removal exists when the average velocity of the water is equal to or greater than a certain minimum value. This minimum value is the velocity required to keep the air pockets that are formed in the pipe stationary.

Experiments showed that between angles 30 and 60 degrees no change in flow was required to keep the bubbles in equilibrium. For angles <15° and >75° the required velocity was found to be reduced. This finding is similar to that found by Gandenberger (1957) but it does differ from those of other authors.

Wisner, P.E., Mohsen, F.N. and Kouwen, N. 1975. Removal of air from water lines by hydraulic means. ASCE, Journal of the Hydraulics Division, Vol. 101, HY2, pp243-257

Experiments were performed for both still water and moving water situations to assess the velocity criteria for the movement of bubbles in pipes. Initially, dimensional analysis was used to show that the sweeping velocity of the bubbles, V_s, is a function of the inertial force Fr, flow Reynolds number, pipe slope and bubble length to pipe diameter ratio.

Pocket size is expressed as a dimensionless quantity n in which $n = \nabla/(\pi/4D^3)$ (after Gandenberger) where ∇ is the volume of the pocket. It is assumed that for the same n and θ there is a family of geometrically similar pockets characterised by the same L_B/D ratio (L_B = length of the pocket, measured along the wall of the pipe).

Details of their experimental results are discussed further in Chapter 6.

Beggs, H.D., and Brill, J.P. 1973. A study of two-phase flow in inclined pipes. Journal of petroleum technology, pp607-617

Beggs and Brill studied the movement of two-phase flow in inclined pipes and concluded that:

- The inclination angle of a pipe in which two-phase flow is occurring definitely affects liquid hold-up (where hold-up refers to the backing-up of water in the flow section) and pressure drop for most flow conditions.
- In inclined two-phase flow, the liquid hold-up reaches a maximum at an angle of approximately +50 degrees and a minimum at approximately –50 degrees from horizontal.
- Input liquid content and Froude number are important parameters in two-phase flow.
- Friction loss in two-phase flow is greatly affected by liquid hold-up.

Baines, W.D., and Wilkinson, D.L. 1986. The motion of large air bubbles in ducts of moderate slope. Journal of Hydraulic Research, Vol. 25, No. 3, pp157-170

The authors studied experimentally the form and motion of air bubbles released into a rectangular duct of moderate slope. They found that the release of a large volume of air into a rectangular duct on a slope produces a large air bubble which moves at constant velocity upward along the roof of the duct.

The experiments revealed that the bubble speed depends only on the duct slope for bubbles of large volume but it depends also on volume for bubbles below a given size. It was found that the bubble height increases with volume for air volumes below a critical volume and above this value the height is constant. There is an abrupt decrease in bubble height at the rear of the bubble and this is associated with a turbulent dissipative region in the underlying flow. In large bubbles on gentle slopes where the flow beneath the bubble is uniform, the dissipative region takes the form of a hydraulic jump.

In rectangular ducts the flow remains two-dimensional as the duct inclination is increased whereas in circular pipes, the flow cross-section and therefore the driving pressure force changes with inclination. Therefore different cross sectional geometries cannot be expected to produce bubble velocity maxima at the same inclination.

Bendiksen, K.H. 1984. An experimental investigation of the motion of long bubbles in inclined tubes, Int. J. Multiphase Flow, Vol. 10, No. 4, pp 467-483

Bendiksen undertook an experimental study of bubble propagation for different angles of pipe inclination, ranging from downward slopes of 30° to upward slopes of 90° (i.e. vertical) for an air-water system. Pipes with diameters of 19.2mm, 24.2mm and 50mm were tested, with the majority of tests were performed using the 24.2mm diameter pipe.

Tests on bubble propagation in still water for upward slopes showed that the critical velocity for bubble propagation increases with inclination angle until about 30°, after which it decreases to a minimum value for an angle of 90°.

As described by Little (2002), Bendiksen's tests with flowing water for horizontal and downward sloping pipes showed that air bubbles are swept along by the flow. The minimum velocity reported was 0.3m/s. It was found that the velocity of the air pocket relative to the flow increased as the water flow rate increased. Also, when the flow is less than some critical velocity the air pocket "turns" and moves backward relative to the water flow. It is unfortunately not possible to establish the minimum velocity required to move the air forward on near horizontal slopes, although Bendiksen does develop an analytical expression relating the velocity at which the air pocket turns relative to the flow.

Dewhirst, R.A. 1991. Optimising the use of air valves in piped water systems, Master of Engineering Thesis, Department of Civil Engineering, The University of Auckland, Auckland, New Zealand

This thesis describes an experimental investigation into the movement of large air bubbles in sloping pipes. The purpose of the work was to determine experimentally the capacity of flow in a pipeline to hydraulically flush air pockets.

Experiments were carried out in two series. The first series looked at the various parameters that were considered to have an influence on the pocket stability, while the second series examined in detail the parameters considered important for predicting the critical velocity for any pipeline. In these tests, a hydraulic jump formed at the downstream end of the air pockets.

Tests were conducted using two pipe diameters (0.074m and 0.14m), with the flow direction being vertically downward. Tests were conducted with both a straight pipe section and pipes with a bend in the vertical plan.

From the first series of tests it was found that the pressure in the pipe and the size of the air pocket had little or no significant effect on the critical velocity. The presence of a bend in the pipe was shown to effect the shape of the air pocket moving along the pipe and this in turn effected the critical velocity required to move the pocket. No effect due to surface tension was noted in the tests, although this had been shown to be important by previous authors.

In the second series of tests the following results were obtained:

- As the inclination angle increased for a given air pocket length, the head loss also increased. However, for the same pocket length, the entrainment capacity of the flow also increases with increasing inclination angle.
- This result implies that, although there is a greater head loss at steeper inclinations for a given pocket size, this pocket will clear much faster through being entrained into the flow.

Overall, it was concluded that there appear to be two possible mechanisms for controlling air pocket stability in a moving flow of water. One mechanism involves a balance between the pocket buoyancy and the force associated with the head loss at the hydraulic jump. The second mechanism involves control of the stability of the air pocket by the shape of the nose of the pocket. The author was unable to identify the dominant mechanism.

Horizontal pipes

James, W. and Silberman, E. 1958. Two-phase flow studies in horizontal pipes with special reference to bubbly mixtures., Technical Paper No. 26, Series B, St Antony Falls Hydraulics Laboratory, University of Minnesota, Minnesota, pp63

An investigation was made into the flow of bubbly mixtures in horizontal pipes, together with some related work on other flow patterns. The pressure drop along the pipe was also calculated.

In the bubble-flow regime it was found that the friction factor is approximately equal to or slightly greater than the friction factor for liquid flow alone in the pipe. The bubbles move at nearly the mean velocity of the liquid while their size is inversely proportional to the liquid velocity and directly proportional to the square root of the pipe diameter.

An equation is provided for the friction factor for flow in the bubble regime. It indicates that the friction factor is actually increased by the presence of bubbles. The authors suggest that this can possibly be attributed to an increase in viscosity. The term inside the square root is the compressibility parameter.

$$\frac{f}{f_l} = 1 + 0.035\sqrt{\left(\frac{\alpha}{1+\alpha}\right)\frac{gRT}{V_l^2}} \qquad (6)$$

where $f = \dfrac{8g\tau_o}{w_l V_l^2}$

τ_p = local mean shear stress around the perimeter
g = acceleration due to gravity
$\alpha = G_g/G_l$ where G is the weight per unit time
R = gas constant

$V_l = Q_l/A$
T = temperature
w = specific weight
Subscripts l and g refer to gas and liquid, respectively.

In the bubble regime the bubbles move at approximately the same speed, or slightly faster than the mean liquid velocity. In other regimes, the gas component moves faster than the liquid, with the mean velocity ratios reaching a maximum in annular flow. The flow pattern outside the bubble regime has little direct influence on relative liquid and gas velocity.

Undulating pipes

Kent, J.C. 1952. The entrainment of air by water flowing in circular conduits with downgrade slopes. Doctoral thesis, University of California, Berkley, California

Kent found that air removal at the summit of a pipe (where upward and downward sloping pipe sections meet) was similar to air removal from a straight section. An air pocket rests near the summit when the buoyancy force of the bubble is greater than the drag force created by the flowing water. Since the buoyancy force of an air pocket is a function of the slope of the conduit, the air pocket can be held in equilibrium at a position where the tangent to the bend has a slope small enough to reduce the buoyancy force equal to the drag force.

He stated that an air pocket would not necessarily move downstream after it has reduced in size sufficiently. The reason for this is that “as the bubble decreases its size, the drag force decreases accordingly. With a decrease in drag force, the generating action of the air pocket is also decreased and the number of bubbles ejected is smaller. Since the action of the air pocket influences the size of the bubbles generated, a reduced action cannot disperse bubbles as small as before. These slightly larger bubbles will move downstream more slowly. As the air pocket continues to reduce in size, the drag force becomes still smaller and the bubbles it is able to generate become larger. In time, the average velocity of the water will be insufficient to overcome the buoyant velocities of the air bubbles generated. The air pocket will continue to generate bubbles but none or only a few of the air bubbles will go completely through the system.”

However, if the velocity of the water is sufficient to remove all the bubbles generated, the air pocket is soon reduced to a size that it can no longer create the turbulence necessary and the air pocket will remain stable in size.

Liou, C.P., and Hunt, W.A. 1996. Filling of pipelines with undulating elevation profiles. ASCE, Journal of Hydraulic Engineering, Vol. 122, No. 10, pp534-539

The paper outlines a model which was developed to describe the unsteady motion of a lengthening rigid water column filling an empty pipeline with an undulating elevation profile. As well as the numerical model the early phase of filling was also investigated experimentally and was found to be comparable with the model results. The authors used the work of Zukoski, Benjamin, and Townsend as well as their own tests to define their limits for air intrusion. In the model they defined the critical velocity parameter as $V_c/(gD)^{1/2} = 0.5$ (where g is acceleration due to gravity and D is the pipe diameter).

Model results showed that, with the presence of a head at the supply tank, the early phase of the filling process was characterised by very rapid acceleration followed by less rapid deceleration of the water column. High, but short-lived velocities can be attained if the supply head is high, the entrance head loss small, and the initial stagnant water column is short.

The importance of the supply head diminishes as the water column lengthens. Both the slope of the pipe segment being filled and the frictional resistance of the entire column influence the velocity. The column accelerates and decelerates according to the undulating profile, the inertia of the water column and the velocity history.

The velocity of the water column peaks early in the filling process and high peak velocities may occur when the submergence is large and the static water column is short.

The conclusion of the project was that the model was found to be applicable when the discharge velocity is sufficiently high or when the pipe diameter is sufficiently small so that air intrusion does not occur.

5.2.3 Hydraulic jumps

Hydraulic jumps sometimes form in downward sloping pipes where a large air pocket is present. The rate of air removal by the pumping action of the hydraulic jump that forms in the pipe was found to be related to the drag force acting on the air pocket.

The violent action of the jump is used only to break up the large air bubbles 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 pumping rate will be reached when the depth of flow under the air pocket has reached normal depth for that discharge and slope.

It was found that the average velocity required to keep the air pockets in equilibrium is not the same for different angles and that the angle of the water surface at the end of the air pocket affects the efficiency of the ejecting forces.

Chanson, H. and Qiao, G.L. 1994. Air bubble entrainment and gas transfer at hydraulic jumps. Research Report No. CE149, Department of Civil Engineering, The University of Queensland, Brisbane, Australia

This report details a study that was undertaken to assess air bubble entrainment at hydraulic jumps with partially developed inflow. It was found that the turbulent shear region exhibits a maximum air content which decays exponentially along the jump. Also, the maximum air bubble size in the shear region was found to be a function of the initial flow velocity. The turbulent shear region contributes substantially to the air-water transfer at a hydraulic jump: its large air content and the small bubble sizes resulting from large turbulent shear stress create a region of very large air-water interface area. This enhances the gas transfer process.

The authors provide a review of the characteristics of air entrained at hydraulic jumps. The following tables summarise the information:

Table 1 Quantity of air entrained at hydraulic jumps (taken from Chanson and Qiao, 1994)

Reference	Geometry	Q_{air}/Q_{water}	Comments
Kalinske and Robertson (1943)	Hydraulic jump in horizontal circular pipe	$0.0066*(Fr-1)^{1.4}$	Model data 2<Fr<25
Wisner et al (1975)	Hydraulic jump in rectangular conduit	$0.014*(Fr-1)^{1.4}$	Prototype data 5<Fr<25
Rajaratnam (1967)	Hydraulic jump in rectangular channel	$0.018*(Fr-1)^{1.245}$	Model data 2.4<Fr<8.7
Rabben et al (1983)	Hydraulic jump in horizontal rectangular pipe	$0.03*(Fr-1)^{0.76}$	Model data. Gate opening ratio: 0.25

Fr is the upstream Froude number.

Table 2 Inception velocity of air entrainment by hydraulic jumps (taken from Chanson and Qiao, 1994)

Reference	Geometry	V_e (m/s)	Comments
Kalinske and Robertson (1943)	Hydraulic jump in horizontal circular pipe	1.0	Model data 2<Fr<25
Rabben et al (1983)	Hydraulic jump in horizontal rectangular pipe	Fr_e=1.0	Model data. Gate opening ratio: 0.25
Chanson (1993)	Hydraulic jump in rectangular channel	0.66 to 1.41	W=0.3m. Fully developed u/s shear flow

Fr_e is the Froude number defined in terms of the inception velocity. $Fr_e = \frac{V_e}{\sqrt{gy}}$, where V_e is the onset velocity for air entrainment, and y is the flow depth perpendicular to the channel bottom.

Ervine, D.A. 1998. Air entrainment in hydraulic structures: a review. Proc. Instn Civ. Engrs Wat., Marit. and Energy, Vol. 130, Sept, pp142-153

The paper presents a review of three mechanisms of air entrainment in hydraulic structures and suggested broad-brush equations to predict the aeration rate. It also considers air bubble transport in closed conduits downstream of the entrainment point, such as a hydraulic jump.

An important conclusion of the review is that the threshold of air bubble transport in a closed conduit is dependent to some extent on the conduit slope:

- For shallow slopes, a vortex trapping parameter (U_1/u_{br}) > 10-12 represents the threshold (U_1 = jet velocity at plunge point, and u_{br} = air bubble rise velocity in still water (0.2-0.25 m/s)).
- For steep slopes, a transport parameter $U_1(d/D)^{1/2}$ > 0.8-0.9 represents the threshold (d = jet thickness at the plunge point, D = closed conduit diameter).
- Intermediate slopes will involve a combination of both parameters.

The author also looked at the quantity of air transported downstream of the entrainment point. As with previous work, he concluded that the quantity of air transported along a closed conduit depends on the rate of entrainment at the plunge point and also on the flow conditions downstream in the developing shear layer.

This means that the length of the conduit downstream of the plunge point is important and Ervine divides the downstream conduit length into three categories:

- *Short conduits*. Short conduits have length to conduit diameter (L/D) approximately less than 5. All the air entrained by the plunge point is transported downstream and out of the conduit. The net air transport rate is equal to the entrainment rate.

$$q_{an} = q_a \qquad (7)$$

where q_{an} = net air transport rate and q_a = air entrainment rate.

