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Development of self-aeration process for supercritical chute flows

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ABSTRACT

When a high-velocity flow discharges into a chute, air is entrained through the free surface. This is relevant to the development of self-aeration for mixture flow. In this study, the air concentration was measured in the self-aerated developing region for various initial flow velocities, depths, and chute slopes. The effect of hydraulic conditions on the bottom self-aeration process was analyzed. Increasing the initial flow velocity and depth was found to increase the rate of air diffusion into the water flow. This positive correlation indicates that flow turbulence is a key factor for the self-aeration development process. The Reynolds number of the flow was found to be an appropriate hydraulic condition for describing self-aeration development. In addition, the constraint of buoyancy on air bubble diffusion into the chute bottom decreased as the chute slope was increased, which made the development process for bottom self-aeration more pronounced. A new empirical equation is presented for predicting the development process of bottom self-aeration in open channel flows.

Introduction

When high-velocity water flows down a chute, the free surface aeration generates (Fig. 1). As the air entrainment develops, bubbles penetrate the water towards the chute bottom along the flow direction until a two-phase flow fully develops and becomes uniform, where the turbulence intensity counterbalances the buoyancy effect exactly and the air concentration is independent of the flow direction.

A large amount of data on the fully developed uniform region is available for predicting the air-water flow properties of supercritical chute flows (Straub and Anderson, 1958; Wood, 1991; Deng et al., 2002 and 2003). Wood (1983) and Hager (1991) investigated the relationship between the air concentration and hydraulic conditions including the flow discharge and channel slope in uniform flows. Basic equations for the uniform aerated region were developed based on turbulent diffusion theory (Chanson 1993). However, there is little literature on the self-aerated developing region in chute flows, especially the bottom self-aeration process along the flow downstream, and the relationship between the flow conditions and slope. Chanson (1997a, 1997b) studied the aerated developing region in a flat chute and described the flow structure, but only one chute slope (4°) was tested, and the maximum mean air content of the cross-section was only 0.12.

The Froude number has been used as the hydraulic condition in many previous investigations on air transport in air–water flows (Pfister and Hager, 2010a and 2010b; Pagliara et al., 2011). Kramer and Hager (2005) investigated air bubble transportation in air–water flows over a chute aerator. Pfister and Hager (2011) studied the development process of self-aeration in a stepped spillway flow from the spillway crest. These studies suggested the air–water structure to be a function of the Froude number of the flow. This is because the cavity characteristics (hollow niches for stepped spillways and rough-rock chutes) were the main considerations in these aeration situations (Guenther et al., 2013; Felder and Chanson, 2014), and the jet length, which is affected by the Froude number, is often used as a characteristic parameter to compute the air entrainment capacity. However, the applicability of the Froude number to the free surface self-aeration conditions of high turbulent chute flows is still unclear, especially the validity of the relationship between the results of a physical model and prototype situations. This is related to "the notion of scale effects which is closely linked with the section of some characteristics turbulent flow properties" (Chanson 2013).

This work aimed to provide some understanding of the self-aeration development process in supercritical chute flows. Various conditions of the approach flow velocity, depth, and chute slope were examined. The total conveyed air (i.e., sum of entrapped and entrained air as proposed by Wilhelms and Gulliver (2005)) was measured, and the effects of the flow conditions and chute slope were analyzed. An explicit relationship was presented for predicting the bottom self-aeration process.

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Fig. 1. Free-surface aeration: (a) spillway in Huangtan Dam (Hu et al. 2012); (b) steep chute in Wudu Dam (Imaged by Jun Deng).

Hydraulic model

Experiments were performed in two model chutes fabricated from polymethyl methacrylate (PMMA). One chute was 12 m long and 0.4 m wide with a bottom angle of $\alpha = 7.5°–17.5°$ (Fig. 2a). The other was 18 m long and 0.3 m wide with $\alpha = 28°$ (Fig. 2b). Here, x = stream-wise coordinate along the chute bottom, and y = coordinate in the perpendicular direction. The roughness height of the model chutes was 0.01 mm. Hsiao (1947) and Wilhelms (1997) showed that the air concentration at the center of the channel is homogeneous in the transverse direction of a 6-in-wide (15.24 cm-wide) channel. This suggests that the effects from a smooth sidewall may be neglected and that the assumption of transverse homogeneity should likewise be valid for the chutes of the present study.

