AIR-POCKET TRANSPORT IN CONJUNCTION WITH BOTTOM-OUTLET CONDUITS FOR DAMS

Ting Liu

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ABSTRACT

Undesired air entrainment in bottom outlet conduits of dams may cause pressure transients, leading to conduit vibrations, blowback, discharge pulsation and even cavitation, and jeopardize the operational safety. Due to design limitations or construction costs, it is impossible to create an air free environment in a pressurized pipe. Therefore, it is essential to understand the air transport in enclosed pipes in order to provide guidance in bottom outlet design and operation. The commonly used criterion of the air-pocket movement in pipe flow is the water flow velocity for starting moving an air pocket, the so-called critical velocity.

In this thesis, the classical Volume of Fluid (VOF) model combined with the k-ε turbulence model is adopted for the computation of the critical velocity of a 150-mm pipe. The computed critical velocities are compared with the experimental results. The governing parameters investigated in this study include pipe slope and diameter, wall shear stress and air-pocket volume. Meanwhile, the carrying capacity (air-pocket velocity/ flow velocity) at all pipe slopes are analyzed. The simulation results of air pockets with different volumes in the bottom outlet conduit of Letten Dam in Sweden are presented in this study.

Moreover, experimental study was conducted to measure the critical velocity for a 240-mm Plexiglas pipe. The results are in agreement with the experiments performed by HR Wallingford (HRW) in 2003 in terms of the effects of pipe slope and air-pocket volume; however, the critical Froude pipe number is slightly smaller in this study. In rough pipes, a larger critical velocity is required compared with that in the smooth pipe. The removal mechanism in the rough pipe involves the successive loss of air caused by turbulence. This explains that the air-pocket size, with the dimensionless air-pocket volume n < 0.015, has little impact on the critical velocity for the rough pipe. In addition, roughness has little impact on the air-pocket velocity when it moves upstream in the downward inclined pipe. The trapped air bubbles most likely remain permanently in the rough pipe.

Keywords: Air-water two-phase flow, critical velocity, diameter effect, roughness, VOF model, bottom outlet, experiment
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## Frequently used terminology

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<tr>
<td>$V$</td>
<td>Volume of air pocket, litre</td>
</tr>
<tr>
<td>$n$</td>
<td>Dimensionless number of the air-pocket volume. $n = 4V/\pi D^3$</td>
</tr>
<tr>
<td>$v$</td>
<td>Flow velocity, m/s</td>
</tr>
<tr>
<td>$D$</td>
<td>Pipe diameter, m</td>
</tr>
<tr>
<td>$v_c$</td>
<td>Critical velocity, m/s</td>
</tr>
<tr>
<td>$u$</td>
<td>Fluid velocity, m/s</td>
</tr>
<tr>
<td>$u_i$</td>
<td>Velocity component in i-direction, m/s</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density, kg/m$^3$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Viscosity, N·s/m$^2$</td>
</tr>
<tr>
<td>$k$</td>
<td>Turbulent kinetic energy, m$^2$/s$^2$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Turbulent dissipation rate, m$^2$/s$^3$</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure, pa</td>
</tr>
<tr>
<td>$x_i$</td>
<td>Cartesian coordinate in i-direction, i=1-2, m</td>
</tr>
<tr>
<td>$F$</td>
<td>Body force, N</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity, m/s$^2$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Pipe slope, degree</td>
</tr>
<tr>
<td>$s$</td>
<td>Tangent of pipe slope $\theta$</td>
</tr>
<tr>
<td>$f_b$</td>
<td>Friction factor between air and pipe wall</td>
</tr>
<tr>
<td>$\sigma_k, \sigma_\varepsilon$</td>
<td>Turbulent Prandtl numbers for $k$ and $\varepsilon$</td>
</tr>
<tr>
<td>$S_k, S_\varepsilon$</td>
<td>User-defined source terms</td>
</tr>
<tr>
<td>$C_{\mu}$</td>
<td>A function of the mean strain and rotation rates, the angular velocity of the system rotation and the turbulence fields ($k$ and $\varepsilon$)</td>
</tr>
<tr>
<td>$S_{2q}$</td>
<td>Source term, which can be specified as a constant or user-defined mass source for each phase</td>
</tr>
<tr>
<td>$G_k$</td>
<td>Generation of turbulence kinetic energy due to mean velocity gradients</td>
</tr>
<tr>
<td>$Y_M$</td>
<td>Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate</td>
</tr>
</tbody>
</table>

**Subscript**

<p>| w | Water phase |
| b | Air bubble/pocket |</p>
<table>
<thead>
<tr>
<th>Terminology</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation</td>
<td>Refer to turbulent effect at the downstream end of a pocket resembling a hydraulic jump which causes bubbles to be ripped off. (Wisner, Mohsen &amp; Kouwen, 1975)</td>
</tr>
<tr>
<td>Entrainment</td>
<td>To describe the movement of the generated air bubbles to downstream. (Wisner, Mohsen &amp; Kouwen, 1975)</td>
</tr>
<tr>
<td>Sweeping velocity</td>
<td>Minimum mean velocity required to transport an air pocket or bubble bodily from a pipeline. (Wisner, Mohsen &amp; Kouwen, 1975)</td>
</tr>
<tr>
<td>Clearing velocity</td>
<td>Minimum velocity for clearing an air pocket out of a pipeline no matter the removal occurs by sweeping or by generation and entrainment. (Wisner, Mohsen &amp; Kouwen, 1975)</td>
</tr>
<tr>
<td>Critical velocity</td>
<td>In a pipe at full flow, the minimum velocity of the liquid (typically water) for completely removing an air pocket from a section of pipe (Little, 2006). Thus, both sweeping and clearing velocity are critical velocity.</td>
</tr>
<tr>
<td>Hovering velocity</td>
<td>Flow velocity of the liquid required to keep an air pocket stationary and stop it moving upstream. It was found by the HR Wallingford (HRW) study to average about 0.9 times of the critical velocity, ranging from about 0.85 for a 0.8° slope to about 0.93 for a 22.7° slope (Little, 2006).</td>
</tr>
<tr>
<td>Air-pocket velocity</td>
<td>The travelling velocity of an air pocket in liquid flow in pipes (Little, 2006).</td>
</tr>
<tr>
<td>Drift velocity</td>
<td>The gas bubble velocity in a stagnant liquid. The civil engineering equivalent of the drift velocity is the rise velocity or bubble rise velocity. (Pothof &amp; Clemens, 2010)</td>
</tr>
<tr>
<td>Superficial velocity</td>
<td>The average phase velocity at a full pipe cross section. There are superficial liquid velocity and superficial air velocity mentioned in this thesis.</td>
</tr>
<tr>
<td>Carrying capacity</td>
<td>Percentage of air-pocket velocity out of the flow velocity. It can be calculated by air-pocket velocity divided by water velocity.</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

