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Phase-detection probe measurements in high-velocity free-surface flows including a discussion of key sampling parameters

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A B S T R A C T

Air–water high-velocity flows are characterised by strong interactions of air bubbles and water droplets. The void fraction ranges from a few percent in bubbly flows to up to 100% at the free-surface and a reliable measurement instrumentation is the phase-detection intrusive probe. Herein new experiments were conducted on a stepped spillway ($\theta = 26.6°$) in transition and skimming flow sub-regimes yielding new insights into the turbulent air–water flow properties including the turbulence intensities and integral turbulent time and length scales. The integral turbulent scales showed self-similarity independently of the flow regime. A sensitivity analysis was conducted on the phase-detection probe signals to investigate the optimum sampling duration and frequency as well as the data analysis parameters threshold, sub-sampling duration, histogram bin sizes and cut-off effects. The results provide recommendations in terms of optimum sampling and processing parameters for high-velocity air–water flows.

1. Introduction

High-velocity self-aerated flows are often called "white waters" because of the entrained air [45,52,15]. The free-surface aeration in high-velocity open channel flows induces a drastic change in the multiphase (gas–liquid) flow structure and its distribution within the water column that have direct implications in terms of bubble-turbulence interactions and associated turbulent mixing processes [4,19]. Most high-velocity free-surface flows are characterised by large amounts of entrained air. The void fractions range from a few percents to nearly 100% in the upper spray region, and the ratios of flow velocity to bubble rise velocity are commonly greater than 10–20.

Classical measurement techniques are adversely affected by the presence of air bubbles and air–water interfaces, and they can produce highly inaccurate readings: e.g., pointer gauge, Pitot tube, acoustic Doppler velocimeter (ADV), laser Doppler anemometer (LDA), particle image velocimetry (PIV) [37,19]. Many air–water flow measurement techniques are available depending upon flow type and void fraction fractions (Boyer et al. [5]. For low void fractions, a phase Doppler anemometer (PDA) may provide some meaningful results in terms of turbulence properties and bubble characteristics [51]. When the void fraction C, or liquid fraction $(1 - C)$, exceeds about 1–3%, the most reliable metrology is the intrusive phase detection probes, notably the optical fibre probe and conductivity/resistivity probe [11,2,16]. The principle behind the optical fibre probe is a change in optical index between the two phases [10,12,41]. The conductivity/electrical probe works based upon the difference in electrical resistivity between air and water [33,47]. Phase-detection intrusive probes are designed to pierce bubbles and droplets and their design is typically based upon the needle probe design developed by Neal and Bankoff [42], Neal and Bankoff [43]. Such probes have been used for over 50 years, including some milestone prototype measurements on the Aviemore Dam spillway in New Zealand [7,8].

High-velocity free-surface flows are typical on spillways with slopes ranging between very flat ($\theta = 3°$) to very steep ($\theta = 60°$). Spillways may be constructed with smooth surface or roughened surface such as rockfill or step elements. An advantageous spillways design is the stepped spillway which provides a stronger air entrainment and energy dissipation performances compared to smooth chutes because the large roughness steps increase the flow resistance. Many experimental studies of stepped spillway flows have been conducted in the last decades for steeply sloped stepped chutes [13,3,39,31] and with embankment dam slopes (e.g. [50,20,6,36,29]. While previous studies provided extensive

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insights into the flow processes at design discharge in the skimming flow regime, little information is available about the air–water flow properties for transition flow discharges apart from a few studies [23,26]. The transition flow regime occurs for intermediate flow rates and hence an inclusive analysis of both transition and skimming flow properties is missing. Herein new experiments were conducted in high-velocity free-surface flows on a large scale stepped spillway model with a slope of $\theta = 26.6°$ comprising both flow regimes. The experiments were conducted with phase-detection intrusive conductivity probes and new results for the transition flow regime include the turbulent air–water flow properties.

As part of the stepped spillway experiments, the limitations and potentials of the phase-detection conductivity probes were investigated to identify optimum sampling parameters. Despite some key contributions [10,16,20], the use of phase-detection probes in high-velocity free-surface flows is restricted by a lack of accurate method to select the optimum sampling parameters, albeit for a few sensitivity analysis for basic air–water flow properties [50,1]. Herein a sensitivity analysis of air–water flow data was conducted to investigate systematically the effects of the sampling duration, sampling frequency and sub-sampling duration on the turbulent air–water flow properties. Furthermore the effects of the air–water threshold, the histogram bin sizes for the voltage signals and the cut-off effect on the lower voltage signals were tested. A procedure for phase-detection probe measurements in high-velocity self-aerated flows is discussed.

2. Instrumentation and signal processing

Phase-detection intrusive probes were used for the measurements of air–water interfaces in the aerated free-surface flows. Two probe configurations were used. A double-tip conductivity probe comprised two identical sensors separated by a streamwise distance $\Delta x = 7.2$ mm (Fig. 1A). Fig. 1A illustrates such a double-tip designed to pierce the air bubbles and water droplets in the mainstream flow direction. The double-tip conductivity probe was used for a detailed sensitivity analysis of sampling parameters in air–water flows. The second configuration comprised two single-tip needle probes separated by a transverse distances Δz (Fig. 1B). A similar probe configuration has been also used by Chanson and Carosi [21], Felder and Chanson [28].

