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Air concentration and bubble characteristics downstream of a chute aerator

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ABSTRACT

Chute aerators separate the flow of water from the bottom of a chute, and air bubbles generated in the cavity zone must go through the impact zone as they travel downstream. In this study, the air concentration and air bubble characteristics along the chute were investigated systematically by a series of model tests that eliminated the effect of the upper aeration region. It was found that the large amount of air entrained in the cavity zone was only partially entrained into the final flow. Based on the lower air discharge properties, the chute downstream of the aerator was partitioned into four reasonable zones: the cavity zone ($0 < x < L$), the impact zone ($L \le x \le L_m$), the equilibrium zone ($L_m \le x \le L_D$), and the far zone ($x > L_D$). The details of the bubble chord length and bubble frequency distributions in each zone were measured. In the cavity zone, the bubble frequency distribution was related to the air concentration by a parabolic law. In the impact zone, the air concentration decreased sharply while the bubble frequency decreased to a lesser extent. Due to the turbulent fluctuation effect, the probability of smaller bubbles increased while the probability of larger bubbles decreased as they progressed down the chute. In the equilibrium zone, the bubble frequency decreased slightly. At the cross section, the range of probability of bubble chord lengths tended to increase from the bottom to the upper surface. The distributions of the mean chord lengths followed approximately a power low distribution. A formula was provided to predict the maximum air bubble frequency in the impact and equilibrium zones.

1. Introduction

When designing large-discharge chutes, it is necessary to prevent the risk of cavitation erosion. Therefore, spillways and flood-discharging tunnels are usually equipped with a chute aerator, which is quite widely used due to its proven success as a countermeasure in the Grand Coulee Dam since 1960. Chute aerators separate the flow at the chute bottom, and air enters into the flow through the lower surface in the cavity zone due to highly turbulent eddies close to the air-water interface. Extensive experiments—mostly based on physical model investigations—have been conducted on chute aerators (Pinto, 1982a and 1982b; Rutschmann and Hager, 1990a and 1990b; Chanson, 1990 and 1993; Kramer and Hager, 2005 and 2006; Pfister and Hager, 2010a and 2011a; Wu et al., 2008).

The characteristics of the jet in the cavity zone downstream of the aerator, such as velocity distribution, air concentration and jet length, have been investigated. Chanson (1996) focused on the air concentration distribution and the velocity distribution in the cavity zone, and a formula for air concentration was presented. Pfister (2010 and 2011) investigated the air concentration characteristics in both the near and far aerator fields based on an extensive test program, and divided the air transport downstream of chute aerators into three zones: the jet zone, the reattachment and spray zone, and the far-field zone. However, the lower and upper aeration regions mix together downstream of the intersection of the lower jet with the chute bottom, even in the cavity, due to the shallow flow depth (Chanson, 1990; Pfister and Hager, 2010b and 2011a). There is also little literature on the air bubble characteristics of the lower jet downstream of the chute aerator. Several researchers (Straub and Lamb, 1953; Volkart, 1980; Clark and Turton, 1988; Chanson, 1997a; Felder and Chanson, 2011 and 2015a) investigated the air-water flow structure and the bubble size characteristics in an open channel. Chanson (1997a) indicated that the bubble sizes were larger than the Kolmogorov microscale and smaller than the turbulent macroscale. In recent investigations, Xu et al. (2010) researched the mechanism of erosion damage by the interaction of a single air bubble and a single cavitation bubble at the micro level with a high-speed dynamic acquisition and analysis system. These recent studies indicated that the air bubble size

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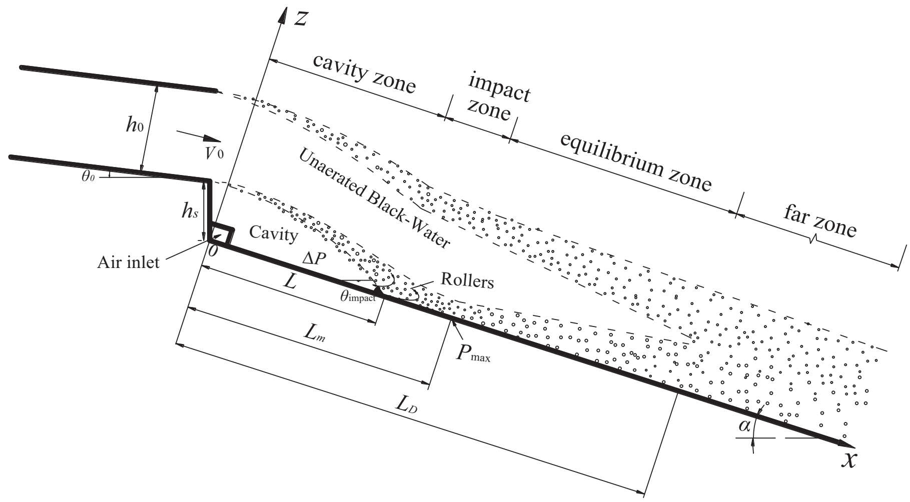

Fig. 1. Definition sketch with relevant parameters.

was a significant parameter for the mechanism of erosion damage. It must be emphasized that there is little experimental data for the lower aeration region. Therefore, further experimental studies on the air bubble characteristics of the lower jet are needed.