There are a large number of bottom outlets in Swedish dams. Many of them were used during the construction period during the 1940s through 1970s to pass natural flow and then were converted to ordinary spillways. Some of them were originally designed as emergency spillways, and included as part of the dam discharge devices to meet the design flow (Yang et al., 2006).

Regardless of the original intention, it is necessary to examine the functionality of a bottom outlet in its flow behavior due to uncertainties during operations. These uncertainties exist:

1. A bottom outlets discharge capacity at full opening can be greater than what they originally devised for;
2. During the dam rebuilding, bottom spillways are often exposed to greater discharge;
3. Other operational conditions such as lowering the reservoir require reliability of bottom outlets;
4. Operational safety must be guaranteed without any unexpected risks such as pipe burst, personal in danger etc.

Bottom outlet functions are essential for increased operation safety and the related problems such as gate vibration, discharge pulsation etc. are mostly caused by trapped air in the conduits. Unfortunately, it is a fact that we understand surface spillways better than bottom outlets (Vischer & Hager, 1998).

Many of the bottom outlets have rarely been used since they were built. From the dam owners’ perspective, it is extremely important to increase the understanding of its hydraulic condition and phenomena which are in connection with bottom outlet operation. There is also a need to increase our knowledge by investigating the problems and their causes.

1.1 Objectives and scope

The overall aim of this thesis is to investigate air transport in pipe flow and especially how the pipe dimension, pipe slope and roughness can affect air transport. I will especially review and try to explain certain disagreements among previous studies. The motive was to provide guidance for bottom outlet design in terms of avoiding air accumulation and/or to minimize the negative impact of entrained air on the bottom outlet structure.

The present research focuses on the investigation of movements of a single air-pocket in pipe flow. As the flow pattern theory is usually experimentally based and results are drawn from the tests in small pipes while the dimension of bottom outlet is quite large. Thus, effect of varying diameter is one focus in this study.

Moreover, effects of pipe roughness, especially the isolated roughness such as protruding joint and irregularities in the tunnels, on air transport are also investigated.

Based on the abovementioned motivations and present understandings, the principal purpose of the study is to investigate the impact of governing parameters such as pipe slope, wall roughness, and air-pocket size on air-pocket transport in conjunction with bottom outlet operations by numerical methods (Paper I) and experimental tests (Paper II & III).

1.2 Disposition of the thesis

In the background part (chapter 2), a review of the theory of air-water two-phase flow is presented in relation to dam hydraulics. Previous studies on air-pocket transport in a pipe flow are also reported.

The main part of this thesis includes numerical modeling and experimental tests:

- The modeling of the air pocket transport in enclosed pipes using FLUENT is shown in chapter 3. The applied air-water two-phase model, which is a combination of Volume of Fluid (VOF) and k-epsilon turbulence model, is introduced. The results and discussion include the modeling of critical velocity at different pipe slopes and its comparison with experiments. Governing parameters are discussed and the
relation between the water and air-pocket velocity is also simulated. A case study of a bottom outlet conduit is presented as well. All the modeling results are concluded in Paper I:

- Experimental test of air-pocket transport in a large pipe is presented in chapter 4. Parameters studied include pipe slope, pipe diameter, roughness and air-pocket volume. Full results and discussion can be found in Paper II &III.

The main conclusions are presented in chapter 5 and future research is suggested in chapter 6.

In the Appendix, three papers and complementary photos of the experiment set-up, instrumentation and results on air-pocket shape are attached.

2 BACKGROUND

Mixed air and water can have strong interaction in many engineering projects. The interaction can be beneficial effects in terms of avoiding negative pressure in an enclosed pipe. However this is not always the case. Undesired air in the pipes and tunnels can cause damages and actions are required to remedy the damages and to improve the design with less air content (Falvey, 1980). In this chapter, the air-water two-phase flow theory is reviewed, together with the phenomena of air transport in circular pipes and the criteria to move the accumulated air out of the pipe in previous study. The air related problems with bottom outlet in practice indicate that air entrainment into the enclosed pipe can be very dangerous.

2.1 Air-water two-phase flow

Air-water two-phase flow in pipes has been investigated by many researchers since early 1950s (Rouhani & Sohal, 1983). Most of the publications examined two-phase flow patterns and their transition including the characteristics and computational problems. The industry for transportation of gas and oil mixtures, in the flow of steam and water in boiler tubes, steam generators and in Boiling Water Reactors have shown a particular interest (Rouhani & Sohal, 1983). Moreover, air-water flow is also of great interest within hydropower industry due to inevitable air in the hydraulic structures, such as in pipes and tunnels for spilling water or leading water to turbines.

2.1.1 Flow pattern/ regime

Differing from single-phase flow, two-phase flow has a respective distribution of the liquid and vapor phases in the flow channel. The respective distributions are observed to have particular identifying characteristics and are defined as two-phase flow patterns. It is important to be able to make predictions of flow pattern and their transitions as heat transfer coefficients and pressure drops in the flow are closely related to the local flow pattern (Thome, 2007).

Based on the theoretical research and literature reviews by Collier (1981), Ruder & Hanraty (1990), Rouhani & Sohal (1983), Alves, Shoham & Taitel (1993), Coleman & Garimella (1999), Estrada (2007) and probably their earlier papers, the flow pattern can be categorized into four types of flow regimes: stratified, annular, intermittent and dispersed (Fig. 1).

