Comparative analyses of phase-detective intrusive probes in high-velocity air-waterflows

Stefan FELDER¹ and Michael PFISTER²

¹ UNSW Australia, Water Research Laboratory, School of Civil and Environmental Engineering, 110 King St, Manly Vale, NSW, 2093, Australia
+61 (2) 8071 9861; s.felder@unsw.edu.au (corresponding author)

² Civil Engineering Department, Haute Ecole d'Ingénierie et d'Architecture de Fribourg (HEIA-FR), CH-1705 Fribourg, Switzerland, michael.pfister@hefr.ch, and Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Abstract

A comparative analysis of a wide range of air-water flow properties was conducted for two types of phase-detection intrusive probes including fiber-optical and conductivity probes. Experiments were conducted on a stepped spillway model for a skimming flow discharge $q = 0.478 \text{ m}^2/\text{s}$ and for $Re = 4.7 \cdot 10^5$ in a flow region just downstream of the inception point of free-surface aeration and in the fully developed flow region. The comparison of a large number of key air-water flow properties showed a very close agreement for the two sensor types including void fraction, interfacial velocity and equivalent clear water flow depth enabling a direct comparison of past and future data collected with either phase-detection probe type. Minor differences were observed in terms of chord sizes, clustered properties and interparticle arrival times linked with the slightly smaller sensor size of the fiber-optical probe. The in-line positioning of the leading and trailing tips of the fiber-optical probe affected the trailing tip properties resulting in elevated turbulence intensities. An optimum dual-tip phase-detection probe design should consist of small probe tips positioned side-by-side.

Keywords (maximum 6)

High-velocity free-surface flows, instrumentation, phase-detection intrusive probes, fiber-optical probes, conductivity probes, air-water flow properties

1. Introduction

High-velocity air-water flows are a common feature of natural water streams and in human-made hydraulic structures. In nature, they can be observed in river rapids, at water falls or in steep mountain streams. In human-made structures (e.g. IAHR 1953),

they can be observed in particular in spillways which may be equipped with various bed roughness ranging from smooth bed to macro-roughness elements such as in stepped spillways. Independent of the spillway roughness, the physical processes leading to the air entrainment are similar. At the upstream end of a spillway, the water is glassy and smooth and a boundary layer evolves at the upstream inlet and develops along the chute. When its outer edge reaches the free-surface the air entrainment starts at the inception point of free-surface aeration. At this point, turbulence forces within the boundary layer are larger than both surface tension and buoyancy (CAIN and WOOD 1981; WOOD 1991; CHANSON 1997). Downstream of the inception point, the two-phase flow is “chaotic” where air is continually entrapped and entrained caused by large turbulence fluctuations within the air-water flow mixture and the flow looks white. The flow free-surface becomes undetermined characterised by large amount of air-water interfaces, break-up and coalesce of air and water entities resulting in air bubbles and water droplets of various sizes and shapes (ISHII 1975; CHANSON 1997; ERVINE 1998). Figure 1 illustrates air-water flows in prototype hydraulic structures.

A large number of experimental studies have been conducted in the past decades uncovering key features of the air-water flows and providing design guidelines for smooth and stepped spillways (e.g. STRAUB and ANDERSON 1958; MATOS 2000; BOES and HAGER 2002; GONZALES and CHANSON 2007; FELDER and CHANSON 2016a). These studies relied on suitable air-water flow instrumentation because classical instrumentation such as Pitot tube, PIV, LDV and ADV cannot produce reliable results when the local void fraction exceeds some 5% (CHANSON 2013). A range of air-water flow instrumentation was developed for air-water flow applications (JONES and DELHAYE 1976; CARTELLIER and ACHARD 1991). In

high-velocity air-water flows, use of phase-detection intrusive probes is most common comprising fiber-optical (FO) and conductivity probes (CP). While both types of phase-detection probes are designed with needle-tip to optimise piercing of air-water entities, the physical principles of the detection of air-water interfaces are different.

The **conductivity probe**(CP) design was first developed by NEAL & BANKOFF (1963). The working principle is based upon the different electric resistivity of air and water (HERRINGE & DAVIS 1974; SERIZAWA et al. 1975). Every time an air bubble gets pierced by a probe tip, the voltage signal drops immediately due to the larger resistivity of air compared to water. The signal is not completely rectangular because of the small size of the probe tips, the wetting and drying time of the tip and the response time of the instrumentation and the data acquisition system (CHANSON 2002). Despite the existence of more complex probe designs such as four-tip designs (KIM et al. 2000), the most common design is a dual-tip conductivity probe where leading and trailing tips are positioned parallel with small transverse distance and known streamwise distance.

A different type of air-water flow instrumentation is the **fiber-optical probe** (FO). Being an intrusive instrumentation, it pierces bubbles or drops by means of a small conic tip made of sapphire. Pulsed infrared light is injected into the latter, being partially or fully reflected depending on the surrounding media. Namely, the medium air or water induces different refraction indices, modifying the intensity of reflection. A semi-transparent mirror combined with a prism deflects the returning light towards a photo-sensitive diode. If fully or partially in gas, the light is reflected and transformed into a voltage signal superior to zero, and if in water, the light is lost generating a voltage around zero. The light pulsation frequency is typically very high, often in the order of 1 MHz. If adding in the vicinity of the leading tip a second trailing tip, then a bubble or

drop can be pierced twice. If the distance between the tips is known, then the interfacial flow velocity can be derived. Optical probes appeared around 1970 (MILLER and MITCHIE 1970) and were extensively discussed by CARTELLIER and ACHARD (1991).

In high-velocity air-water flows, both dual-tip conductivity and fiber-optical probes have been extensively used in the past decades. Various conductivity probe systems were developed and several of them are still in use including a dual-tip conductivity probe system at the University of Queensland (e.g. CUMMINGS 1996; CHANSON 2002; CHANSON and TOOMBES 2002; FELDER and CHANSON 2015), USBR single-tip conductivity probe at the University of Pisa (PAGLIARA et al. 2010), the CQY-Z8a measurement system in China (WEI et al. 2016), a dual-tip system at Nihon University (TAKAHASHI and OHTSU 2012), a dual-tip system at RWTH Aachen University (THORWARTH 2008; FELDER and CHANSON 2014), as well as a newly developed system at WRL, UNSW Australia (FELDER and CHANSON 2016b; FELDER and SEVERI 2016). All conductivity probe systems have different tip diameters, different spacing between the leading and trailing tips (if present), different acquisition and data analyses methods and different sampling parameters. Several studies were conducted so far using fibre-optical probes in high-speed two-phase flow. These include, among others, stepped spillway flows (e.g. BOES and HAGER 2003; PFISTER et al. 2006; ANDRE et al. 2008a,b; PFISTER and HAGER 2011; HUNT et al. 2014), technical chute aeration (KRAMER and HAGER 2005; PFISTER and HAGER 2010a, b; TERRIER 2016), hydraulic jumps (MURZYN et al. 2005), cavitation phenomena (STUTZ and REBOUD 1997), large pipe flow in nuclear engineering (YONEDA et al. 2002), contractions (BERTOLA 2002), and jets (LIMA et

al. 2008; PFISTER and HAGER 2009; ZHANG and ZHU 2013; PFISTER et al.
2014). Most studies use commercial probes manufactured by RBI Instrumentation,
France.