- *Intermediate length conduits*. Intermediate length conduits have a L/D ratio of 5-20. The length is sufficient for some transported air bubbles to rise to the conduit roof due to buoyancy. Some coalescence of air bubbles produces small air pockets at the conduit roof. The quantity of air reaching the exit is a mixture of air bubbles and small air pockets. Full transport occurs when U_o-$U_{o,min}$ > 0.5 m/s (U_o = outlet conduit full velocity, $U_{o,min}$ = threshold value of outlet velocity) or the outlet velocity is 0.5 m/s or greater than the threshold value predicted previously. The net transport rate of air bubbles to the exit of the conduit is given by:

$$q_{an} = q_a \left[1 - e^{-2\left(\frac{U_o - U_{\min}}{u_{br}}\right)} \right] \qquad (8)$$

- *Long conduits*. Long conduits have a L/D ratio > 20. Air bubbles collect at the conduit roof in distinct air pockets, and will only be transported downstream when the flow has the capacity to remove or clear large air pockets in a downward sloping conduit. If the flow does not have this capacity then air pockets build up in size and eventually blow back upstream. Most researchers agree that larger air pockets scale with the conduit dimension, that the clearing velocity can be expressed as a Froude number, and that this value varies to some extent with the downward conduit slope. The net transport rate is the same as for intermediate pipes provided the clearing velocity has been exceeded and the air pockets are removed continuously.

Chanson, H. and Brattberg, T. 2000. Experimental study of the air-water shear flow in a hydraulic jump. Int. Journal of Multiphase Flow, vol 26 (2000) pp583-607.

This paper presents work recently carried out by Chanson and Brattberg to characterise the air-water flow (air concentration profiles, shear layer, velocity distribution) within hydraulic jumps formed on a horizontal channel.

5.2.4 General

Richards, R.T. 1957. Air binding in large pipelines flowing under vacuum, Journal of the Hydraulics Division, ASCE, vol. 83, HY6

Richards describes "air binding" in a pipeline as the trapping of air within the water passage in a manner that prevents the pipe from flowing full. The most severe head losses encountered in circulating water systems flowing under vacuum are the result of large air pockets lying along the downward slope and creating a condition similar to open channel flow.

Generally speaking, for a given water velocity and pipe slope, air binding difficulties increase with pipe size. There is very little published data for large diameter pipes.

Experience indicates that where a large diameter pipe normally flows under vacuum there will be air binding in any non-vented section which slopes downstream from the high point in the system. Exceptions to this general rule have been at slopes immediately following sharp horizontal bends; the turbulence induced by the horizontal bend may break up large air pockets into more easily transported smaller bubbles.

Air removal systems on some example conduits were not effective when they were connected to the high point alone. Instead a system of taps along the downstream slope were provided.

The primary consideration in sizing air removal equipment is to provide enough capacity to maintain the line free of air during operation. A secondary consideration is the rate of initial priming of the system.

Edmunds, R.C. 1979. Air binding in pipes. Journal of AWWA, Water Technology Distribution, pp272-277

Edmunds describes the conditions under which air binding in pipelines occurs. He considered downward sloping pipe sections. For pipes of mild slope, air can be present along the soffit of the pipe in the form of an air pocket which can grow in size in the downstream direction. The trapped air can be removed by the generation of small air bubbles at the downstream end of the pocket, and entrainment into and transport by the fluid, or by sweeping the total air pocket down the pipeline. In pipes with a steep slope, a hydraulic jump is possible. If the jump seals the pipe, air is pumped into the water downstream of the jump. The amount of air entrained is a function of the flow rate downstream of the jump. He states that should hydraulic jumps occur in the line, the air removal capacity may be limited by hydraulic conditions downstream of the jump at low flows and by the air entraining limitations at high flows.

Edmunds summarises a number of earlier works on critical velocities for air bubble movement and provided details of a number of case studies. He also makes suggestions for a design procedure to prevent air binding.

Little, M.J. 2002. Air transport in water and effluent pipelines, 2nd International Conference on Marine Waste Discharges, Istanbul, September 16-20

Little (2002) provided a detailed review of the mechanisms of air pocket transport in pipes. He reviewed a wide range of previous experimental studies including Bendiksen, 1983, Zukoski, 1966, Liou and Hunt, 1996, Benjamin, 1968, Gandenberger, 1957, Mechler, 1966, Kalinske and Bliss, 1943, Kalinske and Robertson, 1942, Falvey, 1980, Wisner, et al, 1975, Edmunds, 1979, Mosvell, 1976. These papers have been included separately in this present review.

Little concluded that:

- Published data are not always consistent with each other or with case histories. Differences may be due to test procedures, data extraction, definitions used and variables other than those plotted.
- Test data show that air bubbles will be transported more readily than air pockets but will tend to agglomerate into air pockets at the pipe soffit.

- Under typical operating conditions air pockets should be transported forward down shallow slopes but will not be transported against steep slopes. For a given pipe diameter and slope, there is a critical flow rate at which air pockets will be trapped.

He recommended that the prediction line for air pocket movement based on the work of Kent is suitable for determining the critical gradient within the limits given.

Asher, W.E., Karle, L.M., and Higgins, B.J. 1997. On the differences between bubble-mediated air-water transfer in freshwater and seawater, Journal of Marine Research, 55, 813-845

This paper describes the differences between bubble plumes in freshwater and seawater. Bubble plumes in freshwater had a higher concentration of large bubbles and a lower concentration of small bubbles than the plumes in cleaned seawater. Therefore caution should be applied when applying the results from one media to the other.

5.3 SLUG FLOW REGIME

5.3.1 Vertical pipes

Wallis, G.B. 1969. One-dimensional two-phase flow, McGraw Hill, New York, U.S.A.

This book provides detailed information on two phase flow systems. Section 10.3 deals with vertical slug flow and a general representation of bubble rise velocity in vertical slug flow is presented. The authors provide methods for estimating flow and pressure relationships for such flow conditions.

Martin, C.S. 1970. Vertically downward bubbly and slug flow of an air-water mixture in a pipe. Bericht Nr. 511, Institut für Hydromechanik, Der Universität Karlsruhe, Karlsruhe, Germany

Martin studied experimentally both the bubble and the slug regimes in vertically downward pipe flows. Relevant findings can be summarised as:

- The transition from bubbly flow to slug flow in a vertically downward air-water mixture was found to occur if the volumetric concentration of air is greater than 0.235. The difference in entrance conditions between the cases of natural aeration and forced aeration has no apparent effect on the transition.
- Individual slugs propagate at a velocity greater than a corresponding Taylor bubble (this is an air pocket with a domed top that has been observed in vertical plug flows).
- The slugs can be quite irregular in shape, possessing a tendency to travel along the wall of the conduit.

5.3.2 Sloping pipes

Wallis, G.B. 1969. One-dimensional two-phase flow, McGraw Hill, New York, U.S.A.

Section 10.5 describes the relationships between slug velocity and pipe angle based on previous studies by Runge and Wallis (1965). The results are presented as a series of four graphs (shown here as Figures 9a to d) which relate the velocity ratio (v_θ/v_∞) to the pipe angle. The velocity ratio is the ratio between the bubble velocity in sloping pipes, v_θ, and those in vertical pipes, v_∞.

The results are presented over different ranges of the Eötvös number, E, defined here as:

$$N_{Eo} = \frac{gD^2(\rho_f - \rho_g)}{\sigma} \tag{9}$$

where ρ_f and ρ_g are the fluid and gas densities respectively, D is the pipe diameter, and σ is the fluid surface tension.

N_f is a dimensionless number defined as:

$$N_f = \frac{\left[D^3 g(\rho_f - \rho_g)\rho_f\right]^{1/2}}{\mu_f} \tag{10}$$

where μ_f is the viscosity of the fluid

The results show that the bubble velocity in inclined pipes generally exceeds the value in the same pipe placed vertically. It is not clear from the information provided whether the flow direction is upward or downward in the vertical direction.

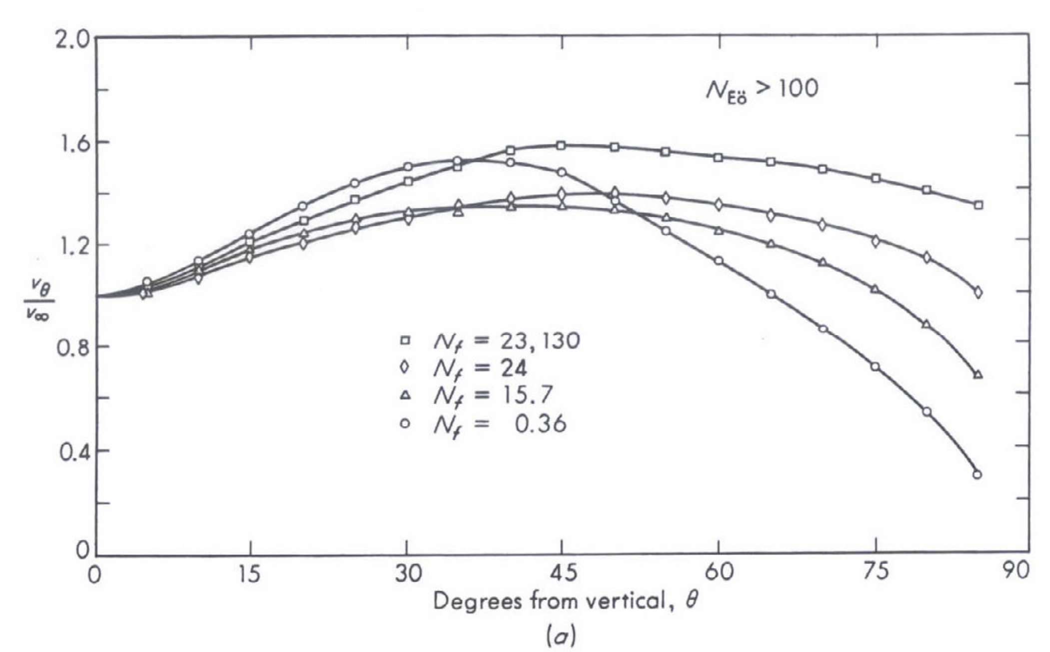

Figure 9a Rise velocity of slug-flow bubbles in inclined pipes for N_{Eo} > 100 (taken from Wallis, 1969)

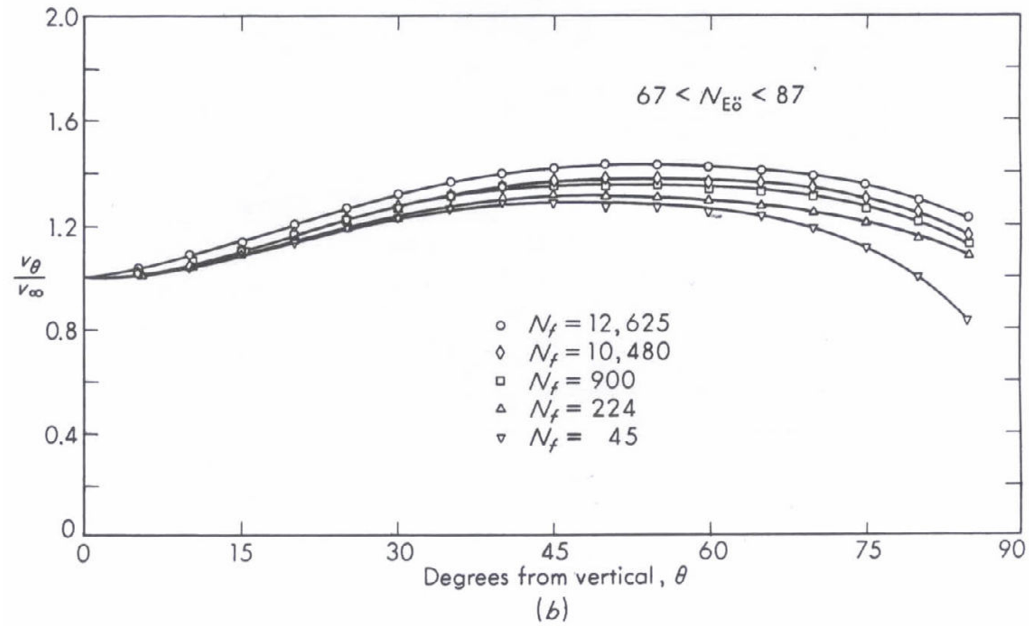

Figure 9b Rise velocity of slug-flow bubbles in inclined pipes for 67 < N_{Eo} > 87 (taken from Wallis, 1969)

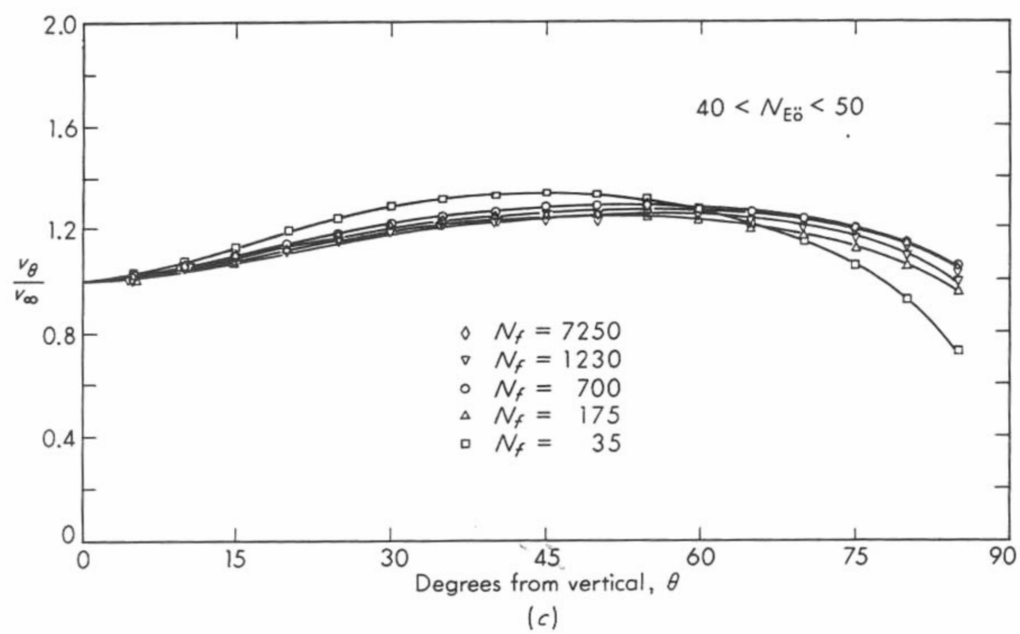

Figure 9c Rise velocity of slug-flow bubbles in inclined pipes for 40 < N_{Eo} < 50 (taken from Wallis, 1969)

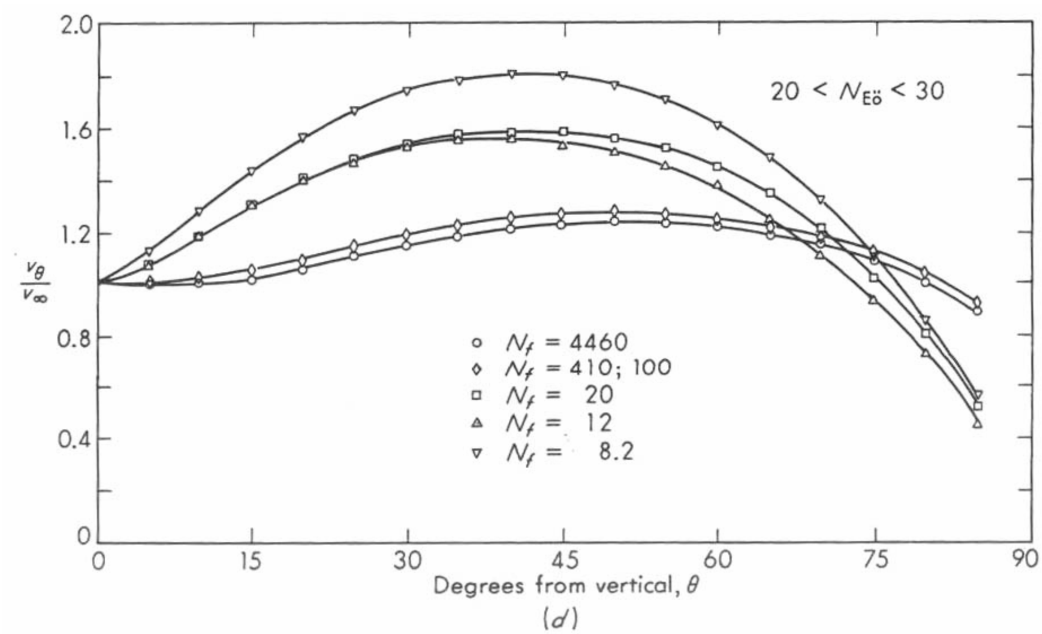

Figure 9d Rise velocity of slug-flow bubbles in inclined pipes for 20 < N_{Eo} < 30 (taken from Wallis, 1969)

Taitel, Y., Sarica, C., and Brill, J.P. 2000. Slug flow modelling for downward inclined pipe flow: theoretical considerations, International Journal of Multiphase Flow, Vol. 26, pp833-844

The authors undertake a theoretical examination of the processes of slug dissipation in a downward sloping pipe section. They examine the physical phenomena of slug dissipation in downhill pipes and propose a method for calculating the downhill dissipation distance. The term dissipation refers to a change in flow regime from slug flow to either bubbly or stratified flow.