**Stratified flow:** It is a pattern with the liquid flowing along the bottom of the pipe and gas along the top, at relatively low flow rates of vapor and liquid. This flow pattern is described as stratified smooth flow due to the smoothness of the inter-surface. With increasing the gas velocity, instability of the liquid surface gives rise to waves that travel in the direction of the current, thereby, stratified wavy flow forms.

**Annular flow:** As the gas velocity increases further from stratified wavy flow, it will result in a formation of a gas core with a thicker liquid film at the bottom of the pipe than at the top. The liquid film may be continuous around the periphery of the duct. A spray or droplet flow pattern, where the majority of the flow was entrained in the gas core and is carried as dispersed droplets, is also observed.

**Intermittent flow:** it is characterized by the alternate appearance of slugs and gas bubbles in the pipes. The major difference
between *elongated bubble flow* (plug flow) and *slug flow* is that in the elongated bubble flow there are no entrained gas bubbles in the liquid slugs.

**Dispersed flow**: Dispersed bubble flow usually occurs at high liquid flow rates. The liquid phase is continuous while the gas phase is distributed as discrete bubbles. The bubbles tend to travel in the upper half of the conduit. This pattern is sometimes called *froth flow*.

In horizontal pipe, the gravity on air and water will drive the lighter phase – gas to the upper part, while in vertical concurrent flow, the flow pattern shows a more symmetric form. The basic flow patterns are similar to the horizontal flow patterns. Fig. 2 shows some of the most commonly observed two-phase flow patterns in vertical pipes.

The qualitative description of the above flow patterns in horizontal and vertical flow are not the only ones that are observed or generally accepted by all investigators. There are 84 different flow patterns suggested by Simpson et al. (1975). This indicated the complexity of the two-phase flow. However, the flow patterns mentioned above provide an overview of two-phase flow regimes.

Pipe slope is an important factor affecting the flow pattern. Omni-angle flow-pattern maps were given and a detailed calculation scheme on how to determine flow patterns for gas–liquid flow in tubes was proposed (Fig. 3) (Oliemans & Pots, 2006). The flow-pattern map in its most generalized form is incorporated in computer codes for the design of two-phase gas-pipelines and well tubing. With such a code, one can generate a map in which, for a certain pipe inclination \( \theta \), the occurrence of a flow pattern is determined by the Densimetric Froude numbers for liquid and gas \( (F_L\text{ and }F_G)\). With the help of the generated flow pattern map (Fig. 4) at a given pipe slope, one can predict the likely flow pattern in the corresponding pipe system by knowing the basic fluid properties and system set-up.

In an example of a 101.6-cm pipe with gas-oil flowing at 150 bars, an overview of the occurrence of two-phase flow patterns at various pipe inclinations from \(-90^\circ\) to \(90^\circ\) was computed with the code.

The flow-pattern map of a gas-oil flow in the pipe at \(5^\circ\) inclined downwards is computed with the help of the code and presented (Fig. 4) (Oliemans & Pots, 2006).

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**Fig. 1 Description of flow regimes and patterns in horizontal concurrent flow** (Coleman & Garimella, 1999).
Fig. 2 Flow patterns in vertical concurrent flow (Rouhani & Sohal, 1983).

Fig. 3 Two-phase flow-pattern map flowchart (Oliemans & Pots, 2006).
Air-pocket transport in conjunction with bottom-outlet conduits for dams

2.1.2 Possible flow pattern in hydraulic structures

Of the vapor-liquid two-phase systems, we are concerning about air and water. As we know, air brought into hydraulic structures by high-velocity water has a low flow rate compared to the water flow rate. By knowing the pipe diameter and slope, a flow map of air-water two-phase flow can be computed as well using the method proposed above. However, for simplicity, a rough estimation is made based on the flow map (Taitel & Dukler, 1976). Flow patterns of distinct interest in the pipe design, includes bubble/plug flow and slug flow (Lauchlan et al., 2005). Furthermore, according to the experiments by (Pothof & Clemens, 2010), four types of flow patterns were observed in downward pipe flow with around 1 m/s superficial liquid velocity and very small superficial air velocity, stratified flow, blow-back flow, Plug flow and Bubbly flow. Thus, transition between the flow patterns provides criteria to estimate air-water interfacial phenomenon.

2.2 Air entrainment in bottom outlet conduits

Mixed air-water flow occurs in open channels, closed conduits and free fall water flow. Different mathematical models are required for simulating different flow situations.

A bottom outlet can be a pressurized conduit when the conduit flows full. In some other designs, the flow is aerated by an aerator in the tunnel giving a free surface. In this case, it is regarded as open channel flow. The former design type is considered in this study.

2.2.1 Bottom outlet

A bottom outlet of a dam is primarily a safety structure. It is used for emptying a reservoir, flushing sediment and diverting discharge in addition to surface spillways (Vischer & Hager, 1998). It is a design requirement to have bottom outlet in many countries for safety reasons.

A type of bottom outlet with a long spill conduit is examined in this study (Fig. 5). The gate is located at the bottom of the reservoir. The full reservoir water level at the
conduit entrance leads to high water velocity in the bottom outlet conduit.

2.2.2 Source of air and air pocket formation

Air may enter the tunnels or conduits from the shaft/gate or be enclosed from the submerged outlet downstream. Air can be brought into the pipes due to the drag force of flowing water, or during the filling process.

Air bubble are small droplets of air with ellipsoidal shape entrapped in water by turbulent action such as a hydraulic jump or the impact of a falling nappe of water, ranging from 1 mm to 5 mm (Wisner, Mohsen & Kouwen, 1975). According to nomenclature found in the literature, air pockets are distinct from air bubbles with diameters of a few mm, since their volumes range from less than 6 per cent of one diameter's length of pipe to more than one diameter's length of pipe, i.e. \( n < 0.06 \) to \( n > 1 \), where \( n = 4V/\pi D^3 \), \( V \) is air-pocket volume and \( D \) is pipe diameter (Little, 2006).

