Abstract

Experiments are carried out in a test rig, consisting of a Plexiglas pipe with an inner diameter of 240 mm and an inclination of 18.2°, to investigate air-water two-phase flows in conjunction with bottom spillways. Results show that the critical velocity, which is the minimal water velocity to start moving an air pocket, in the rough pipe, is independent of the air-pocket volume; in the smooth pipe it doesn’t increase with increasing diameter as much as the previous researchers indicated. Pipe roughness doesn’t affect the velocity of the air-pocket when it moves upstream in the downward inclined pipe.

1. Introduction

Undesired air entrainment in a bottom spillway, can cause pressure transients leading to conduit vibrations and discharge pulsations, thus jeopardizing the operational safety. Among the 38 bottom outlets investigated in Sweden, 8 out of the 9 problems detected are caused by air entrainment, due to which many of them are not used any more [1].

Researches on a single air-pocket movement were performed in different pipe diameters. The criteria with regard to the flow velocity to clear air pockets out of the pipe were developed through experiments. However, the results are not fully consistent with each other or not well connected [2]. The critical
velocity or clearing velocity, which is the minimal water velocity to make an air pocket start moving downstream, is mainly dependent on the surface tension, viscosity, Froude number and pipe slope ($\alpha = \text{pipe slope with the horizontal}$). In large pipes where the surface tension can be neglected, the critical velocity for a certain pipe slope is proportional to $\sqrt{gD}$ ($g = \text{gravitation}$, $D = \text{pipe diameter}$), as concluded by Estrada [3]. However, the dependency on $D$ cannot be established as most experiments were carried out in a single diameter. Furthermore, air bubbles tend to agglomerate into air pockets at the pipe soffit; the irregularities in the pipe wall can cause air pocket to adhere [4]. This makes the effect of the pipe roughness on air-pocket movement an interesting issue to study. In this paper, the main issues examined are the diameter and roughness effects on the critical velocity in respect of air-pocket transport in pipe flows.

2. Experimental configurations

A test rig is constructed in the hydraulic laboratory of Vattenfall R&D in Älvkarleby, Sweden. The rig consists of 10 m-long transparent Plexiglas pipes with an inner diameter of 240 mm. The upstream water tank has an overflow weir that provides a constant water head. On the downstream side, the pipe outlet is submerged at a constant water level. The layout of the test section is shown in Fig. 1. The section inclines downwards at $\alpha = 18.2^\circ$ and is subjected to a water head of $H = 3.0 – 3.8$ m and a flow velocity up to about $v = 1.0$ m/s. The test section consists of a 2 m-long pipe with two metal elbows on both sides. Pipe roughness is also tested as it is an important factor affecting the air-pocket transport in pipe flows. Transparent round beads with a diameter of 3 mm are glued on the upper wall of the test section. The glued area is about 70 cm by 13 cm. The beads are applied close to each other and the area coverage rate of the beads is 81%.

The flow rate in the rig is measured with the help of an overflow weir and also with a magnetic flow meter. The velocity of air pocket is measured with stopwatch and video camera. The shape of air pocket is recorded by digital camera and video camera.

Air pocket is introduced by injecting air with syringe at the pipe intersection. The air-pocket volume $V$, either directly measured or converted to volume at the atmospheric pressure, is written in a dimensionless form [5]:

$$n = 4V(\pi D^3)$$

In the test, the dimensionless air-pocket size $n$ is $n = 0.001 - 0.014$. The critical velocity (denoted as $v_c$) is measured in the following way. First an air pocket of a certain volume is injected from the downstream of the test section. The flow rate is small so that the air pocket can rise upstream. Then the flow velocity is increased gradually until the air pocket starts moving downstream. The current water velocity is this measured which is the critical velocity for the given air pocket.