- For low liquid and gas flow rates the liquid slugs are carried over to a downward inclined section after passing a top elbow and they are expected to travel some distance before they dissipate. The flow becomes stratified.
- There is not sufficient gas to form an elongated bubble and the gas moves forward as dispersed bubbles

They present a simple model for the calculation of the slug dissipation length for both cases.

Woods, B.D., Hurlburt, E.T., and Hanratty, T.J. 2000. Mechanism for slug formation in downward inclined pipes, International Journal of Multiphase Flow, Vol. 26, pp977-998

This paper looks at the effect of small downward inclinations on the formation of slugs. Experiments were carried out with air and water at atmospheric pressure, in a 76mm diameter pipe, having a length of 23m and downward inclinations of 0.2, 0.5, and 0.8°.

Slugging is characterised by the intermittent appearance of highly aerated masses of liquid that fill the whole cross section of the pipe and travel approximately at the gas velocity (a definition of the gas velocity was not provided in the paper).

The authors describe the work of previous authors such as Barnea et al (1980), who examined air-water flows with upward inclinations of 0.25, 0.5, 1, 2, 5, and 10° and with downward inclinations of 1, 2, 5 and 10°. Pipes of 25.5mm and 19.5mm diameter were used. Andreussi and Persen (1987) carried out studies with air and water flowing in a 50mm pipe that was inclined downward at 0.65 and 2.1° and Stanislav et al (1986), with air and water flowing in a pipe with upward inclinations of 0-9° and a diameter of 25.8mm. These studies show that higher liquid flow rates are required to produce slugs in downflows. For upflows the opposite is the case.

The present study looked at flow in quite shallow downward slopes. As noted by the previous authors, it was seen that as the declination increases, the liquid flow required to initiate slugging increases. For example, at low gas velocities, the critical liquid flow in a pipe at a downward inclination of 0.8 degrees is approximately four times the value for the horizontal pipeline. At higher gas flow rates the sensitivity to declination was reduced.

For low gas velocities in a horizontal pipe, waves with lengths of 0.16-0.20m grow until they reach the top of the pipe. These waves evolve from smaller wavelength waves (0.08-0.10cm) through a non-linear growth mechanism. At high gas velocities, the liquid height is not large enough for this mechanism to be operable. In these cases slugs evolve from the coalescence of roll waves. The large amplitude small wavelength waves observed in horizontal flows, at the transition to slug flow, are damped if the pipelines are inclined slightly downward.

As the pipe declination increases there is an increase in the height of the liquid required to initiate slugging. Declination was seen to stabilise the liquid layer.

Overall, it was found that the transition to slug flow was associated with the appearance of very long wavelength waves; the frequency of slugging is equal to the frequency if these waves.

5.3.3 Horizontal pipes

Wallis, G.B. 1969. One-dimensional two-phase flow, McGraw Hill, New York, U.S.A.

The flow of slugs in horizontal pipes is described in Section 10.4. For this situation the velocity of the slugs is not always the same as the average velocity of the liquid. The authors present the results of Suo and Griffith (1963), who performed experiments to assess slug flow velocities, as shown in Figure 10. The figure shows the relationship between the bubble velocity and the total volumetric flux. At very low Reynolds numbers the gas moves at the same velocity as the fluid, whereas at high Reynolds numbers the velocity ratio, j/v_b tends to 0.84, where j is the total volumetric flux and v_b is the bubble velocity.

The total volumetric flux is defined as:

$$j = \frac{Q_g + Q_f}{A} \qquad (11)$$

where Q_g and Q_f are the gas and fluid flow rates and A is the pipe area.

In Figure 8, λ is defined as:

$$\lambda = \frac{\mu_f}{D\rho_f\sigma} \tag{12}$$

where μ_ϕ is the fluid viscosity, ρ_f is the fluid density, D is the pipe diameter, and σ is the fluid surface tension.

The experiments by Suo and Griffith (1963) were performed over the range:

$$E < 0.88 \tag{13}$$

where E is the Eötvös number, defined by equation (9). Over this range it is considered that stratification effects were small and the buoyancy forces could be neglected.

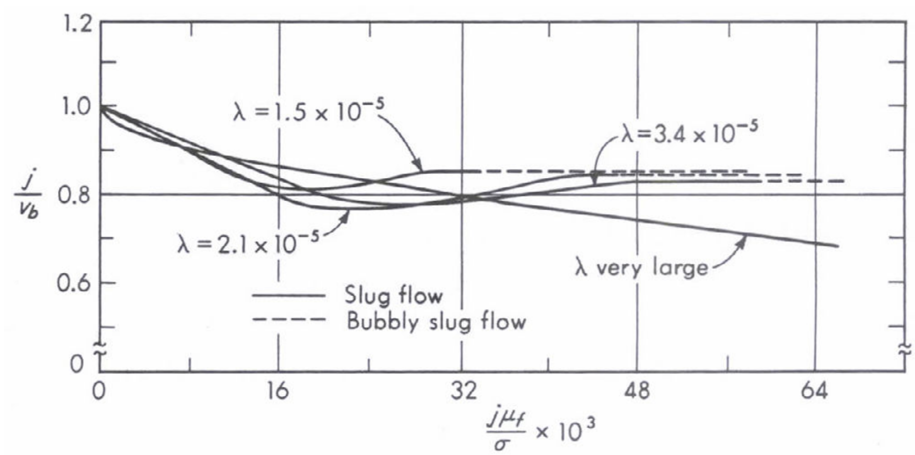

Figure 10 Velocity ratio as a function of $j\mu_f/\sigma$. (taken from Wallis, 1969)

Lin, P.Y. and Hanratty, T.J. 1987. Effect of pipe diameter on flow patterns for air-water flow in horizontal pipes, International Journal of Multiphase Flow, Vol. 13, No. 4, pp549-563

This paper describes the results of an experimental study of air-water flow in horizontal pipelines (2.54 and 9.53cm diameter) flowing at close to atmospheric conditions. One of the key conclusions of this work was that pipe diameter only has a small effect on flow transitions, with the exception of the stratified/slug transition. At low gas velocities a strong effect of pipe diameter on this transition was shown. Interestingly, they used an instrumental technique to detect the presence of slugs because it can become quite difficult to do visually for high gas flow rates.

Bozkus, Z. and Wiggert, D.C. 1992. Hydromechanics of slug motion in a voided line. In Unsteady Flow and Fluid Transients, Bettess and Watts (Ed.). Balkema, Rotterdam

The following description of the article is taken from the abstract.

"In an experiment, liquid slugs are propelled into an empty horizontal pipe under various driving pressures; the pipe reach terminates at an elbow whereon the slug impacts and disintegrates. Pressure waveforms recorded at various locations along the system reveal the complex and somewhat random nature of the transient. High-speed movies of the evolving slug prior to impact show that significant air entrainment and break-up of the slug occurs… "

In the conclusions it states that "nearly all of the slugs exhibit significant air entrainment as they travel the length of the pipe. In addition, the larger slugs rupture into two distinct masses…".

Issa, R.I. and Kempf, M.H.W. 2003. Simulation of slug flow in horizontal and nearly horizontal pipes with the two-fluid model, International Journal of Multiphase Flow, Vol. 29, p65-95

This paper describes "a mechanistic approach to the prediction of hydrodynamic slug initiation, growth and subsequent development into continuous slug flow in pipelines…. The approach is based on the numerical solution of the one-dimensional transient two-fluid model equations. The advantage of this approach is that the flow field is allowed to develop naturally from any given initial conditions as part of the transient calculation; the slugs evolve automatically as a product of the computed flow development. The need for many phenomenological models for flow regime transition, formation of slugs and their dynamics can thus be minimised."

The authors show that the model is capable of capturing the growth of instabilities in stratified flow leading to the generation of slugs. The computed rates of growth of such instabilities compare well with the values obtained from Kelvin-Helmholtz analyses. Simulations were also carried out for a large number of pipe configurations and flow conditions that lead to slug flow. These include horizontal, inclined and v-section pipes. The results of computations for slug characteristics are compared with data obtained in the literature and good agreement was found.

5.3.4 Undulating pipes

Zheng, G. Brill, J.P. and Taitel, Y. 1994. Slug flow behaviour in a hilly terrain pipeline, International Journal of Multiphase Flow, Vol. 20, no. 1, pp63-79

When slugs flow in a hilly terrain pipeline that contains sections of different inclination they undergo a change in length as the slugs move from section to section. In addition, slugs can be generated at low elbows, dissipate at top elbows and shrink and grow in length as they travel along the pipe.

The work described in the paper is for a slug-tracking model that follows the behaviour of all individual slugs and is capable of simulating the aforementioned processes. Two cases are considered: the case of steady slug flow, for which each slug maintains its identity as it flows from one section to another; and the more complex case, where new slugs are generated and disappear, and the slug identity along the hilly terrain is not maintained. Comparisons with experimental data demonstrate the capability of this slug tracking method and show that the proposed model is able to simulate correct slug behaviour in a hilly terrain pipeline.

5.3.5 General

Hansen, E.A. 1986. Two Phase Flow in Pipelines and Risers, Series Paper 40, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark

Hansen (1986) describes the onset of slug formation and movement in two-phase flow systems. This type of flow regime can occur at a local low point in a pipe system where a horizontal or inclined pipe is connected to a vertical pipe. It can be described as follows:

The liquid cannot be transported away from the low point, and the low point will be blocked. This will result in a rise in pressure at the low point, because the gas in the horizontal or inclined pipe is being compressed. This rise in pressure causes the liquid level in the vertical pipe to move upward simultaneously with the back of the liquid column moving backward. When the liquid level reaches the top of the vertical pipe and starts to run over, the back point of the liquid column will move forward. There is no longer any blockage of the gas. The gas will be blown out and the pressure drops in the system. The liquid that runs to the low point will after a certain time again block the low point, and the oscillations will be repeated. Severe slugging results in large oscillations of pressure and a very uneven flow.

Edmunds, R..C. 1979. Air binding in pipes, Journal AWWA, Water Technology/Distribution, p272-277

Edmunds provides summaries of previous work. Some of the issues of air movement in pipes found by previous investigators include:

Kennison (1933) – Where the energy grade line of a pipe during flow has a slope steeper than the pipe slope, bubbles move more easily because of the increasing pressure gradient.

Whitsett and Christiansen (1969) – They reported air problems caused by cascading. Their experience indicated that the most severe problems occurred with hydraulic jumps at vertical or horizontal bends in pipes. They recommend keeping the line and grade straight from the peak of the line to below the static water surface if cascading is necessary. Unfortunately, the author does not define the meaning of the term ‘cascading’.

6. Criteria for air bubble/pocket movement

As described by Little (2002), there is no well accepted analytical solution for the transport of long air pockets, or indeed for the transport of dispersed bubble flow. At present, information must be drawn from existing experimental results.

Dimensional analysis (Bendiksen 1984; Falvey 1980; Wisner et al 1975) shows that the critical velocity to move an air bubble is a function of surface tension, Froude number, Reynolds number and pipe slope. Where the effects of surface tension are negligible, the critical velocity for a given pipe slope is proportional to $(gD)^{1/2}$, where g is acceleration due to gravity and D is the pipe diameter.

The papers reviewed in this section all provide experimental results relating to the critical velocity for air bubble movement in an air-water pipe system. The results of each of the authors are compared and an overview of the present state of knowledge is provided.

Kalinske, A.A. and Bliss, P.H. 1943. Removal of air from pipe lines by flowing water. ASCE, Civil Engineering, Vol. 13, No. 10 pp480-482

Based on their experimental data, Kalinske and Bliss provide a curve of Q_c^2/gD^5 versus slope, where Q_c is critical flow, g is the acceleration due to gravity and D is pipe diameter. The curve showed the point at which air starts to move in a pipe. For downward slopes, θ, higher than approximately 5% (2.9°) the following equation can be fitted:

$$\frac{V_c}{\sqrt{gD}} = 1.509\sqrt{\tan\theta} \tag{14}$$

For slopes less than 5% (2.9° or 1:20) the experimental data deviates from this prediction equation, and in the region 0-2% (0° – 1.1°) the critical velocity decreases as the slope increases.

Kent, J.C. 1952. The entrainment of air by water flowing in circular conduits with downgrade slopes. Doctoral thesis, University of California, Berkley, California

Kent's experimental results have been used by many authors to describe the movement of air bubbles in pipe systems. He presented the critical velocity in terms of flow Froude number as a function of the pipe slope, and this has been adopted throughout this paper as a simple means of comparing the various experimental results. Kent's tests were carried out using a pipe of approximately 100mm diameter.

The critical velocity required to keep stationary the air pockets that are formed in a pipe was given as:

$$\frac{V_c}{\sqrt{gD}} = C_o^{1/2}\sqrt{\sin\theta} \tag{15}$$

where his experimental results gave a value of $C_0 = 1.53$ (using consistent units). Kent carried out tests for 15, 30, 45 and 60 degree downward sloping pipes of approximately

100mm diameter for a range of bubble volumes. The minimum velocity required to move the air pockets was found not to be dependent upon the bubble volume, as shown in Figure 11. The size of the air pockets is denoted by n where

$$n = \frac{4\nabla_b}{\pi D^3} \tag{16}$$

∇_b is the bubble volume, and D is the pipe diameter.