The measurement of the air–water interfaces is an Eulerian observation of air bubbles and water droplets at a fixed location within the air–water flows over a specific sampling duration. At that location, the air bubbles and water droplets are detected when they pierced the probe tips. This results in a square wave voltage signal as illustrated in Fig. 2. In Fig. 2A, a voltage signal of about 4 indicates the probe tip in water and a voltage of 0.5 is equivalent to an air voltage. The raw signal is not squared and therefore a signal processing technique must be used to identify the air and water voltages. Fig. 2B illustrates the PDF of the raw voltage signals with bin sizes of 0.1 V for the data shown in Fig. 2A. For this data set, the amount of air and water is close and two distinctive voltage peaks are visible indicating air and water voltages. Different types of processing techniques have been used to identify the air–water phases and good overviews were given by Cartellier and Achard [11], Toombes [50]. Two classes of processing techniques are common. One is based upon threshold criteria derived from the PDF of the raw voltage signals and another identifies air and water phases according to a change in slope of the raw voltage signal.

Herein a simple (single) threshold technique was used to analyse the raw voltage signals and to calculate the basic air–water flow properties including void fraction and bubble count rate. The single threshold technique is robust. It is best suited to cover the wide range of void fractions in the whole air–water flow column. The single threshold technique can identify the instantaneous void fraction $c = 1$ in air and $c = 0$ in water. The instantaneous void fraction may be used to calculate the time-averaged void fraction, the bubble count rate, the air/water chord times, the bubble/droplet chord lengths and the streamwise particle grouping. In the present study, the instantaneous void fraction was used to quantify the time the probe tip was in air and to calculate the time-averaged void fraction:

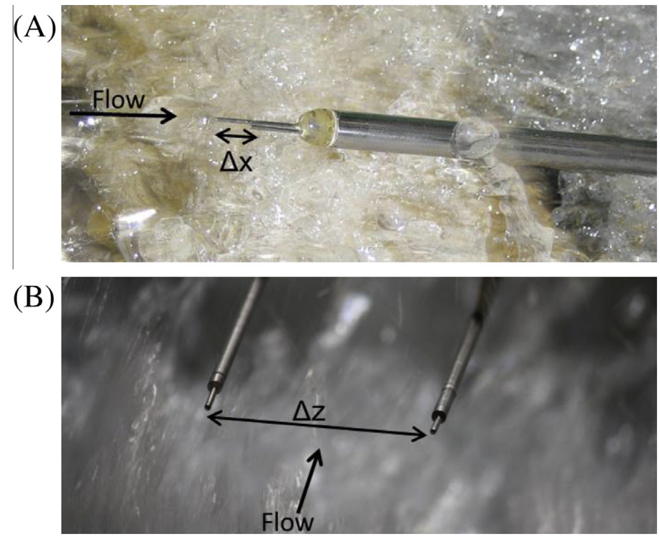

Fig. 1. Conductivity probe designs developed at the University of Queensland. (A) Double-tip probe ($\varnothing = 0.25$ mm, $\Delta x = 7.2$ mm, $\Delta z = 2.1$ mm) – view in elevation. (B) Single-tip probes ($\varnothing = 0.35$ mm, $\Delta x = 0$ mm, $\Delta z = 50.7$ mm).

$$C = \frac{\sum_{i=1}^{n} c}{n} \quad (1)$$

where n is the number of samples. The calculation of the bubble count rate was based upon the number of water to air interfaces. The air bubble and water droplet chord times were defined as the time between air to water and water to air interfaces respectively and the multiplication with the local velocity provided the air bubble and water droplet chord lengths. The chord sizes were not the bubble diameters, but characteristic streamwise air–water sizes [22].

The calculation of further air–water flow properties is based upon statistical analyses of the raw Voltage signals. A cross-correlation between the two 2-tip probe sensor signals provides the cross-correlation function and the maximum cross-correlation coefficient $(R_{xy})_{max}$ [35,15,24]. The ratio of the sensor separation Δx to the transit time T of the maximum cross-correlation gives the local time-averaged interfacial velocity:

$$V = \frac{\Delta x}{T} \quad (2)$$

The broadening of the cross-correlation function compared to the auto-correlation function of the leading sensor may provide some information about the turbulence intensities in an air–water flow [38,16]. Chanson and Toombes [22] derived an equation for a dimensionless expression of the turbulence velocity fluctuations:

$$Tu = 0.851 \times \frac{\sqrt{\tau_{0.5}^2 - T_{0.5}^2}}{T} \quad (3)$$

where $\tau_{0.5}$ is the time scale for which the cross-correlation function is half of its maximum value such as: $R_{xy}(T + \tau_{0.5}) = 0.5 \times R_{xy}(T)$, and $T_{0.5}$ is the characteristic time for which the normalised auto-correlation function equals: $R_{xx}(T_{0.5}) = 0.5$.