In the research community of high-velocity free-surface flows, the two types of phase-
detection intrusive probes exist in parallel depending upon the preferences of
researchers. Using only one type of phase-detection intrusive probe, researchers have
produced various experimental results improving the fundamental understanding of gas-
liquid flows and providing design guidelines for practical applications. To the
knowledge of the authors, to date no direct performance comparison of fiber-optical and
conductivity probes has been conducted. Such a comparative analysis is significant to
allow the direct comparison of existing experimental results and validation of the phase-
detection intrusive probe systems. Herein, novel data were collected in high-velocity
air-water flows using both state-of-the-art fiber-optical and conductivity phase-detection
intrusive probes simultaneously.

(A) SiahBishe Dam (Iran) spillway (Photo courtesy: Pöyry Switzerland LTD, Switzerland)

(B) Hagneck run-on-the-river HEP weir (Switzerland).

Figure 1: Air-water free-surface flows on prototype spillways

2. Experimental configuration and instrumentation

2.1 Experimental facility

Experiments were conducted in a large size stepped spillway model at LCH, EPFL. The stepped chute had a slope of 30° , a width of $W = 0.5$ m and was equipped with 120 uniform steps of $d = 0.03$ m height over the full length of the channel (Fig. 2). At the upstream end water was supplied via a pump recirculation system to a jet-box (subscript

1) with a gate opening set at $h_1 = 0.097$ m (Fig. 2A). The experiments were conducted for a discharge per unit width of $q = 0.478$ m²/s corresponding to a Froude number at the jet-box of $Fr_1 = 5.05$, to a Reynolds number defined in terms of the hydraulic diameter of $Re = 4.7 \cdot 10^5$ and to $d_c/d = 9.5$, where d_c is the critical flow depth. These flow conditions were selected to minimize scale effects in the air-water flow mixture (FELDER and CHANSON 2009; PFISTER and CHANSON 2014). The stepped spillway facility of the present study has been used previously by ANDRE et al. (2008a,b) by TERRIER (2016), and by OSTAD MIRZA et al. (2017). Figure 2A shows a sketch of the experimental set-up and the definitions of key parameters. Figure 2B shows a photo of the stepped chute, the air-water flows in the skimming flow regime and the measurement trolley with the instrumentation.

Experiments were conducted in the skimming flow regime which is the representative flow regime for stepped spillway design discharges. In pseudo-uniform skimming flows the free-surface is parallel to the pseudo-bottom formed by the step edges, and the flow is aerated naturally at the inception point of free-surface aeration when the turbulence next to the free-surface is stronger than surface tension and buoyancy forces (CHANSON 1997). The measurements were conducted at two longitudinal positions including one location just downstream of the inception point of free-surface aeration ($(x-L_1)/d_c = 0.84$) and one towards the downstream end of the stepped chute ($(x-L_1)/d_c = 13.45$) (Fig. 2A). These two positions represented two distinctive air-water flow regions of stepped spillways. The location just downstream of the inception point was characterized as a rapidly varying flow region with little entrained air and some variation of transverse flow properties through irregular air streaks at the surface. The second flow region was towards the downstream end of the stepped chute in a flow

region with fully developed air-water flows. These two characteristic locations were
 representative of air-water stepped flows and the results of the comparative analysis
 may be applicable to other air-water flows. At each longitudinal position, experiments
 were conducted at three transverse positions to allow the same measurement position for
 the two types of phase-detection intrusive probes in channel centre line ($z/W = 0$) and
 0.05 m off the centre ($z/W = 0.1$) (Fig. 3C). Due to the positioning of the sensors, one
 additional transverse position was recorded for the fiber-optical probe at $z/W = 0.2$ and
 for the conductivity probe at $z/W = -0.1$. The additional positions were used to assess
 the uniformity of the air-water flows in a cross-section.

(B) Photo of experimental setup and measurement trolley with instrumentation;
Skimming flows: $q = 0.478 \text{ m}^2/\text{s}$; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$ (Flow direction from top left
to bottom right)

Figure 2: Experimental facility in the present study: $W = 0.5 \text{ m}$; $h = 3 \text{ cm}$; $\theta = 30^\circ$, $h_1 =$
97 mm

2.2 Instrumentation

The measurement of the air-water flow properties was conducted with two different
state-of-the-art dual-tip phase-detection intrusive probes (Fig. 3). The first sensor was
a fiber-optical probe manufactured by the French company RBI (Fig. 3A). It consisted of
two identical probe tips with a minimum tip diameter of $\varnothing (=30\mu\text{m}) = 0.03 \text{ mm}$. The
sensors were positioned in-line and separated in flow direction by a small distance $\Delta x =$
1.77 mm. The leading probe tip was positioned 57° and the trailing tip 45° to the

horizontal, to achieve an in-line positioning without any transverse shift ($\Delta z = 0$ mm) (Fig. 3). The idea of this design is that air-water interfaces will be detected by the two probe tips in short succession. The fiber-optical probe with this particular arrangement has been used in several previous studies at EPFL and ETH Zurich. The tips were connected to a laser unit from RBI which generated and translated the optical signals into Voltage raw signals.

The second sensor was a 2-tip conductivity probe manufactured in-house at WRL, UNSW Australia. The probe consisted of two identical tips made of hypodermic needles with an outer diameter of $\varnothing = 0.5$ mm and an inner electrode of $\varnothing = 0.125$ mm platinum wire (Fig. 3A). The two electrodes were isolated by an epoxy. The trailing tip was separated by a streamwise distance of $\Delta x = 5.17$ mm and a transverse distance of $\Delta z = 1.05$ mm from the leading tip and both sensors were positioned parallel to the main flow direction (Fig. 3B). The conductivity probe was excited by an electronic box manufactured at WRL. While the conductivity probe was a newly developed sensor, it has been successfully benchmarked against a well-established conductivity probe in a recent experimental study of air-water flows in hydraulic jumps (FELDER and CHANSON 2016b). The working principle of the conductivity probe was based upon a different resistivity of air and water resulting in different Voltage signals when air or water phases were detected by the two probe electrodes (Fig. 4).

The distances between the leading and trailing tips for both phase-detection intrusive probe designs were measured with a microscope to an accuracy of ± 0.01 mm. The two phase-detection intrusive probes were positioned as shown in Figure 3B with a transverse separation between the two leading tips of $\Delta z = 0.05$ m. Both leading tips were positioned in flow direction at the same vertical elevation above step edge, With a

mm accuracy.

The two probes were mounted on a trolley which was equipped with a motor drive to control the position y above the step edge with high precision within $\Delta y = 0.25$ mm. Both dual-tip conductivity probes were sampled simultaneously at a frequency of 500 kHz and for 45 s. While FELDER and CHANSON (2015) showed that a sampling rate of 20 kHz is sufficient for a sampling duration of 45 s, a much higher sampling rate was used in the present study due to the higher sampling requirements of the fiber-optical probe. The sampling duration of 45 s was found sufficient for conductivity probe measurements in high-velocity air-water flows (FELDER and CHANSON 2015). The simultaneous sampling of the four sensors was achieved with a high-speed acquisition system (NI USB-6366) connected to a PC equipped with a LabVIEW acquisition software designed by WRL. Due to the large data volume, raw Voltage data were recorded in binary format still resulting in file sizes of more than 500 MB per measurement location.