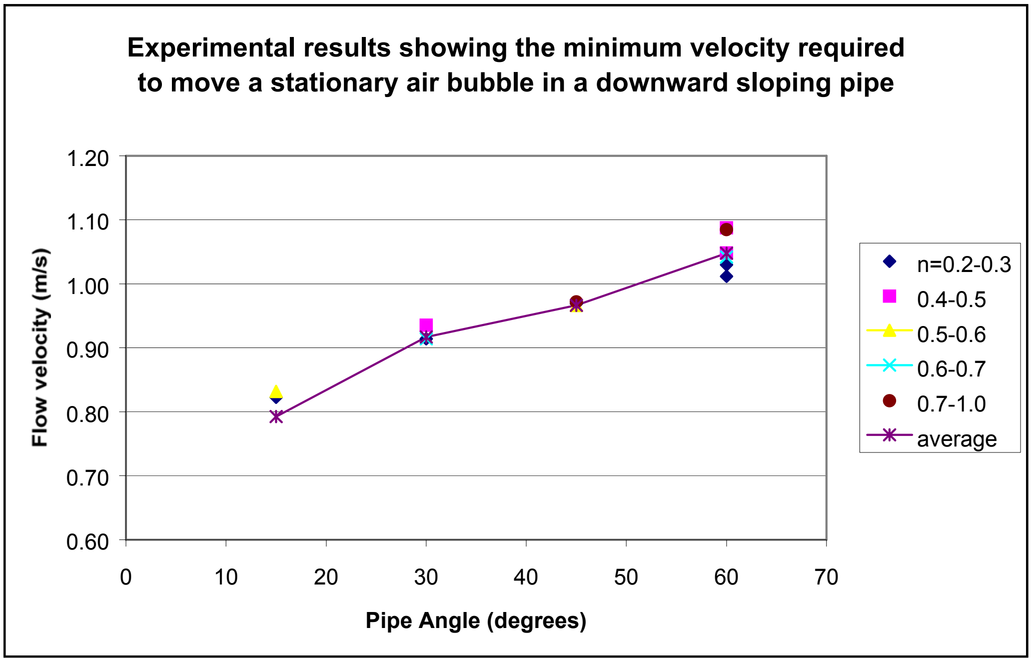

Figure 11 Experimental data of Kent (1952) showing minimum flow velocities for the transport of bubbles in a downwardly sloping pipe

Gandenberger, W. 1957. Design of overland water supply pipelines for economy and operational reliability(rough summary of work by W.A. Mechler, discussion of "Factors influencing flow in large conduits", Report of the Task Force on Flow in Large Conduits of the Committee on Hydraulic Structures, ASCE, vol. 92, HY4, 1966) *Gandenberger, W., 1957. Uber die Wirtshaftliche und betriebssichere Gestaltung von Fernwasserleitung, R. Oldenbourg Verlag, Munich, Germany*

Gandenberger's work (as summarised by Mechler 1966) resulted in the development of a graph which showed, for a pipe diameter of 1.0m, the water velocities corresponding to incipient movement of bubbles of different relative sizes from a high point into a downward inclined section of varying slope. The graph gives the minimum average water velocity required to clear a given volume of air from a peak in the profile for a certain inclination of the leg through which the water is flowing downward. The data from this graph are reproduced in Figure 13 for comparison with results from other authors.

Mechler states that the values in the graph are comparable to the equation of Kent when C_o =1.4. There is however an incongruity in this statement as the equation of Kent gives increasing values of V_c for 15 to 60 degrees whereas the data given by Gandenberger increase to a peak at around 50 degrees and then decrease again as the pipe gradient increases.

Wisner, P.E., Mohsen, F.N. and Kouwen, N. 1975. Removal of air from water lines by hydraulic means. ASCE, Journal of the Hydraulics Division, Vol. 101, HY2, p243-257

Wisner et al undertook a series of experiments to investigate the relationship between $V_r/\sqrt{gD}$ and Re, where V_r is the rise velocity of the air pocket, D is the pipe diameter, and Re is the flow Reynolds number ($=V_rD\rho/\mu$ where μ is the dynamic viscosity of the water and ρ is the density of the fluid). The tests were performed with air pockets of different sizes in a 244mm diameter downward sloping pipe. The pipe slope tested was 18.5°.

Experimental results in still water showed that for values of Reynolds number above 10^5, $V_r/\sqrt{gD}$ becomes independent of Reynolds number. Also, for the same slope the experiments suggest that $V_r/\sqrt{gD}$ becomes independent of the pocket volume for $n \geq 0.8$, where n is the pocket volume parameter ($\nabla_b = n\pi D^3/4$ where ∇_b is the pocket volume).

The variation of the rise velocity with slope was found to be complicated by the change of shape of the bubble with slope. The authors plotted the variation of rise velocity versus slope for their experiments along with those of Gandenberger, covering a range of angles from 10° to 60°. No experimental results are available outside this range.

Results of tests in moving water on the limit length and velocity showed that within the range of the available experimental results, an equilibrium may be achieved for a particular size of pocket and flow velocity. They showed that for a particular diameter and slope there is one stable length and corresponding velocity. The authors concluded that through comparison with previous experimental work:

1. The limit velocity may not become a constant quantity with increasing diameter, but may decrease with diameter (within the range of available tests, i.e. pipe diameters between 100mm and 244mm); and
2. The pocket limit length does not become constant beyond 100mm diameter but decreases at a decreasing rate.

A comparison of previous and present experimental results showed that the critical velocity for removal of air is given as the envelope equation:

$$\frac{V_c}{\sqrt{gD}} = 0.25\sqrt{\sin\theta} + 0.825 \qquad (17)$$

This equation does not appear to take into account the secondary effect of pipe diameter, as mentioned in (1) above or air volume.

Wisner et al suggest that design values of the velocity parameter should not be much higher than this limit as this will introduce problems of blow back. They suggest, from experience, that the most satisfactory performance would be achieved if the velocity parameter were kept within +5% of the limit.

An important conclusion of this work was that clearing of isolated air pockets entrapped during filling may require very high velocities for fast clearing.

Wisner et al. also quote the work of Veronese (1937), who observed that for pipes larger than 0.1m in diameter air bubbles would be swept out at a certain "limit velocity". Veronese found that the "limit velocity" for a 0.1m diameter pipe was 0.59 m/s. No mention is made as to the inclination of the pipe to the horizontal.

Mosvell, G. 1976. Pra 8 Air in outfall pipes, Project committee for the treatment of wastewater, (in Norwegian)

Moswell refers to the work of Kent to describe the minimum critical velocity required to move air pockets in a pipe. He provided a best-fit curve to the data of Kent as given by:

$$\frac{V_c}{\sqrt{gD}} = \left(0.55 + 0.5\sqrt{\sin\theta}\right) \tag{18}$$

for pipe slopes from 15 to 60 degrees.

Falvey, H.T. 1980. Air-water flow in hydraulic structures. Engineering Monograph No. 41, United States Department of the Interior Water and Power Resources Service, Denver, Colorado, pp143

Falvey summarises results for bubble motion in closed conduits flowing full using Figure 12, reproduced here. This shows limits for movement for both air pockets and air bubbles. The limits given for bubble movement and air pocket movement have been used for comparison with the other prediction equations described herein.

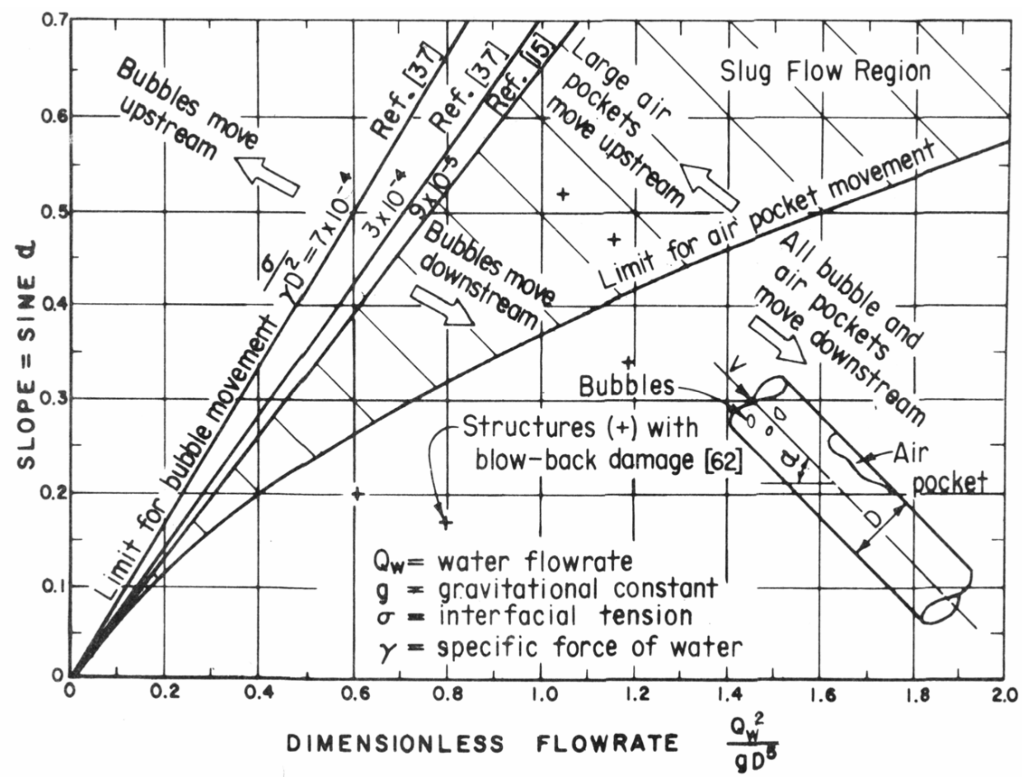

Figure 12 Graph showing flow rates required to transport air bubbles and pockets in pipes of varying slope (taken from Falvey, 1980)

A.R.I. www.arivalves.com

A.R.I is a valve manufacturer that has produced a program for the user to size and place air valves within a pipe system. The program was developed in conjunction with Prof. van Vuuren from the University of Pretoria, in South Africa. As part of the program the following relationship is used to establish the ability to transport air hydraulically.

$$\frac{V_c}{\sqrt{gD}} = 0.25\sqrt{\sin\theta} + 0.4 \qquad (19)$$

No information is provided as to the basis of this equation.

Alves, I.N., Shoham, O., and Taitel, Y. 1993. Drift velocity of elongated bubbles in inclined pipes, Chemical Engineering Science, Vol. 48, No. 17, pp3063-3070

Alves et al provides a short review of existing estimates of drift velocity of elongated bubbles in pipes. Drift velocity is defined as the buoyancy-induced velocity that results in propagation of bubbles in a pipe with stationary liquid. For the present review the drift velocity is considered to be the critical velocity for bubble movement in a stationary liquid.

In terms of vertical flow they note that the potential flow analysis presented by Davies and Taylor (1950) gives

$$\frac{V_c}{\sqrt{gD}} = 0.33 \qquad (20)$$

while more accurate calculations by Dumitrescu (1943) show a constant of 0.35 instead of 0.33.

The horizontal flow situation is less clear. Some authors claim that the drift velocity is zero for the horizontal case since the buoyant force does not act in the flow direction. Others, such as Bendiksen (1984), who tested small diameter pipes in the range of 0.02 to 0.05m, have shown that the drift velocity does exist for the horizontal flow case, and may in fact exceed the value for the vertical flow case. It is thought that the drift velocity in horizontal pipes results from the elevation difference along the bubble nose region.

Benjamin (1968) provides a theoretical analysis of this situation, which results in the equation:

$$\frac{V_c}{\sqrt{gD}} = 0.542 \qquad (21)$$

For the inclined pipe situation no models have been proposed and the results of experimental investigations are the primary source of data. Many of the studies examined by the authors report "peculiar" behaviour, whereby the drift velocity increases as the angle of inclination decreases from the vertical. The drift velocity then decreases towards the horizontal position with the maximum drift velocity occurring at an intermediate angle of inclination between 30° and 50° from the horizontal.

According to Bonnecaze et al (1971) the gravity potential of the flow that drives the liquid velocity along the curved surface at the bubble nose first increases and then decreases as the angle of inclination changes from the vertical position to the horizontal position.

The authors present a theoretical approach for estimating the drift velocity of inclined pipes along with experimental data. The experimental data showed that the velocity tends to increase as the inclination angle increases, reaching a maximum at about 40°. Further increase in the inclination angle resulted in a decrease in the drift velocity. The model was able to predict these values of drift velocity for the range of pipe inclinations.

Walski, T.M. et al. 1994. Hydraulics of corrosive gas pockets in force mains. Water Environment Research, Vol. 66, No. 6, Sept/Oct, pp772-778

This paper details a model study of a pumping main (force main), undertaken at Wilkes University. The study was for the Wyoming Valley Sanitary Authority (WVSA) West Side Force Main, which was 4.5km long and had a diameter of 0.5 to 0.92m. The pipe was modelled using a 50mm diameter clear PVC pipe.

It was found that the following relationship could be used to describe the air flow conditions in the pipe.

$$\frac{0.88V_{nom}^2}{gDS^{0.32}} = P' \qquad \text{or} \qquad \frac{V_{nom}^2}{gD} = \frac{P' S^{0.32}}{0.88} \tag{22}$$

where P' = 1 for equilibrium and P' > 1 for gas to move downstream. V_{nom} is the nominal velocity with no air in the pipeline, S is the pipe slope, and D is the pipe diameter.

Dewhirst, R.A. 1991. Optimising the use of air valves in piped water systems, Master of Engineering Thesis, Department of Civil Engineering, The University of Auckland, Auckland, New Zealand

The author presents a theoretical calculation for the estimation of the critical velocity required to move air pockets in sloping pipes. The following equation was developed:

$$V_c^2 = 2g\left[\frac{V_p \sin\theta}{A} + \left(\frac{D}{2} - y_3 + \frac{\overline{D}_3 A_3}{A}\right)\cos\theta\right]\left(\frac{A_3}{A_3 - A}\right)^2 \tag{23}$$

where A is the pipe cross-sectional area, A_3 is the area of water at the downstream end of the bubble (before the hydraulic jump section forms), D is the pipe diameter, $\overline{D}_3$ is the distance perpendicular to the pipe, from the water surface to the centroid of A_3, V_c is the critical velocity in the pipe upstream of the pocket, V_p is the volume of the pocket, and θ is the angle of inclination of the pipe.

The analysis showed that the head loss in the system occurs at the downstream end of the pocket where a hydraulic jump forms. Upstream of the jump the water surface resembles a free surface and the flow is analogous to open channel flow. These findings were supported by the experimental results (detailed in Section 5.2.2). The main difference between the theoretical considerations and the experimental results was that the experimental results found the critical velocity to be independent of pocket volume; however this could not be resolved in the theoretical analysis.

It is not possible to plot Equation 23 on Figure 13, however the experimental results showing the critical velocity for different pipe slopes are included.

Corcos, G. 2003. Air in water pipes, Agua Para La Vida, 2nd Edition, www.aplv.org

The paper is a manual for designers of gravity water supply systems in rural areas. It provides a method for assessing if and where air problems are likely to occur in gravity water supply systems and gives a methodology for designing such systems. A computer program can be downloaded to automate the design.

The following equations are provided for estimating the critical flow rate required to move air pockets in pipelines.

$$\frac{V_c}{\sqrt{gD}} = 0.484 \tag{24}$$

V_c is the critical velocity for moving air out of a horizontal pipe section and preventing any further accumulation of air. It states that the critical flow rate depends only on the diameter of the pipe in the region of the air pocket.

$$\frac{V_s}{\sqrt{gD}} = 0.638 \tag{25}$$

V_s is the velocity required to move stationary air pockets downstream past a sloping part of the pipe. D is the internal diameter of the pipe.

Summary

The prediction equations outlined in this section are presented in Figure 10, along with some of the air bubble movement criteria for still water. The equations and data presented in this graph have been taken from the reports and papers described in this review. They have been plotted as the dimensionless flow velocity (Froude number) versus the square root of the pipe slope angle (downward sloping). It can be seen that there is a wide variation between the different prediction equations.

The authors Bendiksen and Gandenberger both present results whereby the critical flow velocity to move the air bubble increases with slope angle from the horizontal to reach a peak at downward angle of inclination of 30° to 50°. For any further increases in slope angle the critical velocity decreases, reaching a minimum at 90° (vertical pipe flow). In contrast to these results, Kalinske and Bliss found the critical velocity to reach a minimum for a downward pipe angle of 1.2° and then increase for either flatter or steeper slopes. These results and observations are supported by the work of various authors such as Zukoski (1966) and Alves et al (1993), who measured the drift velocity of bubbles in pipes with stationary flow for a range of pipe inclination angles.