The flow to the chute was fed through a smooth convergent nozzle, and the initial water depth d_0 was variable. The central stream-wise air concentration distribution was measured with a phase-detection needle probe (CQY-Z8a Measurement Instrument, China; Chen and Shao 2006). The measurement was based on using the different voltage indices at the platinum tip between the air and water phases. The profiles were measured at the flow cross-sections perpendicular to the chute bottom at intervals of 2–3 mm up to the free surface. At different scanning times (t = 2–40 s) and sampling frequencies (F_{sample} = 20–300 kHz), the air concentration and air bubble frequency were almost stable at a certain measured point, as shown in Fig. 3. 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 $F_{\mathrm{sample}} = 200$ kHz per channel for a scan period of $t = 5$ s.

Approach flows with variable initial depths d_0, velocities V_0, relative Reynolds number $Re_0 = V_0 D_0/\nu$, and Froude numbers $\mathrm{Fr}_0 = V_0/(gd_0)^{0.5}$ were generated in the intake connected to the chute, where ν = kinematic water viscosity and g = gravitational acceleration. D_0 is the hydraulic diameter of the initial water flow in the chute and is defined as

$$D_0 = \frac{Wd_0}{W + 2d_0}, \tag{1}$$

where W is the chute width. The initial average water velocity V_0 is defined as

$$V_0 = \frac{q_w}{d_0}, \tag{2}$$

where q_w is the unit flow discharge. Four series tests were conducted, as presented in Table 1, including different hydraulic conditions.

Air concentration characteristics

Detailed air concentration profiles at different flow cross-sections along the stream-wise were measured for all the tests (Table 1), and the documentation are available as digital supplementary data (see Electronic Annex 1 in the online version of this article). Fig. 4 shows typical air concentration profiles at flow cross-sections. The previous studies of Wood (1983) and Chanson (1995) used the characterized aerated flow depth y_{90} (where the air concentration was 0.90) as the dimensionless method for the fully developed uniform zone of a self-aerated flow. For the developing zone, the variation in y_{90} is related to the initial test conditions, including the approach V_0, d_0, and α. Thus, the parameter y/d_0 describes the dimensionless air concentration distribution at the cross-section considering the initial water depth d_0 as a variable in this study.

Based on the Chézy theory for an open-channel flow, a uniform water flow corresponds to a specific flow condition for a certain slope in principle; this includes the flow velocity and hydraulic radius. In the present study, the initial velocities in all tests with different approach flow depths and chute slopes were generally less than the theoretical value for a uniform condition, as shown in Fig. 5. For a small chute slope ($\alpha = 9.5°\sim13.5°$) and initial flow hydraulic radius $D_0 = 0.038$ m, the difference between the test and theoretical velocities was relatively small, and the variation in the air-water flow depth along the stream-wise direction was not significant considering the enhancement effect of self-aeration on the flow depth (Fig. 4(a)). For a large chute slope ($\alpha = 28°$) and initial flow depth $D_0 = 0.052–0.067$ m, the variation in the air–water flow depth along the stream-wise direction was more pronounced and was caused by the greater difference between the actual and theoretical velocities (Fig. 4(b)). Thus, the present tests mainly considered the non-uniform accelerating process.

The mean cross-sectional air concentration C_{mean} is defined as the integration of the local values $C(y)$ over the flow depth between the chute bottom at $y = 0$ and the free surface y_{90}:

$$C_{\mathrm{mean}} = \frac{1}{y_{90}} \int_{y=0}^{y_{90}} C(y)dy \tag{3}$$

Fig. 6 shows the stream-wise variation of the mean cross-sectional air concentration (S1-1–S1-5). For all test series (Electronic Annex 1), C_{mean} increased in the stream-wise direction downstream. According to Hager (1991), the average air concentration C_{mean} for a uniform air–water mixture flow in an open channel is given by

$$C_{\mathrm{mean}} = 0.75(\sin\alpha)^{0.75}. \tag{4}$$

For the present slope conditions of $\alpha = 9.5°$, 13.5°, 17.5°, and 28°, the mean air concentrations for a uniform aerated flow should be 0.19, 0.25, 0.30, and 0.43, respectively. The measured amount of air entrainment was relatively low. Thus, the self-aeration in the test area was in the developing zone, and the mixed air-water flow did not reach the fully developed uniform region.

For all tests, the average air concentration was already greater than 0.03–0.05 at about $x/d_0 = 5$. This indicates that self-aeration