(A) Photo of fiber-optical probe (FO) (top) and conductivity probe (CP) (bottom), flow direction from left to right

(B) Skethc of the positioning of the phase-detection intrusive probes from side, Positioning of leading tip probes at same x and y locations (white circle)

Figure 3: Phase-detection intrusive probes in the present study

2.3 Signal processing

The post-processing of the raw Voltage signals was conducted with a Fortran code developed by FELDER (2013). Note that the FELDER (2013) code was also used for the fibre-optical probe raw Voltage signal processing, and not the software of the manufacturer. The code allowed for the efficient processing of all recorded data applying the same calculations to both fiber-optical and conductivity probes. Typical raw Voltage signals of the leading tips of the two phase-detection intrusive probes are illustrated in Figure 4. For the fiber-optical probe, the Voltage corresponding to an air phase was typically about 5 Voltage and for water about 0 Voltage. For the conductivity probe, the signal was opposite linked with the different working principle of the

resistivity probe. The Voltage signal corresponding to water was about 4.3 Voltage. Every time an air phase was pierced by the sensor, the Voltage signal dropped suddenly to a value of about 0.9 Voltage linked with the much higher resistivity of air compared to water (Fig. 4). While the signals of both phase-detection intrusive probes showed some noise with stronger noise for the conductivity probe, the noise did not affect the air-water flow properties as derived by the code. While the phase-detection intrusive probes were sampled simultaneously, they did not record precisely the same air-water interphases due to the transverse separation of the sensors and the instantaneous Voltage raw signals differed (Fig. 4).

Figure 2: Raw Voltage signals of leading tip of phase-detection intrusive probes (FO&CP): $q = 0.478 \text{ m}^2/\text{s}$; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$; Step edge 101, centre line, $y = 55 \text{ mm}$

The raw signals for both fiber-optical and conductivity probes were post-processed using a single-threshold of 50% of the distinctive peaks of the bimodal probability

distribution function of the raw Voltage signal (CARTELLIER and ACHARD 1991). The threshold of 50% was applied at every location because it was the most suitable threshold value for the various flow regions in air-water skimming flows on stepped spillways (FELDER and CHANSON 2015). At each measurement position, the respective raw signals yielded the instantaneous void fraction time series c and the time averaged void fraction C for the 45 s measurement interval. The number of changes per second from either the air-to-water or water-to-air interphases was quantified in terms of the bubble or droplet count rate F , and the air and water phases between the interphase changes provided information about the air bubble and water droplet chord times respectively representing characteristic streamwise air/water sizes (CHANSON and TOOMBES 2002).

In further analyses, several clustered properties were investigated providing information about the streamwise structure of the two-phase flow (HEINLEIN and FRITSCHING 2006). Cluster analyses were performed for all experiments based upon the near-wake criterion in which particles (i.e. air bubbles or water droplets) were considered as travelling in a cluster if the length scale between successive air bubble or water droplet chords was smaller than the size of the leading bubble/droplet chord (GUALTIERI and CHANSON 2010). The cluster analyses encompassed a wide range of parameters including the percentage of bubbles/droplets in clusters, the number of clusters per second, the average number of particles per cluster and the average chord sizes of particles in clusters. A further analysis of the particle chords provided the inter-particle arrival time for air bubble and water droplets chords of similar sizes for which a similar behavior may be expected (EDWARD and MARX 1995).

For the two phase-detection intrusive probes, auto- and cross-correlation analyses of the

respective probe signals were performed at each sensor location providing the auto- and cross-correlation functions R_{xx} and R_{xy} , the maximum cross-correlation coefficient in a cross-section $(R_{xy})_{\max}$ and the corresponding average travel time between the leading and trailing tips of the respective probes. The average travel time and the streamwise distance Δx between the leading and trailing sensors provided the local time-averaged interfacial velocity V . The integration of the auto- and cross-correlation functions to the first crossing of the x-axis provided the auto- and cross-correlation integral time scale T_{xx} and T_{xy} (CHANSON and CAROSI 2007). The deviation of the cross-correlation function from a Gaussian distribution yielded information about the turbulence levels Tu of the aerated flows (CHANSON and TOOMBES 2002):

$$Tu = 0.851 \times \frac{\sqrt{\tau_{0.5}^2 - T_{0.5}^2}}{T} \quad (1)$$

where $\tau_{0.5}$ is the time scale for which the cross-correlation function is half of its maximum value such as $R_{xy}(T+\tau_{0.5}) = 0.5 \times R_{xy}(T)$. Potential noise of the signal was removed with the shape of the auto-correlation function of the leading tip using the characteristic time $T_{0.5}$ for which the normalised autocorrelation function equals $R_{xx}(T_{0.5}) = 0.5$. Further details about the signal processing technique and software can be found in FELDER (2013).

The measurement accuracy of the conductivity probe was estimated to provide void fractions with an accuracy of $\Delta C/C = 4\%$ and interfacial velocities with an accuracy of about $\Delta V/V = 5\%$ ($0 < C < 0.95$) and 10% for $C > 0.95$ and $C < 0.05$ (FELDER and CHANSON 2015). The measurement accuracy of the fiber-optical probe was estimated via air discharge based on anemometer reference velocities by PFISTER (2002). He concludes that roughly $\Delta q/q = 3\%$, implicitly including the velocity and air

concentration accuracy.

3. Comparative analysis of basic air-water flow properties

For both measured profiles, the distributions of basic air-water flow properties are illustrated in Figure 5 as a function of dimensionless depth above step edge y/d_c including void fraction C , bubble count rate F and interfacial velocity V . The distributions of these properties were in agreement with the literature including S-shape void fraction profiles, largest bubble count rates in the bulk of the flow for $0.4 < C < 0.6$ and interfacial velocities following a power law distribution.

The comparative analyses of the phase-detection intrusive probes, showed a very close agreement for the void fraction distributions independent of the instrumentation (Fig. 5A). For the same position along the flume, only insignificant differences were observed between void fractions at transverse positions indicating a uniform distribution of air-water flows in the centre part of the flume ($0.2 \leq z/W \leq -0.1$). No differences between the two probe types were observed for $C > 0.1$. Differences were however observed in the bubbly flow region close to the step edge with larger void fractions detected with the fiber-optical probe of up to $C_{(FO)}/C_{(CP)} = 1.25$ for $C < 0.1$ at the downstream end of the flume and of up to $C_{(FO)}/C_{(CP)} = 1.3$ for $C < 0.02$ just downstream of the inception point. The differences appeared to be linked with the different tip sizes and physical mechanism of the two types of instrumentation. Overall the very close agreement of void fractions was significant since the void fractions are typically used for calculation of key design parameters including flow depth and energy dissipation performances. The comparative analysis highlighted that void fractions can be recorded accurately with both types of phase-detection intrusive probes (Fig. 5A).

Some minor differences between the probe types were observed in terms of the dimensionless bubble count rate $F \times d_c / V_c$ (Fig. 5B). While there was good agreement for the leading tip signals for the respective instrumentation at various transverse positions, the fiber-optical probe was able to detect a larger number of particles throughout the cross-section. The differences were in particular observed in the strongly aerated flow region at the downstream end of the stepped chute ($(x-L_I)/d_c = 13.45$) and in the bubbly flow region for $C < 0.3$ (Figure 5B). The fiber-optical probe had a smaller probe tip which was able to detect smaller air bubbles in this region resulting in differences of bubble count rates of up to +30%. It appeared that the fiber-optical probe was able to detect changes from air-to-water and from water-to-air with a “partial” light loss more effectively. The tip of the conductivity probe must be fully surrounded by water or air to detect a particle and sometimes the signal might not drop below the threshold due to the wetting and drying time of the probe tip, due to bubbles/droplets smaller than the probe tip or due to a simultaneous partial covering of the sensor tip by air and water (Fig. 4). In Figure 4, this feature is visible in signals only dropping to Voltages of about 3 to 4. The fiber-optical probe is probably able to detect a small parcel of fluid immediately in front of the sensor tip allowing a more distinct detection of the air or water phases. Furthermore, the signal response time appeared to be faster for the fiber-optical probe compared to the conductivity probe. These effects were observed in bubbly flow only ($C < 0.1$).