This study aimed to investigate the lower jet independently and to completely avoid interference with the upper aeration region. The air concentration and the distributions of bubble chord length and bubble frequency along the chute were systematically investigated using a hydraulic model. An understanding of the air concentration and bubble size downstream of the chute aerator was provided.

2. Hydraulics model

The experiments were conducted in a rectangular chute that was 0.25 m wide and 5 m long, which was fabricated from polymethylmethacrylate (PMMA). The roughness height of the chute was 0.01 mm. Water discharge up to 500 Ls^{-1} was supplied by a constant head system and measured to an accuracy of $\pm 1\%$ with a rectangular sharp-crested weir. The cavity was kept sufficiently open to the atmosphere that the pressure in the cavity was approximately equal to atmospheric pressure.

A sketch of the aerator is shown in Fig. 1. The flow to the chute was fed through a smooth convergent nozzle. The nozzle had a flat bottom that was aligned with the flume bottom, two elliptic convergent sidewalls and an elliptic convergent roof. The nozzle exit was 0.15 m high and 0.25 m wide, and the initial water depth h_0 was kept constant. θ_0 was the angle between the emergence and the horizontal plane; α, the chute bottom angle; h_s, the step height; V_0, the average flow velocity; and ΔP, the negative pressure in the cavity. Here, x was the streamwise coordinate along the chute bottom, and z was the perpendicular coordinate, originating at the aerator lip. The model test was conducted with the parameters (α, θ_0, h_s, V_0) listed in Table 1. The parameters L, L_m and L_D are defined in the following paragraphs.

The central streamwise air-water velocity and air concentration distribution were measured with a phase-detection needle probe (CQY-Z8a Measurement Instrument, China; Chen and Shao, 2006). The needle probe consists of two identical tips with an internal concentric electrode made of platinum and an external stainless steel electrode with a 0.7-mm diameter (Fig. 2). Both tips were aligned in the flow direction and excited by an electronic circuit which was designed to have a response time of less than 10 μs. The measurement was based on the difference in voltage indices at the platinum tip between the air and water phases. The tip diameter was 0.05 mm. Chanson (2002) and Felder (2015) detailed the working principles of conductivity probes.

Table 1
Model Test Runs ($h_0 = 0.15$ m).

Run	V_0 (m/s)	hs (m)	θ_0 (°)	α (°)	Fr_0
T1-1	5.0	0.025	0	5.7	3.8
T1-2	6.0	0.025	0	5.7	4.9
T1-3	7.0	0.025	0	5.7	5.8
T1-4	8.0	0.025	0	5.7	6.6
T2-1	5.0	0.045	0	5.7	3.8
T2-2	6.0	0.045	0	5.7	4.9
T2-3	7.0	0.045	0	5.7	5.8
T3-1	5.0	0.065	0	5.7	3.8
T3-2	6.0	0.065	0	5.7	4.9
T3-3	7.0	0.065	0	5.7	5.8
T4-1	5.0	0.045	0	9.9	3.8
T4-2	6.0	0.045	0	9.9	4.9
T5-1	6.0	0.045	5.7	5.7	4.9
T5-2	7.0	0.045	5.7	5.7	5.8
T5-3	8.0	0.045	5.7	5.7	6.6
T5-4	9.0	0.045	5.7	5.7	7.4
T6-1	6.0	0.045	9.9	9.9	4.9
T6-2	7.0	0.045	9.9	9.9	5.8
T6-3	8.0	0.045	9.9	9.9	6.6
T6-4	9.0	0.045	9.9	9.9	7.4
T7-1	6.0	0.045	14.1	14.1	4.9
T7-2	7.0	0.045	14.1	14.1	5.8
T7-3	8.0	0.045	14.1	14.1	6.6
T7-4	9.0	0.045	14.1	14.1	7.4
T8-1	4.0	0.045	5.7	14.1	3.3
T8-2	4.6	0.045	5.7	14.1	3.8
T8-3	5.0	0.045	5.7	14.1	4.1
T8-4	6.0	0.045	5.7	14.1	4.9

The grid spacing for the air concentration of the air-water flow measurement was 0.03–0.10 m along the chute bottom and 2–5 mm perpendicular to the bottom in the direction of the flow depth. At different scanning times ($t = 5$–40 s) and sampling frequencies ($F_{sample} = 20$–200 kHz), the air concentration was almost stable at a certain measured point, as shown in Fig. 3. Felder (2015) and Wei (2016) also conducted sensitivity studies on the sampling frequency. Thus, the scanning time and sampling frequency were considered to have no effects on the experimental results in the present study. The signals from the conductivity probe were recorded at a scan rate of $F_{sample} = 100$ kHz per for a 10 s scan period. The pressure was measured with a scan rate of 100 kHz