If the air bubbles couldn’t transport with the water flow and thereby accumulates at the top of the conduit or higher points of the pipeline, air pockets will form when bubbles join together. The air transport capacity in the water in enclosed pipelines depends mainly on the water flow and the buoyancy force (Pozos et al., 2010). Air bubbles are more ready to move with the water since its buoyancy force long the flow direction is smaller than the air pocket. Therefore, air pockets affect the transport capacity of air more in pipe flow because air accumulation will cause larger water head loss and unsteady flow.

2.2.3 Problems in bottom outlets caused by trapped air

Many Swedish dams have bottom outlets. However, most of them are no longer used after construction, partially because undesired air in the pressurized system has negative effects and cause problems resulting in serious damages.

The problems include reduced discharge capacity of bottom outlets at full gate opening, vibrations of the gates/conduits and pulsations at the discharge in the downstream and cavitation in the conduits. All of these would jeopardize the safety operation of bottom outlet. The operational safety must be guaranteed without unexpected risks. The reliability of bottom outlets is required.

An inventory of bottom outlets in Sweden included 38 dams (Dath & Mathiesen, 2007). The discharge capacity of bottom outlets is usually determined with the help of physical scale-model tests or computations. Around half of these 38 bottom outlets were tested with scaled models. The problem with computations to find out the discharge capacity is that the calculations are correct at the maximal discharge. Problems associated with partially pressurized flow would occur, leading to numerically incorrect results.

In the investigations, 8 out of 9 detected problems during the bottom outlets operations were directly related to air as shown in Table 1.

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**Fig. 5 A longitudinal profile of bottom outlet with long conduit.**
Air-pocket transport in conjunction with bottom-outlet conduits for dams

Pressure transients

Conduit vibrations and blowback may occur when there is pressure transients produced in the bottom outlet. Guo and Song (1991) studied the hydrodynamics of drop shafts under transient flow conditions and reported several blowouts of manhole covers. Falvey and Weldon (2002) identified the trash rack damages at the Dillon Dam Intake because of the release of large air pockets. Zhou et al. (2002) concluded that air trapped in penstocks can induce high-pressure surges. To avoid air induced problems in pressurized tunnels, air entrainment must be minimized and under control.

Discharge pulsations

Pulsations at the discharge outlet in the downstream were observed in the bottom outlet of the Letten Dam in Sweden (Liu & Yang, 2011). The bottom outlet conduit is horizontal, 2.55 m in diameter and about 110 m in length (Fig. 5). The downstream outlet is submerged so the whole conduit is pressurized. Problem was observed when the bottom outlet was used on 2006/11/24 (Fig. 6).

The possible reason is that air is brought into the bottom outlet conduit by high water velocity from the intake tower but cannot be continuously removed under the operation condition as air bubbles (Liu & Yang, 2011). Air pocket forms due to the build-up of air bubbles along the roughness inside the conduit and are released when the flow velocity is high enough under the air pocket. Pulsations happened when the large air pockets are released.

Cavitation

Cavitation is a result of the formation of a bubble or void in liquid. It usually occurs when liquid is subjected to a rapid reduction of the local pressure under constant temperature. Water flowing in hydraulic structures containing air bubbles of various sizes and with impurities would provide necessary conditions to initiate cavitation (Vischer & Hager, 1998).

If cavitation occurs close to flow boundaries, possible damage may happen. If the bubble collapses near a boundary, the pressure intensity generated by shock wave is so large that they may cause cavitation damage to the solid boundary. The damaging process starts at the downstream end of the collapsing cavitation bubbles on the structure surface. An elongated hole is formed on the boundary surface after a while. Then the hole grows larger and larger within minutes, meanwhile, the impacting area cracks and the fallen pieces are swept away by the flow. The damage can be enormous since only a very short time period is needed for destroying the structures. Cavitation damage of an 11 m-deep hole occurs in the spillway invert of the left tunnel of Glen Canyon dam in USA (Fig. 7).

2.3 Air pocket transport in enclosed pipe

As described by many researchers, air pockets can accumulate at summits of water lines by air entrainment (Estrada, 2007). The problems can be devastating. There are two ways to remove the air, either by hydraulic means or by mechanic means through installation of, e.g. air valves and/or aerators at the right location. The latter has a high cost but usually efficient.

Study on a single air pocket in pipe flow can be the simplest way to understand the air pocket transport in pressurized pipes. However, disagreements exist among various investigators and there may be parameters which are neglected but should have an important influence on air pocket transport in the pressurized pipes.

| Table 1 Reported problems in bottom outlets (Dath & Mathiesen, 2007) |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|
| Type                        | A   | B   | C   | D   | E   | Other | Total |
| Reported problems           | 1   | 4   | 1   | 1   | 2   | 0     | 9     |
| Reported problems directly  | 1   | 4   | 1   | 0   | 2   | 0     | 8     |

Type A: rock tunnel bottom outlet. Type B: shaft bottom outlet with partial pressurized water way. Type C: bottom outlet culvert. Type D bottom outlet without or with very short waterway. Type E: combined surface and bottom outlet.
Fig. 6 Air release from the bottom outlet of Letten Dam, Sweden.

Fig. 7 Damages of tunnel due to cavitation of Glen Canyon dam in USA (Falvey, Cavitation in chutes and spillways, 1990).

Fig. 8 Forces acting on air pocket in flowing water (arrow 1: flow direction; arrow 2: drag force; arrow 3: buoyancy force; arrow 4: wall shear stress).

2.3.1 Forces on an air pocket in pipe flow

There are two main forces acting on an air pocket in the flow direction (Fig. 8): the drag force as a result of the flowing water, the buoyancy force in the flow direction that is dependent on the air-pocket volume and pipe slope. Besides, surface tension and viscosity effect are significant in small tubes. However, if $D \geq 175 \text{ mm}$ these two effects are likely to be small (Zukoski, 1966, Baines & Wilkinson, 1986).

Wall shear stress in two-phase flow is one of the main factors governing the air-pocket transport phenomena (Wongwises, Pornsee & Siroratsakul, 1999). However, this term is zero when the air pocket is static and is likely to be neglected for a moving air pocket estimated from dimensionless analysis (Paper II).