The effect of the sensor positioning of the phase-detection probes is shown in Figure 5C, where the bubble count rates are illustrated for the leading and trailing tip signals for selected positions. While there is close agreement for the conductivity probe results, the fiber-optical probe shows strong differences in bubble count rates between leading

and trailing sensors due to the in-line positioning of the sensors (Fig. 5C). The in-linedesign of the fiber-optical probe leads to a wake behind the leading tip resulting in large quantities of “extra” air which is reflected in both larger void fractions (not shown here) and increased bubble count rates of more than 300% (Fig. 5C). While this aspect may be irrelevant for air-water flow properties recorded with the leading tip only, other properties rely on calculations with both simultaneously sampled probe sensors. For these properties, the in-line arrangement of the herein used fiber-optical probe results is erroneous. In contrast, the conductivity probe design allowed consistent recording of air-water flow properties despite a small transverse separation $\Delta z = 1$ mm between leading and trailing tip.

Good agreement between interfacial velocity distributions was observed at all measurement positions (Fig. 5D). Small differences were only observed in the upper spray region ($C > 0.99$) in which the flow was characterised by ejected water droplets above the air-water flows. The close agreement of the interfacial velocities is an important finding since it confirms the usability of both sensor types for determination of a key flow parameter. Furthermore the present findings showed that the sensor design did not affect the time-averaged local velocities and that the differences in leading and trailing tip signals for the fiber-optical probe did not affect the calculation of the average travel time of air and water entities.

(A) Void fraction distributions, leading tip signals

(B) Bubble count rate distributions, leading tip signals

(C) Bubble count rate – Comparison leading and trailing tip signals

(D) Interfacial velocity, leading and trailing tip signals

basic air-water flow properties at different longitudinal and transverse positions: $q = 0.478 \text{ m}^2/\text{s}$; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$

4. Comparative analysis of turbulence properties

An auto-correlation analysis was performed for the leading sensors and a cross-correlation analysis between the leading and trailing tip signals of the respective phase-detection intrusive probes at all positions. Typical auto- and cross-correlation functions are illustrated in Figures 6A & B for selected flow conditions between $0.04 < C < 0.94$. The results showed typical correlation functions with a clear peak in cross-correlation at the average travel time between the two sensor tips corresponding to the maximum cross-correlation coefficient $(R_{xy})_{\max}$. The overall shapes of the correlation functions were in good agreement, while the conductivity probe showed consistently larger peak correlation values (Fig. 6A & B). The differences may result from slightly higher noise levels of the conductivity probe as could be visually observed in the raw signal (Fig. 4). Due to the different streamwise distance between leading and trailing tips ($\Delta x = 1.77 \text{ mm}$ for the fiber-optical probe and $\Delta x = 5.17 \text{ mm}$ for the conductivity probe), the time lag at $(R_{xy})_{\max}$ was approximately three times larger for the conductivity probe (Fig. 6B). This observation was consistent with the close agreement of interfacial velocity distributions for the two types of phase-detection intrusive probes (Fig. 5D). Notably the cross-correlation function for the fiber-optical probe did show a very consistent correlation function independently of the observed differences between leading and trailing tips (Fig. 5C) resulting in meaningful interfacial velocity signals (Fig. 5D). The distributions of maximum cross-correlation coefficients are shown in Figure 6C revealing some differences between the two phase-detection intrusive probes. The

conductivity probe data showed a monotonic increase of $(R_{xy})_{\max}$ with increasing flow depth up to $C = 0.9$, and a small decline in $(R_{xy})_{\max}$ for $C > 0.9$ independent of the sensor location. The observations of $(R_{xy})_{\max}$ were consistent with previous experimental conductivity probe data of air-water skimming flows exhibiting a skewed parabolic relationship between $(R_{xy})_{\max}$ and C (FELDER 2013). For the fiber-optical probe, the maximum cross-correlation coefficients were almost constant $(R_{xy})_{\max} = 0.5$ for $0.05 < C < 0.2$. For $0.2 < C < 0.95$, $(R_{xy})_{\max}$ increased monotonically up to a maximum at $C \approx 0.95$. The monotonic growth rates were different for the two measurement positions. It is believed that the in-line positioning of the fiber-optical sensors influenced these values. Despite these differences, the time steps for $(R_{xy})_{\max}$ resulted in consistent observations of interfacial velocities for the two phase-detection intrusive probes.

Based upon the auto- and cross-correlation functions, several turbulent properties were calculated including the turbulence intensity Tu , as well as the auto- and cross-correlation time scales T_{xx} and T_{xy} . The turbulence intensity distributions are illustrated in Figure 6D. While both sensors showed typical shapes with maximum turbulence levels in the intermediate flow region ($0.4 < C < 0.6$) and small values of Tu close to the step edge and at the free-surface, the turbulence intensities for the fiber-optical probe were about 3 to 4 times larger. The observations of Tu measured with the conductivity probe were consistent with experimental results for steady skimming flows on stepped spillways using a conductivity probes (e.g. CHANSON and TOOMBES 2002; FELDER and CHANSON 2011). In contrast, the turbulence levels for the fiber-optical probes were similar to observations of turbulence intensities on a pooled stepped spillway which exhibited strong flow instationarities (FELDER and CHANSON 2014). For the

instationary flows, FELDER and CHANSON (2014) applied a triple decomposition technique to split the signal into fast and slow-fluctuation velocity components revealing true turbulence intensities of similar order compared to steady skimming flows on stepped spillways. The present observations of the fiber-optical data suggested that some unsteady mechanism may have led to the increased turbulence levels containing both fast and slow velocity fluctuations. Visual observations of the air wake behind the leading tip confirmed an unsteady local air entrainment mechanism initiated by the probe geometry.

In Figures 6E & F, the auto- and cross-correlation time scales are illustrated in dimensionless terms. For both phase-detection intrusive probe types, the shapes of the time scales were consistent for $C < 0.95$ with maximum time scales in the intermediate flow region and smallest time scales close to the step edge. For $C > 0.95$, the cross-correlation time scales tended to zero for the fiber-optical probe, while the conductivity probe data showed no decline. Overall, the cross-correlation time scales were consistently larger for the measurement with the conductivity probe. This finding was in agreement with the observations of consistently larger correlation functions (Fig. 6A & B). The cross-correlation time scales were about 20% larger in the bulk of the flow for the conductivity probe measurements. The distribution shapes and the magnitude of time scales for the conductivity probe measurements were consistent with previous observations of time scales in air-water skimming flows on stepped spillways based on conductivity probe measurements (e.g. CHANSON and CAROSI 2007; FELDER and CHANSON 2011, 2016c). Nevertheless, both sensors provided time scale of a similar order of magnitude.