3. Results and Discussions

The critical velocity in the $18.2^\circ$ downward section is tested for both smooth and rough pipes. The shapes of the air pockets are shown in Fig. 2. The air pockets stick easily to the rough surface where beads are lower or missing, thereafter showing roughly a triangular shape, sometimes asymmetric, instead of a wedge-shaped as in the smooth pipe. Little gave the following equation for the critical velocity in smooth pipes [6]:

$$\frac{v_c}{\sqrt{gD}} = 0.56\sqrt{S} + a$$
Where, \( S = \sin \alpha \) and the term \( \alpha \) on the right-hand side is a constant depending mainly on \( n \). A similar relationship is also obtained in this study, with however somewhat different constants. Fig. 3 shows that, in the test range, the critical velocity in the smooth pipe increases with increasing air-pocket volume. However, in the rough pipe there is no such a relation between the critical velocity and air-pocket volume. The reason is that the air-removal process is different. The air pocket in the rough pipe cannot be transported downstream as a whole - it keeps losing volume while attached to the roughness. In the smooth pipe, the air-pocket volume can be transported as a whole body, despite small bubbles are rippled off from the air-pocket tail. Thus, the critical velocity in the rough pipe is regarded as the lowest value of all the measured values of \( v_c \), 0.72 m/s, due to its independency of the air-pocket volume. This also indicates that at the water velocity of 0.72 m/s, all sizes of air pockets in the rough pipe at 18.2° can be cleared out, if the pipe is long enough.

Moreover, for air pockets with \( n < 0.008 \), the critical velocity is smaller in the smooth pipe than in the rough pipe due to lower wall shear stress acting on the air pocket. If a large air pocket can exist in the smooth pipe as turbulence is weaker, \( v_c \) may be larger in smooth pipe than that in rough pipe.

HR Wallingford (HRW) performed tests on air-pocket transport in acrylic pipe with \( D = 150 \text{ mm} \) [7]. Researchers showed the critical velocity increases with increasing pipe slope. The HRW results with \( \alpha = 16.5^\circ \) and \( 22.5^\circ \) are here compared with the KTH result with \( \alpha = 18.2^\circ \). In Fig. 3, the critical Froude number, \( F_c = \frac{v_c}{\sqrt{gD}} \), in the KTH tests with \( D = 240 \text{ mm} \) is smaller than in the HRW with \( D = 150 \text{ mm} \). This indicates that the critical velocity doesn’t increase with increasing diameter as much as equation 2 indicates.

**Fig. 1.** Experimental set-up with the test section inclined at 18.2° (arrow M: flow direction)

**Fig. 2.** Shape of 20 ml air pocket in the 18.2° downward pipe (left: top view in rough pipe; middle and right: top and side view in smooth pipe) (arrow: flow direction)
For both the smooth and rough pipes, the air-pocket velocity is evaluated when the air pocket moves upstream against the flow, which occurs at low water velocity. In Fig. 4, the diagonal imply that the upward velocity in the smooth and rough pipes is the same. As the test values are close to the lines, there is no obvious sign of velocity reduction of air pocket movement in the rough pipe. The reason can be that, as observed during the tests, the effect of surface tension is strong on the air pocket upstream side (front), while the downstream side (tail) behind is characterized by a turbulence wake. When the air pocket moves upstream, the region of turbulence wake cannot attach to the roughness. If the roughness blocks the front of the rising air pocket, its shape quickly adjusts thanks to the buoyancy force and the air pocket keeps moving upstream. The roughness does not obviously affect the air-pocket velocity when it moves against the flow in the downward inclined pipe.

Fig. 3. Critical velocity in relation to air-pocket volume in smooth versus rough pipe, comparison between KTH and HRW results

![Graph showing critical velocity in relation to air-pocket volume in smooth versus rough pipe](image1)

Fig. 4. Comparison of air-pocket velocity moving upwards in smooth and rough pipes

![Graph showing comparison of air-pocket velocity moving upwards in smooth and rough pipes](image2)
4. Conclusion

The study illustrates the air-pocket transport in the 240 mm pressurized pipe downwards inclined at 18.2°. The effects of pipe diameter and roughness are tested and evaluated. The critical velocity in the rough pipe is independent of the air-pocket volume and is higher than that in the smooth pipe for air-pocket sizes smaller than $n = 0.008$. All sizes of air pockets in the rough pipe can be cleared out at the water velocity of 0.72 m/s. The critical velocity obtained by KTH doesn’t increase as much with increasing diameter as Little’s equation indicates. For air pockets moving upstream, the reduction of the air-pocket velocity in the rough pipe is not observed in a noticeable way in comparison with that in the smooth pipe.

Acknowledgments

This study is part of a PhD program in the area of dam safety financed by the Swedish Hydropower Centre (Svenskt Vattenkraftcentrum, SVC), Stockholm.

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