The remaining prediction equations show increasing critical velocity with increasing downward pipe slope, up to a maximum for vertically downward pipe flow.

Gandenberger's results also show the critical velocity to be dependent on the volume of the bubble for n = 0.02 to 1.0. Wisner et al found that for n > 0.8 the velocity was independent of bubble volume, and Kent's results do not show any strong dependence between the two parameters. Only Kent gives any details of the bubble volumes used in his tests.

For the horizontal pipe there appears to be the greatest confusion. Falvey suggests that the critical velocity is zero for movement of both bubbles and air pockets in horizontal pipes. In the discussion by Mechler of Gandenberger's work he continues the curves, given in Figure 13, to zero for horizontal slopes. As shown in the Figure, other authors suggest however, that there is some minimum velocity greater than zero for movement of air bubble and pockets in horizontal pipes. The values range from $V_c/\sqrt{(gD)} = 0.35$ to around 0.8. For a 200mm diameter horizontal pipe this gives a critical velocity range of 0.49 to 1.12m/s.

Notes for Figure 13: n is the bubble size, defined as $\frac{4\nabla_b}{\pi D^3}$ (Equation 16)

E is the surface tension parameter $\frac{g\rho_l D^2}{\sigma}$ (Equation 2)

*no information available as to basis of the equations

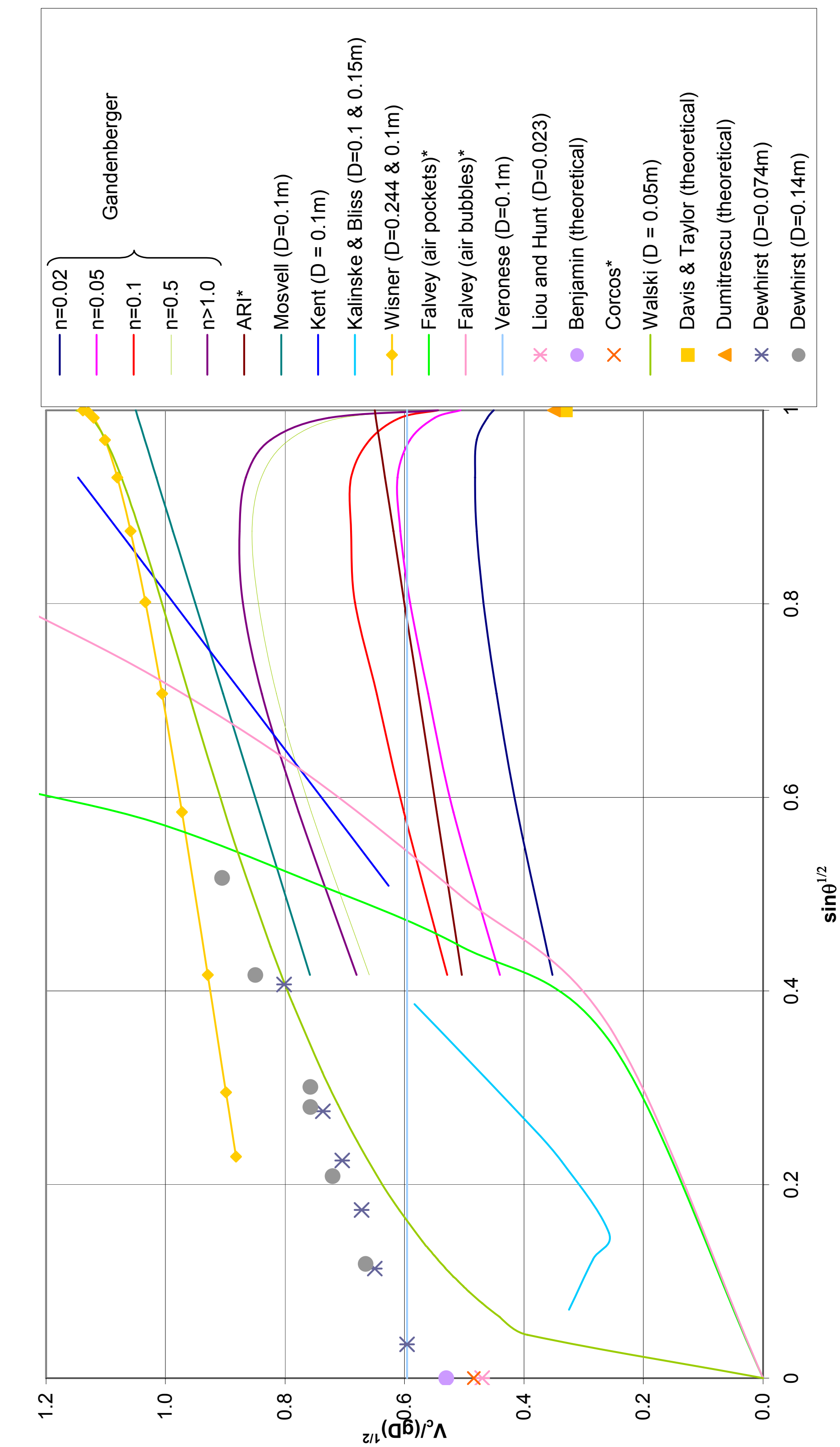

Figure 13 ***Comparison of various prediction equations and experimental results for the critical velocity of air bubble transport through water in downward inclined pipes***

7. Air removal using valves

7.1 INTRODUCTION

CIRIA Report 170 (Reader et al 1997) defines an air valve as “a valve positioned at a strategic point in a system to vent air under normal operating conditions or when refilling, or to allow air in when the system is being drawn down”.

On pipelines transporting liquids they perform one or all of these three functions in the following ways:

a) the high volume rate discharge of air during filling of an empty piping system
b) the high volume rate intake of air into a pipeline being drained
c) the discharge from a pressurised pipeline of air remaining or introduced after filling or of air released from solution.

There are different types of air valve that operate to fulfil some or all of these functions and within each valve type there are variations in design. The following sections give an overview of typical types of air valve and the different problems associated with their use. A summary is also provided of available knowledge on how to select air valves and where they should be located on a pipeline.

7.2 TYPES OF AIR VALVE

A single large orifice performs functions of rapid discharge or intake of air during filling or emptying of a system; a single small orifice is used to discharge air from a pressurised system; while a double orifice type valve can be used to perform all three functions. Each of these types of air valve is described here in more detail.

7.2.1 Large orifice air valves

Falvey (1980) states that large orifice air valves should be used to permit air to escape during filling. He notes that a ‘large orifice’ refers to diameters greater than 25mm. This type of air valve is designed to remain closed after the pipeline is filled so they do not permit the release of small amounts of air during operation of the pipeline. These valves will open immediately when the pipeline pressure drops below atmospheric.

Falvey suggests that the air velocities discharging from an air valve should not exceed 30m/s so as to prevent the air valve being blown shut, a phenomenon often referred to as ‘dynamic closure’.

There are a variety of types of large orifice valve including non-kinetic valves, and kinetic valve designs. The information on valve types and performance is based primarily on information provided by Vent-o-mat, a South African air valve manufacturer (Balutto, 1996).

Non-kinetic air valves

These valves are characterised by hollow control floats. In general, the orifice through which the air passes is circular and below it is a ball which floats in water. As the air is released, the water level will rise and the float will close the orifice.

There are a number of problems associated with this type of air valve design. They include (Balutto, 1996):

- "Poor sealing at low working pressure. In order to produce a leak-tight seal against a resilient seat located around the circumference of an orifice the ball float must be perfectly spherical. This is difficult to achieve in practice and to compensate for non-uniformities in the ball float very soft seating seals are often used. These can adhere to the float and prevent the operation of the orifice."
- "Deformation and jamming. The hollow structure of the ball type float makes them susceptible to distortion and permanent deformation when subjected to high pressure and shock loads. It has been found in practise that the float can elongate and become wedged into the orifice, thereby preventing it from functioning."
- "Premature closure. This is often referred to as "dynamic closure" and refers to the tendency of ball type air valve designs to be closed by the float at very low differential pressure without any further discharges. High volume rate tests performed by the C.S.I.R in South Africa on a number of commonly used air valves indicated that many of them were prone to dynamic closure at low differential pressures (3-5kPa). This was well below the manufacturers claimed discharge performance, which in most cases started at a differential pressure of 10kPa."
- "Limitation of the orifice size and its effect on performance. The discharge of air valves is affected by the large orifice diameter. Some manufacturers state that the ball float diameter should not be less than three times the large orifice diameter otherwise it will wedge into the orifice and become jammed. For economic reasons this results in the designer choosing a smaller large orifice and consequently the discharge performance is adversely affected."
- "Venturi effect. For all air valve designs with spherical floats there is a tendency for the large orifice control float to partially close the large orifice during air intake. This is due to the creation of a lower pressure zone on the upper part of the float compared to the pressure experienced in the pipeline."

Kinetic air valves

Kinetic air valves were mainly developed to overcome the dynamic closure phenomenon. They are able to discharge air at a high rate but without early closure of the outlet orifice. This is achieved by altering the internal configuration of the valve and therefore its aerodynamic characteristics so that during air discharge the large orifice float is biased towards the inlet orifice thereby preventing early closure of the outlet orifice. The details and effectiveness of such an internal configuration differ for each valve manufacturer.

As these types of valve are discharging air at high velocities they can create problems for the operation of the pipeline, including (Balutto, 1996):

- "An air valve discharging air at high differential pressures and velocities, will on closure, induce high, damaging pressure transients. The effect on the pipeline dynamics is equivalent to the rapid closure of an isolating valve."
- "Water spillage can occur where the large orifice float fails to react when high velocity water enters the valve chamber. This results in the water covering the control float, effectively holding the float down, whilst exiting through the large orifice. The amount of water spilled can be substantial and flood the valve chamber. An additional effect of the spillage of water is to induce a pressure surge in the pipeline."

- "Seal failure. This is the failure of the seal between the valve and the isolator which can occur on closure of the large orifice and results in water spillage. It is a result of the transient pressures created on closure. Tests have indicated that this phenomenon occurs at 80-85 bar, which implies that the transients created by the kinetic valves discharging at high differential pressures are in excess of 85 bar."
- The venturi effect, as described previously, can occur.

Three stage air valves

These values use the blow-shut phenomenon to step down the area of the large orifice and therefore limit the differential pressure to acceptable limits. The staged closure of the large orifice can be carried out in such a way that the rate of discharge can be limited to a predetermined capacity by adjusting the size of the orifice for the different stages. This reduces the requirement to restrict the discharge velocity of air through the valve to 30m/s (van Vuuren, 2001).

7.2.2 Small orifice air valves

Single small orifice air release valves are designed to automatically release pockets of accumulated air. They are only suitable for applications where small volumes of air need to be discharged from a pressurised pipe system. Their most common location is on or near centrifugal pumps, the action of which tends to release air from liquid solution or draw air into the system. The criterion for siting small orifice air valves along a pipeline is uncertain.

The effective discharge of such a valve is a function of the relationship between the area of the small orifice and the mass of the control float. Therefore the mass of the float must be greater than the force created by the working pressure acting on the orifice area. If the float is too light or the orifice too large then the float will be held against the orifice and no air can be discharged.

7.2.3 Double orifice air release valves

Double orifice air release valves perform the functions of both the large and small orifice valves thereby combining the characteristics of the two types.

7.2.4 Other air valve designs

Hydraulically controlled air valves

This type of air valve function in the same way as a conventional double orifice air valve except that it has an externally mounted mechanical damper to control the rate at which the valve closes. During air discharge, air does not have any effect on the closure rate which therefore can permit discharge of water for a pre-set closure time. Spilling of water can induce a pressure surge in the pipeline.

Non-return air valves

These are conventional air intake valves fitted with a small orifice air release valve. They allow unrestricted air intake but control the air discharge. Because air is only released through the small orifice, liquid oscillation (pressure surges) can result. They can also lengthen the filling operation procedures.

Controlled air transfer technology (CATT)

This terminology is applied to a mechanism featuring a double acting air valve and a surge/water hammer alleviation mechanism to automatically prevent phenomena such as surge, water hammer, flow restrictions, pipe breaks and vacuums from occurring in water pipelines.

The South African manufacturer of Vent-O-Mat air valves states that their valve design operates according to CATT.

7.3 TESTING AIR VALVE PERFORMANCE

Most data published by manufacturers is based on theoretical calculations or on using tests where air is blown through the large orifice (air discharge test in reverse). Both these methods have been shown to be inaccurate. The only way to accurately determine the air discharge capability of an air valve is to simulate the air discharge test in a specialist facility, such as a wind tunnel, which enables large airflow rates to be generated.

7.4 SELECTION AND SIZING OF AIR VALVES

The large orifice diameter of an air release valve should not be confused with the nominal inlet size of the valve. The nominal inlet size is the diameter of the inlet into the valve from the pipe whereas the large orifice diameter refers to the diameter of the opening where the air exits the valve into the atmosphere. These two dimensions are not necessarily similar. It is the large orifice area and the valve's dynamic characteristics that determine performance, not the nominal inlet diameter. It cannot be taken for granted that different valve designs of the same nominal diameter will perform equally.

Generally, the small orifice diameter remains the same irrespective of the nominal valve size but may change for different working pressures. The nominal valve size has no influence on the small orifice size.

Falvey (1980) states that if the desired capacity cannot be achieved with a single air valve, valves can be placed in clusters of up to four on a single vent pipe from a pipeline.

From manufacturers' information, it is generally considered that locating air valves for air intake will suffice for air discharge. However the sizes selected may not be large enough for air to discharge efficiently. In addition, the positioning of valves for air intake may not allow for the collection of air that is transported along the pipe while the pipe is in operation.

AWWA (2001) has a chapter on selection and designing of valve orifice sizes. A methodology is provided for estimating the valve orifice size required in an air valve. It is noted that it is important to verify with the valve supplier/manufacturer that the valve will operate with the required orifice diameter at the expected maximum pipeline pressure.

7.5 POSITIONING OF AIR VALVES

Most available guidance suggests that the analysis of the pipeline gradient with respect to the hydraulic grade line is the principle method of identifying suitable locations for air valves. All the positions along the pipeline profile where the pipe elevation is below the hydraulic grade line should be identified. The following section gives details from a number of references on where air valves should be located.

Willis, J. 1990. Design and positioning of air valves, South African Institution of Civil Engineers

From the report of Willis (1990) the following priority locations are identified for placement of air valves for air intake:

- High points (summits) which can fall below the hydraulic grade line (HGL).
- 3-4 m below the summit points formed by the intersection of the HGL and the pipe profile.
- Negative breaks, profile points where the upward slope decreases or the downward slope increases.
- 3-4m below the negative break points formed by the intersection of the pipeline profile and the HGL.

The author does not state whether the designer should consider the HGL at only high flows or for all flows over which the pipeline will operate.

It is suggested that the location of air release valves is the same as above but they are also required on descending sections of pipeline for filling

It is difficult to size air valves on the descending section. In practice it is usual for air release valves in the descending section to be one or two standard sizes less than that at the apex.

The situation of air release valves on the descending, horizontal and shallow angled ascending sections of a pipeline is decided in terms of the relative distance between locations, taking into account the valves already positioned for intake purposes.

The work of Prof. van Vuuren, University of Pretoria, (referred to by Willis, 1990) found that there is a critical volume of air, which when released within a water filled pipe, could potentially induce damaging pressure surges. His experiments showed that it was possible for a critical volume of air to accumulate in a certain volume or length of pipe during filling.

Based on work undertaken by Prof. S.J. van Vuuren, it was suggested that intervals between air release valves should be determined from:

$$L_c = 85\frac{D}{150} \tag{26}$$

where L_c is the critical length and D is the pipe diameter in mm. This assumes that the critical volume ratios will occur and that the induced surge pressure should not be greater than four times the design working pressure of the pipe.