(A) Auto-correlation functions (Step edge 41; $z/W = 0.1$)

(B) Cross-correlation functions (Step edge 41; $z/W = 0.1$)

(C) Maximum cross-correlation coefficient

(D) Turbulence intensity

(E) Auto-correlation integral time scale

(F) Cross-correlation integral time scale

Figure 6: Comparison of phase-detection intrusive probe (FO & CP) measurements of advanced air-water flow properties at different longitudinal and transverse positions: $q = 0.478 \text{ m}^2/\text{s}$; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$

5. Comparative analysis of microscopic air-water flow properties

A further series of comparative analyses was conducted for characteristic microscopic air-water flow properties including particle chord sizes, cluster properties based on the near-wake criterion and the inter-particle arrival times. These parameters were based upon analyses of the leading tip signal only. Typical particle chord time probability distribution functions are shown in Figure 7 for both phase-detection intrusive probes. For all graphs in Figure 7, the chord time data represent bin sizes of 0.1 ms; e.g. 0.2

444 msrepresents a bin of chord times within the range of 0.1 to 0.2 ms. The comparison of
445 air bubble chord times at identical measurement positions showed consistently a
446 proportionally larger number of air bubbles chord sizes for the fiber-optical probe. This
447 observation was in particular observed for chord times smaller than 0.1 ms indicating
448 that the fiber-optical probe was able to detect more smaller air bubbles. This aspect was
449 obviously linked with the smaller sensor size of the fiber-optical probe. Similar results
450 were found for the water droplet chord sizes where consistently a larger number of
451 smaller droplet chord times were observed for the fiber-optical probe for chord sizes
452 smaller 0.1 ms. The findings of proportionally larger numbers of smaller chord sizes
453 were consistent with the observations of larger bubble count rates for the fiber-optical
454 probe. It appeared that the fiber-optical probe was able to detect smaller particles
455 resulting in a larger number of detected particles per second. This finding had little
456 effect upon the time-averaged void fraction since the smallest particles did not
457 contribute significantly to the overall air and water interfaces respectively. For chord
458 sizes larger 0.1 ms, little differences were observed between the two phase-detection
459 intrusive probes.

(A) Probability distribution functions of air bubble chord times (Step edge 41; $z/W = 0$)

(B) Probability distribution functions of water droplet chord times (Step edge 101; $z/W = 0$)

Figure 7: Comparison of phase-detection intrusive probe (FO & CP) measurements of air bubble and water droplet chord time probability distributions at different longitudinal and transverse positions: $q = 0.478 \text{ m}^2/\text{s}$; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$

Figures 8 illustrates typical dimensionless distributions of cluster properties as a function of void fraction including air bubble cluster properties for $C < 0.3$ in the bubbly flow region and water droplet cluster properties for $C > 0.7$ in the spray region. The dimensionless number of clusters per seconds $F_{cl} \times d_c / V_c$ is shown in Figure 8A as function of void fraction C indicating a larger number of clusters for the fiber-optical probe for $C < 0.3$. For $C > 0.7$, a close agreement was observed for the two sensor types. The differences are more pronounced for the fully-developed flow at the downstream

end of the stepped chute ($(x-L_I)/d_c = 13.45$), while the number of clusters per second was almost identical close to the inception point of air entrainment ($(x-L_I)/d_c = 0.84$). It is believed that an overall larger number of detected bubbles coincided with a larger number of clusters per second. Indeed FELDER (2013) showed a linear relationship between the number of clusters per second and bubble count rate independent of the measurement location. The linear relationship was also observed in the present study independent of the instrumentation type (not shown in this paper).

In Figure 8, further cluster properties are shown comprising the average number of particles per cluster N_{cl} (Fig. 8B), the percentage of particles in clusters P_{cl} (Fig. 8C) and the average chord sizes of particles in clusters sch_{cl} (Fig. 8D). For all these cluster properties, a relatively good agreement was observed between the data recorded with the different phase-detection intrusive probes in the spray region for $C > 0.7$. This finding was consistent with the observations of void fraction and bubble count rates which showed little differences within this part of the flow. Note that there was data scatter in particular in the upper spray region for $C > 0.95$, in a flow region characterized by water droplets ejected above the flow.

Within the bubbly flow region ($C < 0.3$), the differences between the two phase-detection intrusive probes were slightly more pronounced with larger differences in the fully developed flow region at the downstream end of the stepped chute. The fiber-optical probe detected consistently a larger number of air bubbles per cluster (Fig. 8B). This finding was consistent with the observations of bubble count rate and air bubble chord sizes which indicated that the fiber-optical probe was able to detect a larger number of smaller particles. The ability to detect smaller air bubbles can also explain the differences in the percentage of bubbles in clusters (Fig. 8C) and the average chord

495 size of particles in clusters (Fig. 8D). For both cluster properties, the differences were
 496 consistent with a larger percentage of air bubbles detected with the fiber-optical probe
 497 and an on average smaller chord sizes of air bubbles in clusters. Overall the
 498 observations of cluster properties showed a good agreement between the two phase-
 499 detection intrusive probes showing typical cluster distributions and only small
 500 differences in magnitude of cluster properties.

(A) Number of clusters per second

(B) Average number of particles per cluster

(C) Percentage of particles in clusters

(D) Average chord sizes of particles in clusters

Figure 8: Comparison of phase-detection intrusive probe (FO & CP) measurements of cluster properties at different longitudinal and transverse positions: $q = 0.478 \text{ m}^2/\text{s}$; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$

A further comparison between the two phase-detection intrusive probes was conducted based upon an interparticle arrival time analysis (Fig. 9). Figure 9 illustrates typical results for the probability distribution of interparticle arrival times of particles of similar chord sizes. Particles were grouped into 5 different chord size classes where particles were believed to behave similarly. The results for interparticle arrival times for both water droplets (Fig. 9A) and air bubbles (Fig. 9B) showed a consistent result for the two types of phase-detection intrusive probes despite some small data scatter. The only difference between the two probe types was observed for the smallest chord class where a proportionally larger number of smaller interparticle arrival times was observed for

the fiber-optical probe independently of the measurement position. This observation was consistent with the larger number of smaller particles detected with the fiber-optical probe. Overall, the interparticle arrival time analyses showed very close agreement for the two types of phase-detection intrusive probes and both instrumentations appear suitable for the accurate detection of microscopic air-water flow properties.

(A) Interparticle arrival times of water droplets; Step edge 41, $z/W = 0$, $y = 101$ mm,

FO: $C = 0.748$, $F = 180.6$ Hz; CP: $C = 0.776$, $F = 159.7$ Hz

(B) Interparticle arrival times of air bubbles; Step edge 101, $y = 55$ mm, FO: $C = 0.198$, $F = 610.8$ Hz; CP: $C = 0.195$, $F = 538.5$ Hz

Figure 9: Comparison of phase-detection intrusive probe (FO & CP) measurements of interparticle arrival times at different longitudinal and transverse positions: $q = 0.478$ m^2/s ; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$

6. Discussion

The present study was conducted with two phase-detection intrusive probe systems with particular sampling parameters, specific sensor positioning and sensor design. The sampling was conducted simultaneously with the same acquisition system and software and the analysis was conducted based upon identical data analysis parameters and code. While the present comparative analyses provided very similar results for several key air-water flow properties, there were limitations in the present study which should be

addressed in future research. As has been shown recently by FELDER and CHANSON (2015), the results can be affected by the selection of sampling parameters including the sampling time, sampling rate and single threshold levels for the calculation of instantaneous void fractions. The present study was conducted with high sampling rate (500 kHz) and relatively long duration (45 s) and the single threshold was set at 0.5.

The sensors were positioned, as far as feasible, at the same position and were measuring similar but not identical air-water flows. The measurement limitation is not avoidable in intrusive measurements of air-water flows and small inaccuracies will be part of any experimental data. The present results suggested a uniform distribution of air-water flow properties across the center of the flume validating the present comparative analysis and its findings.

The comparative analyses of a wide range of air-water flow properties showed overall a rather close agreement between two different phase-detection intrusive probe systems.