Surface tension and wall shear stress may be important in horizontal flows since it is the only force counteracting on the air pocket against the drag force while when the buoyancy force is missing in the flow direction.

The wall shear stress $\tau_k$ from the water and air phase ($k = w, a$) usually can be determined from the equation (1)

$$\tau_k = f_k \left( \frac{1}{2} \rho_k v_k^2 \right); \ k = w, a$$

Where empirical results are used:
- $k$ = subscript of air and water, w and a.
- $V_k$ = fluid velocity
- $\rho_k$ = fluid density
- $f_k = C_k Re_k^{-n}$
- $Re_k = D_k V_k / \nu$; $k = w, a$
\[ D_k = \text{hydraulic diameter} \]

In turbulence flow region:
\[ C_k = 0.046 \]
\[ n = 0.2 \]

### 2.3.2 Air removal by hydraulic means

Due to the negative effects of air in pressurized systems of dams, no air entrainment into the system is designed. However, this cannot be completely achieved in practice as there are limitations in the design or construction cost is too high (Wickenhäuser & Kriewitz, 2009).

In order to quantify the air pocket transport in relation to the water flow, there are several criteria developed by former researchers in terms of flow velocity, such as critical velocity, sweeping velocity, clearing velocity, hovering velocity and drift velocity. The definition for these terms can be found in the part Frequently used notations and terminology.

Many studies of air removal by hydraulic means have been conducted. Veronese (1937), quoted by Wisner et al. (1975), determined the so-called ‘limit velocity’ to sweep a bubble with limit size in a 0.1-m-diameter pipe to be 0.59 m/s. Kent (1952) indicated that, in a 100-mm-diameter (D) Plexiglas (acrylic) pipe at 0° to 45°, the ‘minimal velocity’ \( (v_{\text{min}}) \) to clear an air pocket with a given volume was

\[ v_{\text{min}} = C_0 \sqrt{gDS} \]

Gandenberger (1957) presented a graph showing the critical velocity at which air bubbles started to move downwards at various pipe slopes. His tests were conducted in glass pipes with diameters of 10.5, 26 and 45 mm. Moreover, he indicated that results from subsequent tests with a pipe diameter 500 mm, a length of 455 m and a slope of 5° were said to agree well with the reported graph. His original results were published in German, translated by Mechler (1966) and referenced by Little (2002).

Bendiksen (1984) performed similar tests in a 24.2-mm-diameter pipe sloping at -30° through horizontal to +30°, in which he concluded that air swept at the pipe Froude number \( \frac{v}{\sqrt{gD}} = 0.62 \). Pozos et al. (2010) showed, in their experiments using a 101.6-mm acrylic pipe sloped downwards, that if the dimensionless water flow rate, defined as \( \frac{Q_w}{gD^5} \), was larger than \( S = \tan \theta, \theta \) is the slope of pipe from horizontal), the air pocket moved downstream.

In the study of Escarameia et al. (2005) using a 150-mm pipe at 0° to 22.5°, design formulae of the critical velocity of air pockets with different volumes were developed as the equation (2)

\[ \frac{v}{(gD)^{0.5}} = a + 0.56 (\sin \theta)^{0.5} \]

where \( a = \)

\[ \begin{align*}
0.45 & \text{ for } n < 0.06 \\
0.50 & \text{ for } 0.06 \leq n < 0.12 \\
0.57 & \text{ for } 0.12 \leq n < 0.30 \\
0.61 & \text{ for } 0.30 \leq n
\end{align*} \]

\[ n = \text{volume of air pocket} / (\pi D^3 / 4) \]

\[ \theta = \text{pipe slope from the horizontal} \]

However, there are no general accepted formulae for the criteria of air bubbles or pocket transport in pipe flow. Disagreements exist among the various prediction equations and are mainly due to the different pipe diameters and materials and test procedures used (Lauchlan et al., 2005).

Dimensional analysis (Bendiksen, 1984, Falvey, 1980, Wisner, Mohsen & Kouwen, 1975) shows that the critical velocity for moving an air bubble is a function of surface tension, Froude number, Reynolds number and pipe slope. When surface tension is negligible, the critical velocity at a given pipe slope is proportional to \( \sqrt{gD} \).

### 2.3.3 Disagreements among previous studies

Of the abovementioned studies, researchers tried to determine the effects of parameters on air transport in flowing water, including the flow velocity, pipe slope and diameter and air-pocket size, where viscosity and surface tension effects were neglected. The main purpose is to develop formulae for hydraulic design and proper prediction of air transport in the hydraulic systems. However,
because most of the results are based on small pipes up to 150 mm or on a large pipe with only mild slopes, the deduced design formulae cannot be used to predict general situations other than these. To work out a general formula considering all the governing parameters involved is a complicated task.

The pipes in practice have much larger diameter e.g. bottom outlets can be as large as a few meters in diameter. Surface tension and viscosity are likely to be neglected under both circumstances, however, if when roughness effect takes place, a proper simplification of the forces on an air pocket may need to be reconsidered. The diameter effect that comes out during the model scaling has not been fully understood.

As concluded by Lauchlan et al. (2005), for the horizontal pipe, there appears to be the greatest confusion. When the air pocket is steady in flowing water, the corresponding wall shear stress is zero through the calculation by eq. (1). Falvey (1980) suggested that the critical velocity is zero and his work was further discussed and refereed by Mechler of Gandenberger’s work. However, it seems there is some minimum velocity greater than zero, with $v_c/\sqrt{gD}$ ranging from 0.35 to around 0.8 (Lauchlan et al., 2005).

2.3.4 Undiscussed issue

Besides, a bottom outlet usually has rough walls or irregularities along the pipe acting on the flow. The wall condition is crucial to the air-pocket transport. This effect cannot be simply captured by a roughness coefficient or Manning’s number. In addition, theories of two-phase flow are experimentally based. Therefore, the study of the roughness effect on the air-pocket transport can be a better representation of the reality.