Willis (1990) also identifies other situations in which the use of air valves should be considered, including:

- The location of a double orifice air release just downstream from a non-return valve will help to dampen water hammer when discharge from a pump ceases.

- Where the end of a pipeline is terminated by a blank end or closed valve, a double orifice air release valve should be installed.
- A single small orifice air release valve should be installed immediately subsequent to abrupt increases or decreases in elevation of a pipeline and on the highest point of centrifugal pump casing.

Balutto, A. 1996. www.ventomat.co.za

The South African air valve manufacturer, Vent-O-Mat, recommends that on ascending sections of considerable length valves should be positioned every 600m to ensure adequate discharge when filling and ample ventilation when the pipe is being drained. For long descending sections and long horizontal sections the same recommendations are given.

van Vuuren, S.J. 2001. The importance of the correct sizing and location of air valves. Pump and valve summit, (location unknown)

Professor van Vuuren provides the following information on the positioning of both large and small air valves on pipeline systems.

Large orifice air valves

- "A large orifice air valve, when used as an alternative for a one-way surge tank (or discharge tank) should be placed as near as possible to and just downstream from the pump check valve."
- "Depending on the longitudinal profile and the positioning of the shut-off valves or non-return valves in the line, a large orifice air valve should be provided to prevent sub-atmospheric pressures in the line when it is drained. To ensure the flexible and effective operation of the pipeline, shut-off valves are normally provided at intervals of between 1500 and 3000m (or more). The result is that the spacing of large orifice air valves is more or less the same due to the requirement that one should be able to drain off any section between shut-off valves."
- "The results of surge analyses indicate where sub-atmospheric pressures might occur and it is suggested that large orifice air valves should be provided wherever the pressure drops below 6.0m absolute.

Small orifice air valves

Small orifice air valves release air while the pipeline is in operation and so the emphasis for the design of such valves is to provide a collection chamber underneath the valve where the air can be captured temporarily and then released through the air valve. The following approach is suggested to determine the position of the small orifice air valve.

- Determine where the air in the pipeline will be transported hydraulically and by working through all sections of the pipeline identify those sections where air is not transported hydraulically.
- Those positions identified are potential locations where a small orifice air valve is required.
- Define the points where the small orifice air valve should be installed by evaluating all the locations identified previously, working downstream.

"If the distance between the small orifice air valves is short (say 250m), it is not necessary to provide a small orifice air valve at all the identified points, provided that the line is effectively filled and that the upstream small orifice air valve effectively releases all the air that reaches it."

The author notes that for effective operation of the small orifice air valve a collector chamber is required to capture the air. It is suggested that the small orifice air valve should be installed on a T-piece, the diameter of which should be at least 50% that of the pipe.

AWWA, 2001. Air-release, Air/Vacuum, and Combination Air Valves, AWWA Manual M51, 1st Edition, American Water Works Association, Denver, U.S.A., pp37

The AWWA Manual M51 suggests that air valves should be installed at the following locations:

- High points. Valves are needed at high points to provide venting while the pipe is being filled, during normal operation of the pipeline, and for air inflow when draining. A high point is defined by the hydraulic gradient and is considered the upper end of any pipe segment that slopes up to the hydraulic gradient or runs parallel to it.
- Increased downslope. A double orifice air valve should be considered at abrupt increases in downslope.
- Decreased upslope. A large orifice valve (air intake and release) or double orifice air valve should be considered at abrupt decreases in upslope.
- Long ascents. A large orifice valve (air intake and release) or double orifice air valve should be considered at intervals of 400m to 800m along ascending sections of pipeline.
- Long descents. A large orifice valve (air intake and release) or double orifice air valve should be considered at intervals of 400m to 800m along descending sections of pipeline.
- Horizontal runs. A combination air valve should be considered at the beginning and end of long horizontal sections, and a large orifice valve (air release) or double orifice air valve should be considered at 400m intervals along horizontal sections of pipeline.
- Venturi meters. Air release valves should be installed upstream of venturi meters to eliminate measurement inaccuracy caused by trapped air.
- Pumps. Air intake/release valves should be installed on the discharge side of deep well and vertical turbine pumps to remove the air in the well column during pump startup and to allow air to re-enter the line after pump shutdown.
- Siphons. To maintain a siphon on a section of pipeline that extends above the hydraulic gradient and that constantly runs under negative pressure, install air release valves at the high point of the siphon to vent the air.

Falvey, H.T. 1980. Air-water flow in hydraulic systems, Bureau of Reclamation, Engineering monograph No. 41

Falvey suggests that air valves should be located at summits along the pipeline or the pipeline should be aligned so that all intermediate summits are eliminated.

Twort, A.C. 1963. A textbook of water supply, Edward Arnold Publishers, London

The following locations for air valves are suggested:

- at the top of each rise in gradient.

- where the pipeline rises steeply and then changes gradient so as to rise less steeply, a valve should be installed at the change in grade.
- Where long stretches of pipe exist with no definable high point, valves should be inserted at least every 800m, especially when the pressure in the main is decreasing and thereby allowing air to come out of solution from the water.

A.R.I. www.arivalves.com

This company provides the following recommendations for the location of air valves:

- on rising mains from pumps to release and admit air
- at local peaks in the system
- at transition points in the hydraulic gradient
- at transition points in the pipe slope, particularly before and after steep slopes
- every 500m along pipe sections of long uniform slope.

Gandenberger, W., 1957. Uber die wirtshaftliche und betriebssichere Gestaltung von Fernwasserleitungen, R. Oldenbourg Verlag, Munich, Germany Design of overland water supply pipelines for economy and operational reliability (rough translation by W.A. Mechler, discussion of "Factors influencing flow in large conduits.", Report of the Task Force on Flow in Large Conduits of the Committee on Hydraulic Structures, ASCE, Vol.92, No. HY4, 1966

With regard to air valves Gandenberger recommends that air valves at long, relatively flat high points be located towards the downstream end of the rise, or that, preferably, in many cases two air valves be installed so that one is at the centre and the other near the downstream end of the summit. It is noted that "at high points air is displaced by moving water downwards at the downstream end of the crest and pulled into the descending leg of the pipe. Allowance for this should be made when locating air valves."

Edmunds, R.C. 1979. Air binding in pipes, Journal AWWA, Water Technology/Distribution, p272-277

Edmunds summarises previously published work on the subject of air in pipelines. It was noted that Whitsett and Christiansen found that the worst case for air problems was when hydraulic jumps form at vertical or horizontal bends in a pipe. They also found that venting downstream of the hydraulic jump controlled pressure surging but did not relieve white water. The term 'relieve white water' is not explained in the text.

He also describes the work of Kennison (1933), who had experience in installing air valves in a number of pipelines. From Kennison's data it appears that air valves should be placed before steeply descending sections of pipe or an allowance should be made for the energy loss equal to the vertical component of the descending pipe section.

Dawson, P. 1980. The effect of air in a rising main. Proc. Symposium on Pumping in Practice, Runcorn, 20 Feb 1980, published in Public Health Engineer

The following notes regarding air valves are taken from the above paper:

- The designer should avoid depressing the main locally at the air valve to give enough depth for the chamber.

- The pipeline should be designed to satisfying CP2010 (BSI, 1970) recommendations.
- The air valve should be mounted above a line-sized tee.

Corcos, G. 2003. Air in water pipes, Agua Para La Vida, 2nd Edition, www.aplv.org

The manual discusses issues related to the placement of air valves in gravity driven pipelines for water supply. A key recommendation is that air valves need to be downstream of the pipeline high point in order to drain the air pocket of air.

Design Standards

BS 8010-2.5:1989 Code of practice for Pipelines – Part 2: Pipelines on land: design, construction and installation – Section 2.5 Glass reinforced thermosetting plastics, BSI

Section 18.3 Air valves
"Air release valves should be provided on liquid pipelines for the release and admission of air during filling and emptying of sections of the pipeline between isolating valves and to bleed off air released from solution during operation of the pipeline."

"The type of air valve chosen (small single orifice, large single orifice, double orifice or kinetic) should be selected after consideration of the duty and location of the valve. Air valves should be located at all topographic high points and high points on the pipeline with respect to the hydraulic gradient and should also be located at intervals along any sections where the gradient of the pipeline is parallel to or less than the hydraulic gradient. On long sections of pipeline of even gradient, air valves should be positioned at intervals of approximately 0.5 km, depending on the diameter of the main and the air valve chosen. Air valves may also be required where the gradient of the pipeline changes."

"The chamber housing an air valve should be designed to be free draining and free from risk of flooding or possible back siphonage."

BS EN 805:2000 Water Supply – Requirements for systems and components outside buildings, BSI

Section 8.5.4.1 Entry and release of air

"Mains shall be provided with facilities to release air at high flow rates when the pipeline is being filled and to permit the entry of air at higher flow rates during drainage. Large orifice air valves and sometimes hydrants are used for this purpose."

"Provision shall also be made for the release of accumulations of air during normal operation. Small orifice air release valves are usually adequate for this purpose."

"The size and types of the air valve required shall be determined by the designer depending on the predicted flowrate of air and the configuration of the system. All points where the gradient of the pipeline changes shall be considered. Reference shall be made to the appropriate product standards for valve selection."

A.17 ad 8.5.4.1 Entry and release of air

"Air collects at high points, the location of which may change depending on the variation of the hydraulic gradient. Air valves incorporating isolating valves should be provided at all possible high points."

BS EN 752-4:1997. Drain and sewer systems outside buildings – Part 4: Hydraulic design and environmental considerations, BSI

Section 9.3
"Where sewers with steep gradients are required consideration shall be given to consequences of high velocities such as:

- possible air entrainment and its effects;
- possible release of hydrogen sulphide;
- possible erosion;
- the need for energy conservation measures on super-critical flow to sub-critical flow…"

8. Effect of entrapped air on transient pressures in pipelines

8.1 INTRODUCTION

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 and Streeter (1978). Many hydraulics textbooks provide a useful elementary overview of the background theory (e.g. Nalluri and 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 entirely dependent on the characteristics of the pipeline concerned and the nature and cause of the transient. 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 and Streeter, 1978) and subsequently elucidated in numerous scientific contributions, some of which are cited herein.

Air pockets can develop in a pipeline by bubble entrainment through the action of pump suction and by air release as the water pressure reduces. The former can result from poor suction well design and through operation cycling which permits excessive drawdown before pump switching or shutdown. The amount of air release from solution depends upon the pressure reduction and other factors and water under normal conditions may contain about 2% dissolved air by volume (Fox, 1977).

Under low pressures the phenomenon of gas release, or cavitation, creates vapour cavities which, when swept with the flow to locations of higher pressure or subject to the high pressures of a transient pressure wave, can collapse suddenly creating further 'impact' pressure rise, 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 and 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 and 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 (water and air voids) flow 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 and Gudmundsson, 2000, Fujii and Akagawa, 2000).

8.2 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 and Streeter 1978, Thorley 1979, 1991, Nalluri and Featherstone 2001). No attempt is made here to provide the mathematical development.

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. These refinements include: making better allowance for energy dissipation (non-steady friction) in the mathematical formulation (Abreu and Almeida, 2000, Prado and Larreteguy, 2002); non-elastic behaviour (Borga et al, 2004, Covas et al, 2003); and variable (pressure) wave speed (Lee, 1994, 2003, Borga et al 2004), the latter being affected significantly by air entrainment as mentioned earlier and Lee’s modelling approach makes explicit allowance for gas release and re-absoprtion during the transient events. Further refinement is called for to account for the cavitation process explicitly, whereby vapour filled voids will grow and collapse as the pressure changes, the standard treatment outlined by Streeter and Wiley (1978) is widely employed but recent discussion has been given (Bergant et al, 2004, Borga et al, 2004), Dudlik 2000).

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 and Gudmundsson, 2000, Fujii and 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.

Lee originally cited the work of several other researchers in support of his findings;- firstly, the observations by Whiteman and Pearsall (1959 and 1962), that the first pressure peaks during pump shut down exceeded model predictions; Dawson and Fox (1983) reasoned that the accumulation of relatively minor changes in flow during the period of the transient had a significant effect upon the peak pressures causing them to rise; whilst, Jonsson (1985) attributes the results to compression of an isolated air cushion next to the check valve. Jonsson justified this by application of a standard (constant wave speed, elastic theory) model and concluded that there would be a lower limit of the volume of air to which the descriptor ‘air-cushion’ would be valid. Burrows and Qiu (1995) had taken Jonsson’s finding as an early independent validation for use of ‘air pockets’ to better explain discrepancies between observed transients and model results. They further suggested that a combination of the ‘variable wave speed’ and ‘discrete air pocket’ approaches might yield a more rigorous model but that high quality field or laboratory data would be necessary to enable proper verification. More recent laboratory and pilot scale studies (Kapelan et al, 2003; Covas et al, 2003) have also identified peak pressure enhancement and transient distortions from suspected air pocket formation. In further evidence, the work of Low and Lee (1998) and Leow and Lee (1998), with the development of variable wave speed numerical models concludes that there is significant evidence that entrapped, entrained and release of air from pressurised piped systems can significantly enhance peak pressures. Independently, Lai et al (2000) investigate waterhammer in the presence of non-condensible gas voids (i.e. air) together with vapour cavities and found that whilst the presence of air is generally beneficial in reducing waterhammer loads, it can result in an increase in the ‘longer term’ transient (i.e. not the first positive pressure peak).

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 and 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 general, 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 Rachid and 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 and 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 and 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.

8.3 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 void (i.e. with the pipeline full of water when the transient is initiated).

Martin (1976) assumed uniform gas compression and neglected liquid compressibility and showed that peak air pressure can be markedly higher than driving pressures within the pipeline systems with an entrapped air pocket at the closed downstream end. An equivalent ‘rigid (water) column’ analysis has also recently been reported by Zhou et al (2004), who cite the hydraulic failure of a gravity sewer system in Edmonton, Canada as a result of a surge equivalent to a rapid filling event. A numerical formulation of a trunk sewer manhole system is given and comparison is made against a laboratory test. For the tested rapid filling conditions, peak surge amplification by a factor of 11 above the driving pressure is reported for small air accumulation. Fuertes et al (2000) also report a successful comparison between experimental (laboratory scale) and numerical (rigid column) analysis of an air void at a local high point along a pipeline.

The work of Chaiko and Brinckman (2002), developed upon the experimental work of Lee and Martin (1999), considers the validity associated with certain assumptions which are generally made when carrying out traditional water hammer analyses. The results from the study, which was not restricted to the rigid column assumption, compare favourably with the work of Lee and Martin (1999) and concur that the traditional method of characteristics (MOC) analysis under-estimates the peak pressures in a system with entrapped air and that further under-estimation occurs with a model where the time-varying length of the liquid is neglected. As part of this study the influence of gas-phase wave transmission on system response and the importance of considering the interactions between the gas-liquid interface with regard to phase pressure and velocity were considered. It was concluded that the most appropriate model, where pockets of air account for greater than five percent of the volume of pipe, would be the model that considered the effects of the interface movement on the liquid domain length assuming uniform gas compression. Although the study particularly focuses on relatively large entrapped pockets of air within pressurised systems, a range of applicability is presented for the models under evaluation for differing proportions of air to liquid. Most pertinent is the finding that standard MOC methods are likely to be acceptable when the liquid fraction in the system exceeds 90%.

Concluding comment: 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 and Zhou (2003), the latter pointing out the potential benefits of installing multiple vessels. Ngoh and 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.

Concluding comment: The surge suppressing capability of air vessels should not be compromised by entrained air. Continuous accumulation of additional air into the vessel from migrating air bubbles or pockets in the pipeline may call for contingency measures.