The void fraction distributions showed a very close agreement indicating that this key air-water flow property can be measured accurately with both types of phase-detection intrusive probes. The local void fractions can be used for calculation of several characteristic air-water flow parameters including the characteristic vertical elevation Y_{90} where the void fraction equals 0.9, the equivalent clear water flow depth d and the depth-averaged mean void fraction C_{mean} :

$$C_{\text{mean}} = \frac{1}{Y_{90}} \times \int_{y=0}^{Y_{90}} C \times dy \quad (2)$$

Table 1 summarises the basic depth-averaged air-water flow parameters of the considered flow profiles in the present study showing a direct comparison of these parameters at measurement positions. The very close agreement of Y_{90} , d and C_{mean} is

significant since these are important design parameters of typical hydraulic structures. Very close results were also observed in terms of the characteristic interfacial velocity V_{90} where $C = 0.9$ (Table 1). The present results highlighted that there appears little effect of type of phase-detection intrusive probe on the design parameters and that experimental data of conductivity probe and fiber-optical probe studies may be directly compared.

Small differences between conductivity and fiber-optical probes were observed in terms of number of detected particles, chord sizes and cluster properties. These differences were directly attributed to the different phase-detection intrusive probe systems. The most important parameter herein appeared to be the sensor tip size. The smaller fiber-optical sensor was able to detect a larger number of smaller particles. The differences in maximum bubble count rate in a cross-section $F_{\max}$ are shown in Table 1 showing a larger number of detected changes in air-water interphases for the fiber-optical probe. In addition to the sensor size, the wetting and drying time of the conductivity probe tips may have played a role. The positioning of the leading sensors differed and it is believed that the conductivity probe sensor position in flow direction may be less intrusive compared to the fiber-optical sensor which was at a downwards facing angle. This aspect was however not investigated in the present study and may require further research.

The positioning of the trailing tip of the fiber-optical sensor in-line with the leading tip resulted in a wake flow entrapping air between the tips. This impacted upon the cross-correlation analyses of the two probe tips resulting in disturbed turbulence intensity. Differences in characteristic parameters of turbulence intensity are also visible in Table 1 where the maximum turbulence levels within a cross-section $Tu_{\max}$ were 3-4 times

larger for the fiber-optical probe.

Table 1 lists also the maximum auto- and cross-correlation time scales in a cross-section $(T_{xx})_{\max}$ and $(T_{xy})_{\max}$ respectively. The characteristic time sales were up to 30% larger for the conductivity probe and were linked with differences in the auto- and cross-correlation functions presented previously. While the differences in time scales were obvious, the time scales of both sensors were in overall agreement with characteristic air-water flow time scales (FELDER and CHANSON 2016c).

Table 1. Comparison of phase-detection intrusive probe (FO& CP) results; Summary of basic air-water flow parameters at different longitudinal and transverse positions: $q = 0.478 \text{ m}^2/\text{s}$; $Fr_1 = 5.05$; $Re = 4.7 \cdot 10^5$

Step edge	$(x-L_1)/d_c$ [-]	z/W [-]	Sensor	C_{mean} [-]	Y_{90} [mm]	d [mm]	$F_{\max}$ [Hz]	V_{90} [m/s]	$Tu_{\max}$ [-]	$(T_{xx})_{\max}$ [ms]	$(T_{xy})_{\max}$ [ms]
41	0.84	0.1	FO	0.238	111.0	84.6	203.0	7.47	4.1	2.579	2.215
			CP	0.240	110.0	83.6	195.4	7.43	0.8	3.345	2.624
		0	FO	0.251	114.5	85.8	242.7	7.33	3.7	2.353	2.032
			CP	0.253	113.3	84.7	222.9	7.34	0.9	2.914	2.507
101	13.45	0.1	FO	0.354	129.3	83.5	648.8	7.56	3.0	2.084	1.665
			CP	0.352	130.1	84.3	570.6	7.58	0.9	3.009	2.325
		0	FO	0.355	130.3	84.1	637.8	7.53	2.9	2.095	1.662
			CP	0.346	129.9	85.0	568.6	7.60	1.0	2.961	2.480

As the differences in bubble count rate and chord sizes indicated, the size of the probe tip is an essential parameter which can affect the detection of the air-water interfaces. The sensors in the present study were of comparable tip sizes (FO: $\varnothing = 0.03 \text{ mm}$; CP: $\varnothing = 0.125 \text{ mm}$) and larger differences in sensor sizes will increase differences in detected

air-water flow properties. In addition to the sensor sizes, the sensor positioning is a further parameter which can be modified. Due to the difference in designs, the sensors may be subject to different deformations or vibrating motions within the flow. These effects were not investigated, but appeared small in the present study.

7. Conclusion

An experimental study of high-velocity air-water flows was conducted on a stepped spillway to compare the performance of two types of phase-detection intrusive probes to detect a range of air-water flow properties. The dual-tip instrumentation were a commercially available fiber-optical probe (FO, from RBI, France) and a conductivity probe (CP) manufactured at WRL, UNSW Australia. The experiments were conducted at different locations within the flow including various transverse positions within a cross-section as well as in fully developed flow and just downstream of the inception point of air entrainment characterized by some instationary air entrainment processes. To optimize the comparison, all sensors were sampled simultaneously with the same data acquisition system and the post-processing was conducted with the same software. The following results were found:

1. Overall, the differences between the two phase-detection intrusive probes were negligible for a number of relevant air-water flow properties and parameters highlighting that results were independent of the tested phase-detective intrusive probe type.
2. The comparative analyses highlighted a very close agreement of the parameters linked to the data recorded by the leading tip, namely void fraction distributions and several characteristic parameters directly deriving from it (including depth-

averaged void fraction and equivalent clear water flow depth). This finding is significant since it indicates that experimental studies conducted with either phase-detection probe type are directly comparable.

3. Minor differences between the data were found in terms of air bubble and water droplet chord sizes, several clustered properties and interparticle arrival times. This is presumably related to the slightly smaller sensor tip of the fiber-optical probe allowing the detection of a larger number of air-water interfaces below 0.1 mm in size. The ability to detect smaller air bubbles resulted in the observation of a larger bubble count rate in the fully developed flow region and for $C < 0.3$ of up to 30%. The differences in the other parts of the air-water flows were minor highlighting a good agreement between the two phase-detection intrusive probe designs. Note that the void fractions were quasi not affected by the higher number of smallest bubble.
4. The interfacial velocity distributions were in close agreement for the two sensors systems confirming the suitability of both systems for measurements of time-averaged air-water flow velocities. The probe design and sensor positioning had no significant influence on the average travel time of particles between the two sensors. Despite of the disturbed signal due to the wake near the trailing tip of the fiber-optical probe (“wake noise”), the main two-phase flow characteristic was obviously recognizable in the correlation analysis.
5. Differences were however observed in terms of the turbulence intensity which was caused by the differences in recorded air-water interfaces between the leading and trailing tips of the fiber-optical probe. The reason was linked with the present in-line positioning of the two tips of the fiber-optical probe which

resulted in a wake flow behind the leading tip sucking in large quantities of air which were recorded by the trailing tip. This resulted in differences of bubble count rate between the two tips of up to 300% and in increased turbulence levels of up to 3 to 4 times the turbulence intensity measured with the conductivity probe. Accordingly, the “wake noise” on the trailing fibre-optical tip became relevant. The conductivity probe tips were positioned parallel separated by a small transverse distance resulting in almost identical void fraction and bubble count rate data for leading and trailing tips.

6. As for the individual probe geometry, it was found that small tips were able to pierce more (and smaller) bubbles and measure thus more adequately the effective flow. Furthermore, an in-line arrangement was not favourable as the trailing tip was affected by the leading tip. Optimal seems a dual tip probe with small tips, positioned beside each other (and not in-line).
7. Strictly spoken, the present comparison was limited to high-velocity free-surface flows. Further, some minor differences from the side-by-side positioning of the probes during measurement cannot be excluded.