3 Numerical Modeling of Air-pocket Transport in Pressurized Pipe

Numerical modeling is a popular way to determine the flow and pressure conditions and free from the scale effect, especially when an experiment is impossible to implement due to high cost or inconvenience. Air-water two-phase flow system has been calculated by different types of models, among which the Volume of Fluid (VOF) model is well elaborated and can be applied to describe the general movement of each phase. A modeling of flow regimes using the VOF model of two-phase co-current horizontal flow is in good agreements with Baker Chart (Schepper, Heynderickx & Marin, 2008) and this indicates that the VOF model can be adopted to simulate the air-water two-phase flow in enclosed pipes.

The applied model, the VOF model combined with the $k$-$\varepsilon$ turbulence model, is introduced in this chapter. Part of the modeling results are given here and complete results can be found in Paper I.

3.1 Numerical model

The VOF model combined with the $k$-$\varepsilon$ turbulence model is adopted for computing the critical velocity of a 150-mm pipe, inclining from 0° to 22.5°.

For computational efficiency, a model in 2D is applied as the main aim is to analyze the effects of governing parameters and to investigate air-pocket transport behaviors in pipe flows.

Mass and momentum conservation:

$$\nabla \cdot (\rho \bar{u}) = 0 \quad (2)$$

$$\nabla \cdot (\rho \bar{u} \bar{u}) = -\nabla p + \nabla \cdot [\mu (\nabla \bar{u} + \nabla \bar{u}^T)] + \rho g + \bar{F} \quad (3)$$

Turbulence $k$ – $\varepsilon$ model:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho u_j k) = \frac{\partial}{\partial x_j} \left( \left( \mu + \frac{\mu_k}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_m + S_k \quad (4)$$
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\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right] - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon}} + C_1 \frac{\varepsilon^2}{k^2} - C_3 \varepsilon^2 G_b + S_e
\]

(5)

Coupling of \( k \) and \( \varepsilon \) via

\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}
\]

**VOF model for phase coupling:**

\[
\vec{u} \cdot \nabla \alpha_q = - \frac{S_{\alpha q}}{\rho_q}
\]

(6)

For the primary-phase volume fraction

\[
\sum_{q=1}^{n} \alpha_q = 1
\]

Model constants

\[
C_1 = 1.44 \quad , \quad C_2 = 1.9 \quad , \quad \sigma_k = 1.0 \quad \text{and} \quad \sigma_\varepsilon = 1.2
\]

Where

\[
C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right]
\]

\[
\eta = S \frac{k}{\varepsilon}
\]

\[
S = \sqrt{2S_{ij}S_{ji}}
\]

3.2 Model setup

A sketch in the computational domain is set up in 2D (Fig. 9). The small rectangular inside the domain is the initial air-pocket shape with a height of 0.0045 m, which is 3\% of the pipe diameter. Initial length of the air pocket varies according to the air-pocket volume, collected from the experiment by HRW. Detailed mesh structure and numerical scheme are described in Paper I. The CFD software FLUENT that is based on the Finite Volume Method (FVM) was used for solving the equations. Computations were performed on remote parallel computers in PDC (Parallel Computer Center) at KTH.

3.3 Modeling results and discussions

The governing parameters, such as pipe slope, wall shear stress and volume of air pocket, are examined. Meanwhile, the carrying capacities at all pipe slopes are analyzed. The simulations of air pockets with different volumes in the bottom outlet conduit of Letten Dam in Sweden are also performed in this study and presented in Paper I.

The modeled critical velocities are compared with the experiments.

3.3.1 Air-pocket shape

The calculated air-pocket shapes are different between in the horizontal and inclined pipe (Fig. 10). The elongated air-pocket in the horizontal pipe and wedge-like shape in the 22.5° inclined pipe are well illustrated and agree well with the observations.

3.3.2 Computed critical velocity

A 0.00075 m wall height, half size of the first layer mesh, is applied to the upper pipe wall in the ‘smooth pipe’ scenario. The comparison between the modeled and experimental critical velocities (Fig. 11) shows the same correlations with the pipe slope, i.e., the tangent of both fitting curves are \( \sim 0.5 \), however, a 0.25 smaller for the modeled values.

The wall shear stress (Fig. 12) turns out to be 0.25 Pa for the water phase and 0 Pa for the air phase. The possible reason is that when the no-slip wall condition is applied on the upper wall, the wall shear stress distribution is calculated based on the standard wall function. The large difference between the air and water density will give wall shear stress of the air phase as 0.

![Fig. 9 Conceptual model of a 2D pipe.](image-url)
However, a non-zero wall shear stress should be considered for the air phase attaching to the upper pipe wall in the model, as this ideal situation doesn’t exist in experiments. Therefore, wall shear stress should be applied at the upper wall in modeling the air-pocket transport. The question is how to make the assumption of the wall shear stress at the air-pipe interface. An assumption is made by assuming the wall shear stress is the same for air and water phase as it is possible to realize in the software.

In Paper I, the air-pocket velocity transport in the corresponding critical velocity based on the model with wall shear stress was shown for the pipe at the inclinations of 0°, 0.8° and 2.5°. The air pocket in the horizontal pipe stops moving downstream when it is stabilized. This indicates a possible overestimation of the wall shear stress in the horizontal pipe. In the other two inclined pipes, the air pockets are able to be transported downstream.

The attempt to make assumption of the wall shear stress can be a way to approach the experiment results. Therefore, it will be further explored in the future modeling.

### 3.3.3 Carrying capacity

An interesting phenomenon was observed from the modelling of the air-pocket velocity in relation to the water velocity. The Air-pocket velocity grows with the increasing water velocity. However, the corresponding carrying capacity, as the ratio of the air-pocket velocity to the flow velocity, rises to a maximum value and then decrease and stabilized at a certain level. It is especially significant in the horizontal pipe (Fig. 13).
The carrying capacity can be used to describe the efficiency of the flow to transport air and it can be used as a criterion for design. However, the validation of this phenomenon needs to be carried out in future research.

4 Experimental test of air-pocket transport

Experiments are also carried out to measure the critical velocity for a larger pipe and to examine the diameter effect by comparing with the experiments by HRW. Furthermore, attention has been paid to the analysis of pipe roughness.