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). Purcell (1997) reports an investigation of check-valve slam in a rising main protected by an air vessel and Dudlik et al (2000) use both experimental observation and numerical modelling in investigating means of suppressing cavity collapse around the closing valve. More recently Bergant et al (2004) report large scale experimental testing of cavity formation in conjunction with check-valves (and air valves).

Jonsson (1985), attempting to explain larger peak pressures than predicted by modelling, attributed the potential cause to compression of an isolated air cushion next to the check valve. He justified this by application of a standard (constant wave speed, elastic theory) model and concluded that there would be a lower limit of the volume of air to which the descriptor ‘air-cushion’ would be valid, so implying that smaller air accumulations may prove problematic. Lee and Leow (2001) employ the variable wave speed approach to account for air entrainment in association with check-valve closure and identify the potential for enhanced high pressure surges to result pointing to the importance of the link between velocity gradients in the transient and gate dynamics in dictating the scale of the resulting pressure peaks. They conclude that numerical simulations are crucial.

Concluding comment: 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.

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.

Concluding comment: 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.

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 surges 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/air entrainment.

8.4 SUMMARY

Air accumulations in a pipeline are both unintentional and unavoidable and in most cases cannot be quantified. 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.

9. Information from practical experience

9.1 GENERAL

Information from practical experience was provided by the project partners. A general view was that insufficient information was available for design of pipelines to prevent air problems and in some cases the guidance in "accepted" design sources was considered to be flawed. From a designer's viewpoint some of the most relevant questions are:

- What are the minimum slopes at which pipes need to be laid to avoid accumulation of air?
- Are these slopes different for downward and for upward slopes?
- Is there a need for pipelines to be laid with an undulating profile?
- In gravity pipelines is it necessary to ensure that the pipe downstream of a high point is steep enough to give a uniform depth of 2/3 (or less) of the pipe diameter? This is meant to facilitate priming and re-priming and allow air to pass up to an air valve.
- Where do air valves need to be provided?

9.2 PIPELINE PROFILE

With regard to the pipeline profile, current design practice manuals such as Pont de Musson 1994 (from company St Gobain) suggest that pipes should be laid at minimum slopes of 1:250 (for downward slope) and 1:500 (for upward slope). Minimum downward slopes of 1:300 are also used in practice. The slope of 1:500 has been suggested as the shallowest gradient that can be constructed with no risk of a backfall, which would otherwise prevent the pipe from draining. It is therefore more of a maintenance requirement than a hydraulic consideration.

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.

9.3 HYDRAULIC CONSIDERATIONS

Minimum design flow velocities to ensure air movement are usually taken in the range of 1 to 2m/s.

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 quoted half-full pipe as the condition to achieve the above.

9.4 DISTANCE BETWEEN AIR VALVES

Minimum distances between 500m and 800m are generally used to site air valves. Different air valve manufacturers offer their own recommendations but they are generally within this range.

9.5 LOCATION OF AIR VALVES

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 below apex points formed by the intersection of the pipeline with the hydraulic gradient line.

10. Conclusions from review

10.1 GENERAL

- There are no generally accepted formulae for the transport of air bubbles or pockets in pipelines and there is a wide variation between the various prediction equations.

- Dimensional analysis (Bendiksen 1983; Falvey 1980; Wisner et al 1975) has shown that the critical velocity to move an air bubble/pocket is a function of surface tension, Froude number, Reynolds number and pipe slope. Where the effects of surface tension are negligible, the critical velocity for a given pipe slope has been taken by several researchers as proportional to $(gD)^{1/2}$, where g is acceleration due to gravity and D is the pipe diameter. Wisner et al (1975) found that for n > 0.8 (n is the non-dimensional size of the air pocket, defined as $\frac{4\nabla_b}{\pi D^3}$, where ∇_b is the pocket volume, and D is the pipe diameter) the critical flow velocity was independent of pocket size. Kent's (1952) results did not show any strong dependence between the two parameters either.

- Most formulae suggested by the various researchers relate the critical velocity of the flow (i.e. the velocity of the flow that produces movement of air pockets (or bubbles), V_c, with the pipe diameter D and slope θ, as well as with the acceleration due to gravity. It should be noted however that many authors' work was carried out using a single pipe diameter and therefore dependence on D could not be established from their experiments. Figure 13, which plots $V_c /(gD)^{0.5}$ against $(\sin\theta)^{0.5}$ summarises the findings relating to air pocket/bubble flow in downward sloping pipes.

- Guidance on air valve design and location is available from several sources, namely from air valve manufacturers. However some of this information is not adequately backed up by independent, large-scale research. New research on air management in pipes of varying slopes should provide data on the actual need for the introduction of air valves along pipelines.

10.2 IMPLICATIONS FOR THE DESIGN OF LABORATORY TEST FACILITY

[The statements below were produced in the first half of 2004, prior to the design of the test rig].

- With regard to the scale of models used for investigative studies, the published literature sheds little light on this matter. However, the work by Zukoski (1966) and by Viana et al (2003) for bubbles in stationary flow suggests that viscosity and surface tension effects will be minimal in pipes of diameter 175mm or larger. Therefore scale effects are likely to be negligible.

- Little useful information was identified regarding the effect of different pipe materials on the transport of bubble or pockets in prototype or laboratory pipes. Zukoski (1966) tested bubble movement in stationary water for both sloping and vertical pipes and found no effect of pipe material for pipe diameters greater than 20mm. No information was found for the flowing water situation.

- Figure 13 suggests that there is a need to clarify the relationship between $V/(gD)^{0.5}$ and the pipe gradient, particularly for shallow gradients but also to extend tests to cover some steeper slopes to establish whether the curve is convex (as suggested by Gandenberger, 1957 and Bendiksen, 1984) or concave (as suggested by Falvey, 1980 and Kalinske and Bliss, 1943). It is proposed to carry out tests using both downward and upward pipes, up to slopes of about 45°, concentrating on the lower slopes.

- It is proposed to concentrate the laboratory investigation on air pocket movement as opposed to bubble movement given that bubbles will tend to coalesce into air pockets and these present generally more critical conditions for the design and operation of pipelines.

11. References

References on air movement and air valves:

Alves, I.N., Shoham, O., and Taitel, Y., 1993. Drift velocity of elongated bubbles in inclined pipes, Chemical Engineering Science, Vol. 48, No. 17, pp3063-3070

Andreussi, P. and Persen, L.N., 1987. Stratified gas-liquid flow in downwardly inclined pipes, International Journal of Multiphase Flow, Vol. 13, No. 4, pp565-575

A.R.I. www.arivalves.com

Asher, W.E., Karle, L.M., and Higgins, B.J., 1997. On the differences between bubble-mediated air-water transfer in freshwater and seawater, Journal of Marine Research, 55, pp813-845

AWWA, 2001. Air-release, Air/Vacuum, and Combination Air Valves, AWWA Manual M51, 1st Edition, American Water Works Association, Denver, U.S.A., pp37

Baines, W.D., and Wilkinson, D.L., 1986. The motion of large air bubbles in ducts of moderate slope. Journal of Hydraulic Research, Vol. 25, No. 3, pp157-170

Balutto, A., 1996. www.ventomat.co.za

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

Beggs, H.D., and Brill, J.P., 1973. A study of two-phase flow in inclined pipes. Journal of petroleum technology, pp607-617

Bendiksen, K.H., 1984. An experimental investigation of the motion of long bubbles in inclined tubes, Int. J. Multiphase Flow, Vol. 10, No. 4, pp467-483

Benjamin, T.B., 1968. Gravity currents and related phenomena, J. of Fluid Mechanics, 31(2). pp209-248

Bonnecaze, R.H., Eriskine, W., Jr. and Greskovich, E.J., 1971. Holdup and pressure drop for two-phase slug flow in inclined pipelines. A.I. CH.E. J., Vol 17, pp1109-1113

Bozkus, Z. and Wiggert, D.C., 1992. Hydromechanics of slug motion in a voided line. In Unsteady Flow and Fluid Transients, Bettess and Watts (eds). Balkema, Rotterdam

BSI, 1989. BS 8010-2.5:1989. Code of practice for Pipelines – Part 2: pipelines on land: design, construction and installation – Section 2.5 Glass reinforced thermosetting plastics, BSI

BSI, BS EN 752-4:1997. Drain and sewer systems outside buildings – Part 4: Hydraulic design and environmental considerations, BSI

BSI, 2000. BS EN 805:2000 Water Supply – Requirements for systems and components outside buildings, BSI

Chanson, H., 1993. Characteristics of undular hydraulic jumps, Research Report No. CE146, Department of Civil Engineering, University of Queensland, Australia, pp109

Chanson, H. and Brattberg, T., 2000. Experimental study of the air-water shear flow in a hydraulic jump. Int. Journal of Multiphase Flow, vol 26 (2000) pp583-607.

Chanson, H. and Qiao, G.L., 1994. Air bubble entrainment and gas transfer at hydraulic jumps. Research Report No. CE149, Department of Civil Engineering, The University of Queensland, Brisbane, Australia

Corcos, G., 2003. Air in water pipes, Agua Para La Vida, 2nd Edition, www.aplv.org

Davies, R.M. and Taylor, G.I., 1950. The mechanics of large bubbles rising through liquids in tubes, Proc. Royal Society London, A 200, 375-390

Dawson, P., 1980. The effect of air in a rising main. Proc. Symposium on Pumping in Practice, Runcorn, 20 Feb 1980, published in Public Health Engineer

Dewhirst, R.A., 1991. Optimising the use of air valves in piped water systems, Masters of Engineering Thesis, Department of Civil Engineering, University of Auckland, Auckland, New Zealand

Douglas, J.F., Gasiorek, J.M. and Swaffield, J.A., 1998. Fluid Mechanics, Longman, 3rd Edition, pp818

Dukler, A.E., 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

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

Edmunds, R. C., 1979. Air binding in pipes, Journal AWWA, Water Technology/Distribution, pp273-277

Ervine, D.A., 1998. Air entrainment in hydraulic structures: a review. Proc. Instn Civ. Engrs Wat., Marit. and Energy, Vol. 130, Sept, pp142-153

Falvey, H.T., 1980. Air-water flow in hydraulic systems, Bureau of Reclamation, Engineering monograph No. 41

Gandenberger, W., 1957. Uber die wirtshaftliche und betriebssichere Gestaltung von Fernwasserleitungen, R. Oldenbourg Verlag, Munich, Germany Design of overland water supply pipelines for economy and operational reliability (rough translation by W.A. Mechler, discussion of "Factors influencing flow in large conduits.", Report of the Task Force on Flow in Large Conduits of the Committee on Hydraulic Structures, ASCE, Vol.92, No. HY4, 1966.

Hansen, E.A., 1986. Two Phase Flow in Pipelines and Risers, Series Paper 40, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark

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

Issa, R.I. and Kempf, M.H.W., 2003. Simulation of slug flow in horizontal and nearly horizontal pipes with the two-fluid model, International Journal of Multiphase Flow, Vol. 29, pp65-95

James, W. and Silberman, E., 1958. Two-phase flow studies in horizontal pipes with special reference to bubbly mixtures., Technical Paper No. 26, Series B, St Antony Falls Hydraulics Laboratory, University of Minnesota, Minnesota, pp63

Kalinske, A.A. and Bliss, P.H., 1943. Removal of air from pipelines by flowing water, ASCE Vol. 13, No. 10, pp480-482

Kalinske, A.A, Robertson, J.M., 1943. Closed conduit flow, ASCE Vol. 108, pp1453-1516

Kennison, K.R., 1933. The design of pipe lines. Journal of NEWWA, 47:27

Kent, J.C., 1952. The entrainment of air by water flowing in circular conduits with downgrade slopes. Doctoral thesis, University of California, Berkley, California

Kobus, H., 1991. Introduction to air-water flows. In Air entrainment in free-surface flows (ed) Ian Wood, IAHR Hydraulic structures design manual, AA Balkema, Rotterdam pp1-28

Lin, P.Y. and Hanratty, T.J., 1987. Effect of pipe diameter on flow patterns for air-water flow in horizontal pipes, International Journal of Multiphase Flow, Vol. 13, No. 4, pp549-563

Liou, C.P. and Hunt, W.A., 1996. Filling of a pipeline with undulating elevation profiles, ASCE, Journal of Hydraulic Engineering, Vol. 122, No. 10

Little, M.J., 2002. Air Transport in Water and Effluent Pipelines, 2nd International Conference on Marine Waste Discharges, Istanbul, September 16-20

Martin, C.S., 1970. Vertically downward bubbly and slug flow of an air-water mixture in a pipe. Bericht Nr. 511, Institut für Hydromechanik, Der Universität Karlsruhe, Karlsruhe, Germany

Metcalf and Eddy Inc., 1991. Wastewater engineering. Treatment, Disposal and Reuse. Irwin/McGraw-Hill, USA, ISBN 0 07 041690 7.

Mosvell, G., 1976. Luft I utslippsledninger (Air at outfalls), Prosjektkomiteén for rensing av avløpsvann (Project committee on sewage), PRA report 8, NIVA (Norwegian Water Institute), Oslo, 1976 (in Norwegian)

Rabben, S.L., Els, H., and Rouve, G., 1983. Investigation on flow aeration at offsets downstream of high-head control structures, Proc. 20th IAHR Congress, Moscow, USSR, Vol. 4, pp354-360

Rajaratnam, N., 1967. Hydraulic Jumps, Advances in Hydroscience, Ed. V.T. Chow, Academic Press, New York, USA, vol. 4, pp197-280

Reader, R.A. Kennard, M.F., and Hay, J., 1997. Valves, pipework and associated equipment in dams – guide to condition assessment, CIRIA Report 170, CIRIA, pp160

Richards, R.T., 1957. Air binding in large pipe lines flowing under vacuum. Journal of the Hydraulics Division, ASCE, Vol. 83, No. HY6, paper 1454, pp1-10

Rouhani, S.Z. and Sohal, M.S., 1983. Two-phase flow patterns: a review of research results. Progress in nuclear Energy, Vol. 11, No. 3 pp219-259

Runge, D.E. and Wallis, G.B., 1965. AEC Rept. NYO-3114-8 (EURAEC-1416)

Salih, .M.A., 1980. Entrained air in linearly accelerating water flow, ASCE, Journal of the Hydraulics Division, Vol. 106, HY 10, p1595-1605

Stanislav, J.F., Kokal, S., and Nicholson, M.K., 1986. Intermittent gas-liquid flow in upward inclined pipes, International Journal of Multiphase Flow, Vol. 12, pp325-335

Suo, M. and Griffith, P., 1963. Paper no. 63-WA-96, ASME

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

Taitel, Y. and Dukler, A.E. 1987. Effect of pipe length on the transition boundaries for high-viscosity liquids, Int. J. Multiphase Flow, Vol. 13, No. 4, pp577-581

Taitel, Y., Sarica, C., and Brill, J.P., 2000. Slug flow modelling for downward inclined pipe flow: theoretical considerations, International Journal of Multiphase Flow, Vol. 26, pp833-844

Twort, A.C., 1963. A textbook of water supply, Edward Arnold Publishers, London

van Vuuren, S.J., 2001. The importance of the correct sizing and location of air valves. Pump and valve summit, (location unknown)

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

Viana, F., Pardo, R., Yanez, R., Trallero, J.L., Joseph, D.D., (2003). Universal Correlation for the rise velocity of long gas bubbles in round pipes, Journal of Fluid Mechanics, vol. 494, pp379-398

Wallis, G.B. 1969. One-dimensional Two-phase Flow. McGraw Hill, New York, U.S.A.