8. Acknowledgements

The authors thank Stéphane Terrier, Cédric Bron, and José Pedro Matos (LCH, EPFL) for their assistance with the experiments at EPFL. The first author thanks Rob Jenkins (WRL, UNSW) for the manufacturing of the WRL double-tip conductivity probe. The second author thanks SNF (Swiss National Science Foundation, 200021_137572/1 and 200020_159967/1).

666 **References**

- 667 ANDRE, S., BOILLAT, J.-L., and SCHLEISS, A. J. (2008a):“Ecoulements aérés sur
668 évacuateurs en marches d’escalier équipées de macro-rugosités - Partie I:
669 Caractéristiques hydrauliques.”*La Houille Blanche*, No. 1, pp. 91-100.
- 670 ANDRE, S., BOILLAT, J.-L., and SCHLEISS, A. J. (2008b):“Ecoulements aérés sur
671 évacuateurs en marches d’escalier équipées de macro-rugosités, Partie II:
672 Dissipation d’énergie. ”*La Houille Blanche*, No. 1, pp. 101–108.
- 673 BERTOLA, V. (2002).“Optical probe visualization of air–water flow structure
674 through a sudden area contraction.”*Experiments in Fluids*, Vol. 32, No. 4, pp.
675 481-486.
- 676 BOES, R.M., and HAGER, W.H. (2003): “Hydraulic Design of Stepped Spillways.”
677 *Journal of Hydraulic Engineering*, ASCE, Vol. 129, No. 9, pp. 671-679.
- 678 CAIN, P., and WOOD, I.R. (1981): “Measurements of Self-aerated Flow on
679 Spillways.” *Journal of Hydraulic Division*, ASCE, Vol. 107, HY11, pp. 1425-
680 1444.
- 681 CARTELLIER, A., and ACHARD, J.L. (1991). "Local phase detection probes in
682 fluid/fluid two-phase flows." *Review of Scientific Instruments*, Vol. 62, pp. 279-
683 303.
- 684 CHANSON, H. (1997): “Air Bubble Entrainment in Free-Surface Turbulent Shear
685 Flows.” Academic Press, London, UK, 401 pages (ISBN 0-12-168110-6).
- 686 CHANSON, H. (2002). "Air-Water Flow Measurements with Intrusive Phase-
687 Detection Probes. Can we Improve their Interpretation ?" *Journal of Hydraulic*
688 *Engineering*, ASCE, Vol. 128, No. 3, pp. 252-255.
- 689 CHANSON, H. (2013). "Hydraulics of Aerated Flows: Qui Pro Quo?" *Journal of*

Hydraulic Research, Vol. 51, No. 3, pp. 223-243.

CHANSON, H., and CAROSI, G. (2007). "Turbulent Time and Length Scale Measurements in High-Velocity Open Channel Flows." *Experiments in Fluids*, Vol. 42, No. 3, pp. 385-401

CHANSON, H., and TOOMBES, L. (2002). "Air-Water Flows down Stepped chutes: Turbulence and Flow Structure Observations." *International Journal of Multiphase Flow*, Vol. 27, No. 11, pp. 1737-1761.

CUMMINGS, P.D. (1996). "Aeration due to Breaking Waves." Ph.D. thesis, Dept. of Civil Engrg., University of Queensland, Brisbane, Australia.

EDWARD, C.F., and MARX, K.D. (1995). "Multipoint Statistical Structure of the Ideal Spray, Part II: Evaluating Steadiness using the Interparticle Time Distribution." *Atomic & Sprays*, Vol. 5, pp. 435-455.

ERVINE, D.A. (1998). "Air entrainment in hydraulic structures: A review." Proc. Instn Civ. Engrs, Water, Maritime & Energy, Vol. 130, pp. 142–153

FELDER, S. (2013). "Air-Water Flow Properties on Stepped Spillways for Embankment Dams: Aeration, Energy Dissipation and Turbulence on Uniform, Non-Uniform and Pooled Stepped Chutes." Ph.D. thesis, School of Civil Engineering, The University of Queensland, Brisbane, Australia

FELDER, S., and CHANSON, H. (2009). "Turbulence, dynamic similarity and scale effects in high-velocity free-surface flows above a stepped chute", *Experiments in Fluids*, Vol. 47, No. 1, pp. 1 – 18; doi.org/10.1007/s00348-009-0628-3

FELDER, S., and CHANSON, H. (2011). "Air-Water Flow Properties in Step Cavity down a Stepped Chute." *International Journal of Multiphase Flow*, Vol. 37, No. 7, pp. 732–745 (DOI: 10.1016/j.ijmultiphaseflow.2011.02.009)

714 FELDER, S., and CHANSON, H. (2014). "Triple Decomposition Technique in Air–
715 Water Flows: Application to Instationary Flows on a Stepped Spillway."
716 *International Journal of Multiphase Flow*, Vol. 58, pp. 139-153 & 3 videos (DOI:
717 10.1016/j.ijmultiphaseflow.2013.09.006)

718 FELDER, S., and CHANSON, H. (2015). "Phase-Detection Probe Measurements in
719 High-Velocity Free-Surface Flows including a Discussion of Key Sampling
720 Parameters." *Experimental Thermal and Fluid Science*, Vol. 61, pp. 66-78 (DOI:
721 10.1016/j.expthermflusci.2014.10.009)

722 FELDER, S., and CHANSON, H. (2016a). "Simple Design Criterion for Residual
723 Energy on Embankment Dam Stepped Spillways." *Journal of Hydraulic
724 Engineering*, ASCE, Vol. 142, No. 4, Paper 04015062, 11 pages.

725 FELDER, S., and CHANSON, H. (2016b). "An Experimental Study of Air-water
726 Flows in Hydraulic Jumps with Channel Bed Roughness." WRL Research Report
727 RR259, Water Research Laboratory, UNSW Australia, 166pages (ISBN:
728 9780733436574)

729 FELDER, S., and CHANSON, H. (2016c). "Air–water flow characteristics in high-
730 velocity free-surface flows with 50% void fraction" *International Journal of
731 Multiphase Flow*, Vol. 85, pp. 186-195.

732 FELDER, S., and SEVERI, A. (2016). "Entrapped Air in High-velocity Free-surface
733 Flows on a Flat-sloped Spillway" Proc. of 20th Australasian Fluid Mechanics
734 Conference, Perth, Australia, 5-8 December 2016

735 GONZALEZ, C.A., and CHANSON, H. (2007). "Hydraulic Design of Stepped
736 Spillways and Downstream Energy Dissipators for Embankment Dams." *Dam
737 Engineering*, Vol. 17, No. 4, pp. 223-244.

738 GUALTIERI, C., and CHANSON, H. (2010). "Effect of Froude number on bubble
739 clustering in a hydraulic jump." *Journal of Hydraulic Research*, Vol. 48, No. 4, pp.
740 504-508.

741 HEINLEIN, J., and FRITSCHING, U. (2006). "Droplet clustering in
742 sprays." *Experiments in Fluids*, Vol. 40, No. 3, pp. 464-472.

743 HERRINGE, R.A., and DAVIS, M.R. (1974): "Detection of Instantaneous Phase
744 Changes in Gas-Liquid Mixtures." *Journal of Physics E: Scientific Instruments*,
745 Vol. 7, pp. 807-812.

746 HUNT, S., KADAVY, K., and HANSON, G. (2014). "Simplistic Design Methods
747 for Moderate-Sloped Stepped Chutes." *Journal of Hydraulic*
748 *Engineering*, ASCE, 10.1061/(ASCE)HY.1943-7900.0000938, 04014062.