There are two types of pipe roughness, isolated and continuous. The former type can be protruding joints and irregularities on the tunnel wall, and the latter is caused by different pipe surface. Both are studied in this experiment.

Paper II and Paper III contain experimental results and the interpretations. Complementary photos of air pocket shape and movement behaviors are listed in the appendix.

4.1 Experiment set-up and instrumentation

The experiment was carried out in the hydraulic laboratory of Vattenfall R&D in Ålvkarleby, Sweden. The rig consists of an upstream tank with an overflow weir, a submerged downstream tank and a 240-mm Plexiglas pipe.

The test section of the rig inclines downwards at 0°, 9.6° (Fig. 1 A) and 18.2° (Fig. 14).

The test section is subjected to a water head of 3.0 – 3.8 m depending on the pipe slopes and a flow velocity of up to about 1.0 m/s.

After tests in the smooth pipe, roughness is applied using transparent beads with 3-mm-diameter to the upper pipe wall, covering the contact region with the air pocket (Fig. 2A). An air pocket is introduced by injecting air with syringe at the pipe intersections (Fig. 3A). The air-pocket size is directly measured by the injection syringe or by registering the dimension of the air pocket and then converted to volumes. All volumes are converted to volume at the atmospheric pressure.

After the air injection into the test section under zero or small flow rate, the flow velocity is increased gradually until the air pocket starts to move downstream. The flow rate is registered and then converted to the mean flow velocity, which is the corresponding critical velocity.

Fig. 14 Experimental set-up of the test section inclined downwards at 18.2° (arrow M: flow direction; arrow N: air injection point).
4.2 Experimental results and discussion

The critical velocities in all the three pipe slopes are measured. The air-pocket velocity in relation to the water velocity, pipe slope and roughness is measured. The effects of diameter and roughness on air-pocket transport are also investigated.

The shapes of air pockets are very long and thin in horizontal pipe (Fig. 4A) therefore it is very easy to break down. When the long air pocket breaks down into several elongated air pockets, by increasing the water velocity, an unsteady air pocket shape shows up (Fig. 5A). It is a shape that ready to release bubbles. In the contrast, an elliptical shape air pocket is stable and more ready to be moved comparing with the elongated air pockets (Fig. 6A).

4.2.1 Diameter effect

Through comparison of the measured critical velocity with that in a 150-mm pipe by HRW (Escarameia et al., 2005), diameter effect is discussed in this section.

The critical velocity in the experimental study agrees with HRW tests in terms of the impact of pipe slope and air-pocket volume. However, it is slightly smaller in the 240-mm pipe (Fig. 15). The same reduction is also observed for \( n < 0.006 \) in the 240-mm pipe.

As indicated by equation 2, a larger critical velocity is required for a larger pipe. The difference is probably caused by the scale effect (Vasil'chenko, 1986) or by a smaller reduction of the effective cross-sectional area that occurs in the larger pipe. This implies that equation 2 doesn’t give precise predictions in the 240-mm pipe, with the air-pocket size \( n \) smaller than 0.014 that is tested (Paper II).

4.2.2 Roughness effect

A rough pipe better represents the reality, especially considering about the rough tunnels.

The shape of air pocket in the rough pipe doesn’t differ much from that in the smooth pipe (Fig. 7A). However, in the horizontal rough pipe, the shape is olive-shape and the air-water interface follows the upper rough wall.

It is observed that the removal mechanism in rough pipes involves the successive loss of air due to turbulence. Therefore, the sweeping velocity doesn’t exist in this situation. The critical velocity is thereby the clearing velocity.

When roughness applied, a much larger critical velocity is required (Fig. 16), and it has weak dependence on the air-pocket size. Independence of the pipe slope is also observed in the 9.6° and 18.2° pipes, probably due to the volume lost in rough pipes.

It is difficult to remove trapped air in the pipe with a limited increase in water velocity. The trapped air bubbles remain most likely permanently in the roughness. Air accumulation at the joints is also observed in horizontal section with less air accumulated at higher water velocity (Fig. 8A).

Moreover, the velocity of air pocket moving upstream in smooth and rough pipe is compared. Test results show that pipe roughness has little influence on the air-pocket velocity. This is because the buoyancy force, which is acting on the air pocket in the downward inclined pipe, drives the air pocket to move upwards without being effectively blocked by the roughness thanks to deformation. The detailed results can be found in Paper III.

**Fig. 15** Comparison of critical velocity with regard to pipe slope with the dimensionless air-pocket volume \( n \) between 0.006 and 0.014 from tests by HRW and KTH.
5 Further Discussions

Comparing the computed results of air pocket shape (Fig. 10) with the experiment observations (Fig. 17), we can see the air pocket shape difference in inclined and horizontal pipe can be well calculated using the VOF model in FLUENT. As the air-pocket shape also represents the pressure distribution in the flow, it also indicates that the VOF model is able to give a reasonable pressure field.

It is observed that all the air can be removed by generation and entrainment when the flow velocity rises to a certain level; we call it the limit velocity \( v_{\text{limit}} \) here. It means that the effect of air-pocket volume on the...
critical velocity disappears when the air volume exceeds this limit velocity $v_{\text{limit}}$. Gandenberger (1957) points out that, for any given pipe diameter, the clearing velocity increases with bubble sizes up to $n = 1$ and thereafter is constant. We call this $n$ as critical volume $n_c$. This assumption is valid for pipe sizes greater than about 0.1 m and for air pockets $n > 1$ as claimed by Gandenberger. However, in the HRW experiments, $v_{\text{limit}}$ is observed when $n > 0.15$ approximately in the inclined pipes (Fig. 18), which was not reported in their books or published papers. Regardless of the disagreement in their researches, it can be concluded that there is such a limit velocity $v_{\text{limit}}$ that is able to break down all sizes of air pocket with volumes larger than $n_c$.

When $n \geq n_c$, air-pocket size has little impact on the critical velocity. The complete air removal can be achieved as $v_{\text{limit}}$ can produce turbulence that is strong enough to break down all sizes of air pockets (generation) and the generated bubbles/air pocket are able to be moved downstream (entrainment) under $v_{\text{limit}}$. When $n < n_c$, the critical velocity is dependent on air-pocket volume.