Walski, T.M., Barnhart T., Driscoll J. and Yencha R., 1994. Hydraulics of corrosive gas pockets in force mains. Water Environment Research, Vol. 66, No. 6, Sept/Oct, pp772-778

Willis, J., 1990. Design and positioning of air valves, South African Institution of Civil Engineers

Whitsett, A.M. and Christiansen, L.E., 1969. Air in transmission mains, Journal of AWWA, 61:11:592, Nov 1969

Wisner, P.E., Mohsen, F.N. and Kouwen, N., 1975. Removal of air from water lines by hydraulic means. ASCE, Journal of the Hydraulics Division, Vol. 101, HY2, pp243-257

Woods, B.D., Hurlburt, E.T., and Hanratty, T.J., 2000. Mechanism for slug formation in downward inclined pipes, International Journal of Multiphase Flow, Vol. 26, pp977-998

Zheng, G. Brill, J.P. and Taitel, Y., 1994. Slug flow behaviour in a hilly terrain pipeline, International Journal of Multiphase Flow, Vol. 20, no. 1, pp63-79

Zukoski, E.E., 1966. Influence of viscosity, surface tension and inclination on motion of long bubbles in closed tubes, J. of Fluid Mechanics, 25(4), pp821-837

References on pressure transients:

Abreu, J.M. and De Almeida, A.B., 2000. Pressure transient dissipative effects: a contribution for their computational prediction, Proc 8th Int Conf on Pressure Surges – Safe Design and Operation of Industrial Pipe Systems, pp499-517.

Anderson, A., 2000. Celebrations and challenges – waterhammer at the start of the 20th and 21st centuries, Proc 8th Int Conf on Pressure Surges – Safe Design and Operation of Industrial Pipe Systems, pp317-322.

Baker, P.J. and Ramos, H., 2000. Selection of transient analysis software for pipeline design – towards a European standard, Proc 8th Int Conf on Pressure Surges – Safe Design and Operation of Industrial Pipe Systems, pp249-259.

Bergant, A., Bournaski, E., Arregul, F. and Kruisbrink, A., 2004. Column separation measurements in a large scale experimental apparatus, Proceedings of the 9th International Conference on Pressure Surges – The practical application of surge analysis for design and operation, British Hydromechanics Research Group (BHRG), Chester, UK, March, pp589-604.

Borga, A., Ramos, H., Covas, D., Dudlick, A. and Neuhaus, T., 2004. Dynamic effects of transient flows with cavitation in pipe systems, Proceedings of the 9th International Conference on Pressure Surges – The practical application of surge analysis for design and operation, British Hydromechanics Research Group (BHRG), Chester, UK, March, pp605-617.

Brunone, B., 1999. European standards for pipelines and pressure transients, ASCE Journal of Hydraulic Engineering, Vol 125, Pt 3, pp221-222.

Burrows, R., 2003. A cautionary note on the operation of pumping mains without appropriate surge control and the potentially detrimental impact of small air pockets, Paper submission for IAHR / IWA International Conference – PEDS-2003 – Valencia, Spain, April 22nd-25th.

Burrows, R. and Qiu, D.Q., 1995. Effect of air pockets on pipeline surge pressure, Proceedings of the Institution of Civil Engineers, Journal of Water, Maritime and Energy, Volume 112, December, Paper 10859, pp349-361.

Burrows, R. and Qiu, D.Q., 1996. The effect of air pockets on pressure surge in sewage rising mains, Hydrodynamics, (Eds.) Chang, Lee and Leung, Balkema, ISBN 90 54 10 860 6, pp1193-1198.

Chaiko, M.A. and Brinckman, K.W., 2002. Models for Analysis of Water Hammer in piping with Entrapped Air, Journal of Fluids Engineering – Transaction of the ASME, Volume 124, pp194-204.

Covas, D., Graham, N., Maksimovic, C., Kapelan, Z., Savic, D. and Walters, G., 2003. An Assessment of the Application of Inverse Transient Analysis for Leak Detection: Part II - Collection and Application of Experimental Data, Proceedings of Computer Control for Water Industry (CCWI), Advances in Water Supply Management, London (U.K.), C. Maksimovic, D. Butler and F. A. Memon (Eds.), pp79-87.

Dawson, P.A. and Fox, J.A. 1983. Surge analysis and suppression techniques for a water supply scheme – a case study, Transactions of the Institute of Measurement and Control, Volume 5, Issue 4, pp134-142.

De Martino, G., Giugni, M. and Viparelli, M. 2000. Pressure surges in water mains caused by air release, 8th International Conference on Pressure Surges - Safe Design and Operation of Industrial Pipe Systems, pp147-159.

Dudlik, A., Schluter, S., Hoyer, N. and Prasser, H-M, 2000. Pressure surges – experimental investigations and calculations with software codes using different physical models and assumptions, Proc 8th Int Conf on Pressure Surges – Safe Design and Operation of Industrial Pipe Systems, pp279-289.

Falk, K. and Gudmundsson, J.S. 2000. Waterhammer in high-pressure multi-phase flow, Proc 8th Int Conf on Pressure Surges – Safe Design and Operation of Industrial Pipe Systems, pp41-54.

Fujii, T. and Akagawa, K. 2000. A study of water hamer phenomena in a one-component two-phase bubbly flow, JSME Int Journal Series B-Fluids and Thermal Engineering, Vol 43, Pt 3, pp386-392.

Fox, J.A., 1977. Hydraulic analysis of unsteady flow in pipe networks, MacMillan Press, London.

Fuertes, V.S., Arregui, F., Cabrera, E. and Iglesias, P.L., 2000. Experimental setup of entrapped air pockets model validation, 8th International Conference on Pressure Surges - Safe Design and Operation of Industrial Pipe Systems, pp133-145.

Hunt, S., 2004. Practical design considerations for undulating sewage pumping mains, Proceedings of the 9th International Conference on Pressure Surges – The practical application of surge analysis for design and operation, British Hydromechanics Research Group (BHRG), Chester, UK, March, pp635-644.

Huygens, M., Verhoeven, R. and Van Pocke, L., 1998. Air entrainment in water hammer phenomena, Advances in Fluid Mechanics II, Volume 21, pp273-282.

Jang, W.L. and Aral, M.M., 2003. Concentration evolution of gas species within a collapsing bubble in a liquid medium, Environmental Fluid Mechanics, Vol 3, Pt 3, pp173-193.

Jonsson, L., 1985. Maximum transient pressures in a conduit with check valve and air entrainment, Proceeding of the International Conference on the Hydraulics of Pumping Stations, British Hydromechanics Research Association, Manchester, pp55-76.

Kapelan, Z., Savic, D., Walters, G., Covas, D., Graham, N., and Maksimovic, C., 2003. An Assessment of the Application of Inverse Transient Analysis for Leak Detection: Part I - Theoretical Considerations, Proceedings of Computer Control for Water Industry (CCWI), Advances in Water Supply Management, London (U.K.), C. Maksimovic, D. Butler and F.A. Memon (Eds.), pp71-78.

Lai, A, Hau, K.F., Noghrehkar, R, Swartz, R., 2000. Investigation of waterhammer inpiping networks with voids containing non-condensable gas, Nuclear Engineering and Design, Vol. 197, Pts 1 and 2, pp61-74.

Larsen, T., 1992. Water hammer at pump shut-down (WHPS), Software user guide, Torben Larsen Hydraulics, Aalborg, Denmark.

Larsen, T. and Burrows, R., 1992. Measurements and computations of transients in pumped sewer plastic mains, Proceedings of the BHR Group / IAHR International Conference on Pipeline Systems, Manchester, pp117-123.

Lee, N.H. and Martin, C.S., 1999. Experimental and Analytical Investigation of Entrapped Air in a Horizontal Pipe, Proceedings of the Third ASME/JSME Joint Fluids Engineering Conference, July 18th-23rd, San Francisco, CA.

Lee, T.S., 1994. Numerical modelling and computation of fluid pressure transients with air entrainment in pumping installations, Proceedings of the International Journal for Numerical methods in Fluids, Volume 19, Issue 2 - July 30th, pp89-103.

Lee, T.S., 1999. Air Influence on hydraulic transient on fluid systems with air valves, Journal of Fluids Engineering – Transactions of the ASME, Volume 121, Part 3, pp646-650.

Lee, T.S. and Leow, L.C., 2001. Numerical study on effects of check valve closure flow conditions on pressure surges in pumping station with air entrainment, International Journal for Numerical Methods in Fluids, Volume 35, part 1, pp117-124.

Lee, T.S., Low, H.T. and Weidong, H., 2003. The influence of air entrainment on the fluid pressure transients in a pumping installation, Int. Journal of Computational Fluid Dynamics, Vol 17, Pt 5, pp387-403.

Lee, T.S. and Pejovic, S., 1996. Air influence on similarity of hydraulic transients and vibrations, Journal of Fluid Engineering- Trans ASME, Vol 118, Pt 4, pp706-709.

Leow, L. C. and Lee, T.S., 1998. Effects of air valve on pressure surges during pumping trip in pumping station, Proceedings of the XIX IAHR Symposium on Hydraulic Machinery and Cavitation, Volumes 1 and 2, pp556-563.

Low, H.T. and Lee, T.S., 1998. Fluid pressure transients with air entrainment, Proceedings of the XIX IAHR Symposium on Hydraulic Machinery and Cavitation, Volumes 1 and 2, pp656-664.

Kajaste, J., 1998. Experiences in simulating pipeline dynamics in large-scale mechatronic fluid power systems, Proc. ICMA'98 – Advanced Mechatronics: First-Time-Right, Vols 1 and 2, pp789-803.

Martin, C.S., 1976. Entrapped air in pipelines, Proceedings of the Second International Conference on Pressure Surges, British Hydromechanics Research Association, The City University, London, September 22nd – 24th, Paper F2, F2-15 - F2-28.

Martin, C.S. and Lee, N.H., 2000. Rapid expulsion of entrapped air through an orifice, 8th International Conference on Pressure Surges - Safe Design and Operation of Industrial Pipe Systems, pp125-132.

Nalluri, C. and Featherstone, R.E., 2001. Civil Engineering Hydraulics – 4th Edition, Blackwell Science, UK.

Ngoh, K.L. and Lee, T.S., 1998. Air influence on pressure transients with air vessel, Proc XIX IAHR Symp on Hydraulic Machinery and Cavitation, Vols 1 and 2, pp665-672.

Prado, A. and Larreteguy, A.E., 2002. A transient shear stress model for the analysis of laminar water-hammer problems. Journal of Hydraulic Research, Volume 40, 2002.

Purcell, P.J., 1997. Case study of check valve slam in rising main protected by air vessel, ASCE Journal of Hydraulic Engineering, Vol 123, Pt 12, pp1166-1168.

Rachid, F.B.F. and Mattos, H.S.C., 1998a. Modelling of pipeline integrity taking into account the fluid-structure interaction, Int. Journal for Numerical Methods in Fluids,, Vol 28, Pt 2, pp337-355.

Rachid, F.B.F. and Mattos, H.S.C., 1998b. Modelling the damage induced by pressure transients in elasto-plastic pipes, Meccanica, Vol 33, Pt 2, pp139-160.

Rachid, F.B.F. and Mattos, H.S.C., 1999. On the suitability of the low Mach number assumption in the modeling of the damage induced by pressure transients in piping systems, Journal of Fluids Engineering – Trans. ASME, Vol 121, Pt 1, pp112-117.

Stewardson, D., Brunone, and Ferrante, M., 2000. Using experimental design to determine transient pressure behaviour, Proc 8th Int Conf on Pressure Surges – Safe Design and Operation of Industrial Pipe Systems, pp611-623.

Tan, S.K. and Zhou, Z.X., 2003. Dynamic interactions between two surge vessels during a flow transient, Int Journal of Nonlinear Sciences and Numerical Simulation, Vol 4, Pt 3, pp289-306.

Thorley, A.R.D. and Enever, K.J., 1979. Control and suppression of pressure surges in pipelines and tunnels, CIRIA Report 84, Sept, CIRIA, UK.

Thorley, A.R.D., 1991. Fluid transients in pipeline systems, D and L George, UK.

Verhoeven, R., van Poucke L. and Huygens M., 1998. Waterhammer protection with air vessels – a comparative study, Advances in Fluid Mechanics II, Vol 21, pp3-14.

Wylie, E.B. and Streeter, V.L. 1978. Fluid Transients, McGraw-Hill International Book Company, New York, pp384.

Whiteman, K.J. and Pearsall, I.S., 1959. Reflux valve and surge tests at Kingston pumping station, BHRA, National Engineering Laboratory, Glasgow, Joint Report 1.

Whiteman, K.J. and Pearsall, I.S., 1962. Reflux valve and surge tests at a station, Fluid handling, XIII, pp248-250 and 282-286.

Zhou, F., Hicks, F. and Steffler, P., 2004. Analysis of effects of air pocket on hydraulic failure of urban drainage infrastructure, Canadian Journal of Civil Engineering, Volume 31, No. 1, January, pp86-94 (9).

12. Bibliography

BSI, 1970. CP 2010-2:1970 Pipelines – Part 2: Design and construction of steel pipelines in land, BSI

Cabrera, E., Fuertes, V.S., García-Serra, J., Arregui, F., Gascón, L., Palau, V., 2003. Reviewing Air Valve Selection, IAHR and IWA Pumps Electronic Devices and Systems Conference, Valencia, Spain

Cromer, S., 1937. An investigation of the flow of mixtures of water and air in vertical columns. MS Thesis, The University of Oklahoma, Oklahoma

Fasso, C.A., 1955. Experimental research on air entrainment in gated outlet works, Proc IAHR 6th Congress, Paper C26

Govier, G.W. and Omer, M.M., 1962. The horizontal pipeline flow of air-water mixtures. The Canadian Journal of Chemical Engineering, Vol. 40, No. 3, pp93-104

Irving, S.J. 1973. Aeration of Water, BHRA fluid engineering, p18

Jansen, F.E., Shoham, O., and Taitel, Y., 1996. The elimination of severe slugging – experiments and modelling. International Journal of Multiphase Flow, Vol. 22, No. 6, pp1055-1072

Kleinschroth, A., Krug, R., Siegerstetter, L.A., and Franke, P.-G., 1985. Measurements on unsteady two-phase flow in a sewerage pipeline, 21st IAHR Congress, Melbourne, Australia, Vol. 5, Theme D, pp175-178

Lara, C.D., 1955. Degayage Naturel dans les pints incline relient les aductions secondaires aux galeries en charge, Proceedings of the 6th General Meeting, International Association for Hydraulic Research, The Hague, Netherlands (in French)

Nydal, O.J., and Andreussi, P., 1991. Gas entrainment in along liquid slug advancing in a near horizontal pipe, International Journal of Multiphase Flow, Vol. 17, No. 2, pp179-189

Wilkinson, D.L., 1982. Motion of air cavities in long horizontal ducts., Journal of Fluid Mechanics, Vol. 118, pp109-122

Zhou, F., Hicks, F.E., Steffler, P.M., 2002a. Transient flow in a rapidly filling horizontal pipe containing trapped air, Journal of Hydraulic Engineering, Vol. 128, No. 6, pp625-634

Zhou, F., Hicks, F.E., Steffler, P.M., 2002b. Observations of Air-Water Interaction in a Rapidly Filling Horizontal Pipe. Journal of Hydraulic Engineering, Vol. 128, No. 6, pp635-639.

13. Acknowledgements

The authors would like to acknowledge the following people for their provision of information for this report, particularly the examples of problems encountered with air in pipelines in practical engineering applications.

Bernard Poole - MWH
Mike Little - Black and Veatch
Peter Clark - Black and Veatch
Tony Machen - Dean & Dyball
Paul Fairhurst - BP