749 IAHR (1953): Proceedings Minnesota International Hydraulics Convention, Part IV
750 (pp. 403-533). Joint Meeting IAHR & Hydr. Div. ASCE, University of Minnesota,
751 St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota.

752 ISHII, M. (1975): Thermo-Fluid Dynamic Theory of Two-Phase Flow, Eyrolles,
753 Paris.

754 JONES, O.C., DELHAYE, J.M. (1976). Transient and statistical measurement
755 techniques for two-phase flows: A critical review. *International Journal of*
756 *Multiphase Flow*, Vol. 3, 89–116.

757 KIM, S., FU, X.Y., WANG, X., ISHII, M. (2000). "Development of the miniaturized
758 four-sensor conductivity probe and the signal processing scheme." *International*
759 *Journal of Heat and Mass Transfer*, Vol. 43, No. 22, pp. 4101–4118.

760 KRAMER, K., and HAGER, W. H. (2005). "Air transport in chute flows."
761 *International Journal of Multiphase Flow*, Vol. 31, No. 10-11, 1181–1197.

762 LIMA NETO, I.E, ZHU, D.Z., and RAJARATNAM, M. (2008):“Bubbly jets in
 763 stagnant water.”*International Journal of Multiphase Flow*, Vol. 34, No. 12, pp.
 764 1130-1141.

765 MATOS, J. (2000): “Hydraulic Design of Stepped Spillways over RCC Dams.” Intl
 766 Workshop on Hydraulics of Stepped Spillways, Zürich, Switzerland, MINOR &
 767 HAGER (Editors), Balkema Publ., pp. 187-194 (ISBN 90 5809 135 X).

768 MILLER, N., and MITCHIE, R.E. (1970):“Measurement of local voidage in
 769 liquid/gas two-phase flow systems using a universal probe.”*Journal of British*
 770 *Nuclear Energy Society*, Vol. 9, No. 2, pp. 94-100.

771 MURZYN, F., MOUAZE, D., CHAPLIN, J.R. (2005):“Optical fibre probe
 772 measurements of bubbly flow in hydraulic jumps.”*International Journal of*
 773 *Multiphase Flow*, Vol. 31, No. 1, pp. 141-154.

774 NEAL, L.S., and BANKOFF, S.G. (1963): “A High Resolution Resistivity Probe for
 775 determination of Local Void Properties in Gas-Liquid Flows.” *Am. Inst. Chem. Jl*,
 776 Vol. 9, pp. 49-54.

777 OSTAD MIRZA M.J., MATOS, J., PFISTER, M., SCHLEISS, A.J. (2017).“The 784
 778 effect of an abrupt slope change on air entrainment and flow depths on stepped
 779 785 spillways.”*Journal of Hydraulic Research* [in press].786
 780 [doi:10.1080/00221686.2016.1255263].

781 PAGLIARA, S., CARNACINA, I., and ROSHNI, T. (2010). “Self-aeration and
 782 friction over rock chutes in uniform flow conditions”, *Journal of Hydraulic*
 783 *Engineering*, ASCE, Vol. 136, No. 11, pp. 959–964
 784 [doi:10.1061/(ASCE)HY.1943-7900.0000270]

785 PFISTER, M. (2002).Kaskadenbelüfter, HydraulischeModelluntersuchung.

786 MScThesis, VAW, ETH Zurich, Switzerland.

787 PFISTER, M., HAGER, W.H., and MINOR, H.-E. (2006):“Stepped chutes: Pre-
788 aeration and spray reduction.”*International Journal of Multiphase Flow*, Vol. 32,
789 No. 2, pp. 269-284, DOI: 10.1016/j.ijmultiphaseflow.2005.10.004.

790 PFISTER, M., and HAGER, W.H. (2009):“Deflector-generated jets.”*Journal of*
791 *Hydraulic Research*, Vol. 47, No. 4, pp. 466-475, DOI: 10.3826/jhr.2009.3525.

792 PFISTER, M., and HAGER, W.H. (2010a):“Chute aerators. I: Air transport
793 characteristics.”*Journal of Hydraulic Engineering*, ASCE, Vol. 136, No. 6, pp.
794 352-359, DOI: 10.1061/(ASCE)HY.1943-7900.0000189.

795 PFISTER, M., and HAGER, W.H. (2010b):“Chute aerators. II: Hydraulic
796 design.”*Journal of Hydraulic Engineering*, ASCE, Vol. 136, No. 6, pp. 360-367,
797 DOI: 10.1061/(ASCE)HY.1943-7900.0000201.

798 PFISTER, M., and HAGER, W.H. (2011):“Self-entrainment of air on stepped
799 spillways.”*International Journal of Multiphase Flow*, Vol. 37, No. 2, pp. 99-107,
800 DOI: 10.1016/j.ijmultiphaseflow.2010.10.007.

801 PFISTER, M. and CHANSON, H. (2014): ”Two-phase air-water flows: Scale effects
802 in physical modeling”, *Journal of Hydrodynamics*, Vol. 26, No. 2, pp. 291-298,
803 DOI: 10.1016/S1001-6058(14)60032-9.

804 PFISTER, M., HAGER, W.H., and BOES, R.M. (2014):“Trajectories and air flow
805 features of ski jump-generated jets”. *Journal of Hydraulic Research*, Vol 52, No.
806 3, pp. 336-346. DOI: 10.1080/00221686.2013.875072.

807 SERIZAWA, A, KATAOKA, I., and MICHİYOSHI, I. (1975): “Turbulence
808 Structure of Air-Water Bubbly Flows – I. Measuring Techniques.” *International*
809 *Journal of Multiphase Flow*, Vol. 2, No. 3, pp. 221-233.

810 STRAUB, L.G., and ANDERSON, A.G. (1958): "Experiments on Self-Aerated Flow
811 in Open Channels." *Journal of Hydraulic Division*, Proc. ASCE, Vol. 84,
812 No.HY7, paper 1890, pp. 1-35.

813 STUTZ, B., and REBOUND, J.L. (1997): "Experiments on unsteady
814 cavitation." *Experiments in Fluids*, Vol. 22, No. 3, pp. 191-198.

815 TAKAHASHI, M., and OHTSU, I. (2012). "Aerated flow characteristics of
816 skimming flow over stepped chutes, *Journal of Hydraulic Research*, Vol. 50, No.
817 4, pp. 427-434.

818 TERRIER, S. (2016): "Hydraulic performance of stepped spillway aerators and
819 related downstream flow features." PhD Thesis 6989, EPFL Lausanne.

820 WEI, W., DENG, J., and ZHANG, F. (2016): "Development of self-aeration process
821 for supercritical chute flows." *International Journal of Multiphase Flow*, Vol. 79,
822 pp. 172–180

823 WOOD, I.R. (1991): "Air Entrainment in Free-Surface Flows." IAHR Hydraulic
824 Structures Design Manual No. 4, Hydraulic Design Considerations, Balkema
825 Publ., Rotterdam, The Netherlands, 149 pages.

826 YONEDA, K, YASUO, A., and OKAWA, T. (2002): "Flow structure and bubble
827 characteristics of steam–water two-phase flow in a large-diameter pipe." *Nuclear
828 Engineering and Design*, Vol. 217, No. 3, pp. 267-281.

829 ZHANG, W., and ZHU, D. (2013): "Bubble characteristics of air–water bubbly jets in
830 crossflow." *International Journal of Multiphase Flow*, Vol. 55, No. October, pp.
831 156-171.