In the rough pipes by KTH, the measured critical velocity is also independent of air-pocket size. It is the same explanation that the intensive turbulence plays important role in the removal mechanism.

In the horizontal pipe, the volume of air pocket cannot remain large because the air pocket is elongated and a large air pocket is very easy to break down into several elongated air pockets. Therefore, both tests by KTH and HRW have a smaller air-pocket volume comparing with that in the inclined pipes.

![Fig. 18 Critical velocity in relation to the dimensionless air-pocket number $n$.](image)
6 Conclusions

In this study, air transport is investigated by numerical modeling using the VOF model and experiments for a large pipe. Governing parameters examined in both methods herein include water velocity, air-pocket size, wall condition, pipe slope and diameter. When the no-slip wall condition is applied at the upper wall, the modeled critical velocity in the smooth pipe has the same correlation with the pipe slope as the experimental results, but is smaller. The air-pocket shape agrees well with the observations in both the horizontal and inclined pipes. In addition, by making an assumption of the wall shear stress at the air-wall interface, air-pocket transport under the experimented critical velocity is calculated. The results show the air pocket stop moving downstream the 0° and 0.8° pipes when it becomes stabilized. This indicates an overestimation of the wall shear stress for 0° and 0.8° pipes. In the 2.5° downward inclined pipe, the air pocket can be removed at the experimented critical velocity. Therefore, the VOF model combined with the k-ε turbulence model can be used to simulate the general movements of the air pocket but a suitable estimation of the wall shear stress needs further investigations. Furthermore, the model in this study is performed in 2D mainly for computational time consideration but turbulence is 3D dominant. So it is of interest to perform the simulation in 3D of air-pocket transport.

The computed carrying capacity at a certain pipe slope demonstrates a maximal level or tends to reach a certain level alike a plateau with some minor fluctuations, which is especially significant in the horizontal pipe. It is an interesting result and validation is needed since the experimental velocity by KTH is not high enough to validate.

In the case study of Letten dam, a wall shear stress is assumed for the upper wall which is 2/3 of the wall shear stress in the water phase under the normal operation velocity 1.37 m/s. Results show that air pocket is moved downstream under the operation velocity. However, to explain the pulsation at the discharge, the distribution of a series of air pockets needs to be modeled as well. The experiment gives interesting results. It confirms other former researchers in terms of the effects of parameters on critical velocity, such as water velocity, air-pocket size and pipe slope. By comparing with HRW, the critical velocity for the larger pipe, D = 240 mm, is smaller than that for the D = 150 mm pipe, which is probably due to the scale effect or smaller reduction of effective cross-sectional area. Detailed explanation is presented in Paper II.

The critical level of water velocity independent of air-pocket size is observed. The removal mechanism is also similar to that in rough pipes. The critical velocity is larger in the rough pipe. However, when the air pocket moves upstream in the downward inclined pipe, there is no sign of reduction of the air-pocket velocity in the rough pipe. In fact it is the cooperation between the buoyancy force and the changeable air-pocket shape that makes the air pocket away from attaching to the roughness or the pipe surface.

However, the trapped air bubble in the roughness, especially in the horizontal pipe, is difficult to remove with a limited increase in water velocity. Permanent entrainment occurs in this condition. In addition, joint effects are observed in the horizontal pipe.

7 Future research

As mentioned before, the assumption of the wall shear stress at the air-wall interface made in the numerical modeling requires a better clarification. The experiments in Älkarleby show the importance of the wall condition. Interesting findings were drawn, leading to prospects in future research. In addition, a system of bottom outlet can be investigated instead of a single air pocket in the pipe flow.

These topics are suggested for my future research:

- Model the D = 240 mm pipe using the VOF model in 2D/3D in FLUENT.
The modeling results can be validated with the existing experimental results.

- **Model a bottom outlet system in 3D.** The whole system consists of reservoir, intake tower, bottom tunnel and outlet. Letten Dam can be used as a case study. Since air cannot be excluded from entering into the tunnel and air and water velocity together will decide the flow pattern in the bottom tunnel, it is important to know how much air entrains in different flow conditions (gate opening) as well.

- **Better establish the assumption on the wall shear stress at the air-wall interface.** The wall shear stress plays an important role in the air-pocket transport. With the suitable wall shear stress implemented in the model, a better agreement between the computed critical velocity and measured one is expected to realize.

- **Validate the limit carrying capacity of air pocket in pipe flow.** The simulation results show that there is a maximal carrying capacity, which means the air-pocket velocity will not continuously grow with increasing flow rate but goes to a limit. Higher water velocity needs to be tested in order to validate the modeling data. The purpose is to predict the maximal air transport capacity in the bottom outlet conduit given a pipe diameter and slope.

- **Investigate the geometric effect on the air-pocket transport.** Bottom outlet tunnels are usually not round in shape as water pipelines but rectangular at the bottom and round at the top (the so-called horse-shoe shape). Both modeling and experimental tests can be conducted and compared.
8 References


9 Appendix I – Complementery photos of the experiment

Fig. 1A The experimental rig with horizontal pipe.

Fig. 2A The layout of roughness. The roughness is applied using transparent beads in the area where air and pipe meets; red beads were used to describe the edge of the rough area.
Fig. 3A Air injection point. Air is injected through the valve.

Fig. 4A Top view of a 100-ml air pocket in smooth horizontal pipe under static flow, air-pocket front (up), air-pocket tail (down).
Fig. 5A The unstable shape of air pocket which is ready to release bubble to the downstream in the horizontal smooth pipe, with a narrow front and a wide tail.

Fig. 6A Stable shape of an air pocket in a horizontal pipe which has an elliptical shape, when flow velocity is lower than the critical velocity.
Fig. 7A Top and side view of a 50 ml air pocket in the rough pipe with 9.6 degree inclination.
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*Fig. 8A* Joint effect in the horizontal pipe under moderate flow rate, top view (left) and bottom view (right).