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On velocity estimations in highly aerated flows with dual-tip phase-detection probes - A commentary

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ABSTRACT

Air-water free-surface flows are extremely complicated to model physically and numerically. The development of the air-water velocity metrology has been relatively slow and is still on-going. Phase-detection needle probes have been successfully used for both laboratory and field measurements in high-turbulence air-water flows, but the signal processing is not trivial. Recently a different method, called adaptive window cross-correlations (AWCC), was introduced for dual-tip phase-detection probe signals in steady air-water flows (Kramer et al. 2019). The technique includes a number of intrinsic limitations, which can lead to very poor data retention rates and does not guarantee better data quality and bias-free outputs. These limitations are discussed in the context of air-water free-surface flows.

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1. Presentation

Although the first successful void fraction measurements in free-surface air-water flows can be dated to EHRENBERGER (1926), the development of the air-water velocity metrology has been much slower. Historically, the first measurements were conducted with modified Pitot tubes (HALBRONN, 1952, VIPARELLI 1953) or an electrical system based upon salt solution advection (STRAUB et al. 1954). In the late 1960s, hot-film probes were used to characterise the velocity and velocity fluctuations in the water phase of gas-liquid flows (DELHAYE 1968, RESCH and LEUTHEUSSER 1972, HERRINGE and DAVIS 1974). The application to free-surface air-water flows was not trivial because of a number of issues including calibration and film contamination (JONES and DELHAYE 1976, LANCE and BATAILLE 1991, CHANSON and BRATTBERG 1998, RENSEN et al. 2005). In parallel, the introduction of needle probe sensor led to the development of various phase-detection probe designs. Velocity measurement techniques were proposed based upon the single-tip probe signal response to interface piercing. SENE (1984) and CARTELLIER and ACHARD (1991) correlated the slope of conductivity sensor signal during piercing to the interfacial velocity, although the piercing response signal might be adversely affected by water impurities and sensor shape defects (CUMMINGS 1996). CHANG et al. (2003) derived the interfacial velocity from the Fourier response of optical-fiber probe signal. With dual-tip phase-detection probes, bubble velocities were calculated based upon various individual bubble event detection techniques (SERIZAWA 1974, LIU and BANKOFF 1993, ROIG et al. 1998, CHANSON 2005). Cross-correlation analyses of dual-tip phase-detection probe signals deliver reliable interfacial time-averaged velocities (HERRINGE and DAVIS 1974,1976, CROWE et al. 1998). Within some basic assumptions, the interfacial turbulence may be derived (Appendix A). Several studies discussed more specifically the effects of the longitudinal sensor separation distance (KIPPHAN 1977, CHANSON and TOOMBES 2001), transverse sensor separation distance (CUMMINGS 1996) and maximum correlation coefficient (ANDRE et al. 2005).

In the last decade, two major developments in air-water velocity measurements have been the total pressure probe and optical flow metrology. Total pressure measurements with miniature diaphragm sensor can deliver a fine characterisation of the velocity and turbulence in the water phase, when accounting for the local void fraction (ZHANG et al. 2016, ZHANG and CHANSON 2018a, WANG et al. 2018). The optical flow approach is based upon the detection of changes in brightness due to reflectance difference associated with passages of air-water interfaces (BUNG and VALERO 2016, ZHANG and CHANSON 2018). Some key limitations are the requirements for two-dimensional flows, the use of high-speed high-resolution video camera, and the adverse impact of sidewall effects (BUNG and VALERO 2015, ZHANG and CHANSON 2018b).

Recently a different signal processing method based upon cross-correlations was proposed for dual-tip phase-detection probe signals in steady air-water flows (KRAMER et al. 2019). Herein, it is argued that the recent conclusions by KRAMER et al. (2020) include a number of broad statements, which do not reflect the

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Fig. 1. Dual-tip phase-detection probe next to the sidewall in a rough-wall boundary layer (stepped chute: h = 010 m, $\theta = 25°$, width: 1 m, shutter speed: 1/8,000 s) - Data set: ZHANG and CHANSON (2018b), $d_c/h = 0.9$, $Re = \rho_w q_w/\mu_w = 0.9 \times 10^5$, step edge 6, probe sensor size: 0.025 mm, flow direction from top right to bottom right (blue arrow).

inherent limitations of the publicised method nor the complexity of air-water flow measurements in free-surface turbulent flows. Both aspects are developed, before future research directions are discussed.

2. Discussion

The adaptive window cross-correlations (AWCC) was developed to be applied to the signals of dual-tip phase-detection probe in steady air-water flows (KRAMER et al. 2019). The concept is based upon repeated cross-correlation calculations of the air-water signal over relatively short time windows to obtain pseudo-instantaneous velocities. While the approach is innovative and worthwhile, a number of major intrinsic limitations must not be forgotten or hidden. For example, the approach is only valid in steady flows, in absence of instationarities; the outputs describe interfacial processes detected by the phase-detection sensors and cannot characterise the turbulence in the water phase nor in the air-phase.

In principle, the AWCC technique smoothes the air-water phase-detection probe signal. The processed signal is not truly comparable to an instantaneous velocity signal, e.g. from a hot film probe and total pressure probe, because of the discrete non-continuous nature of the signal and inherent smoothing. The temporal resolution of the AWCC is locally restricted by the local bubble count rate. The phase-detection probe signal characterises some average in interfacial processes. In practice, the AWCC technique requires a "minimum window size" (KRAMER et al. 2019) corresponding to a minimum number of 'bubbles' per window to yield meaningful cross-correlation outputs. For a stepped spillway air-water flow, KRAMER et al. (2019) suggested a minimum number of five 'bubbles' per window. As an illustration, when the local bubble count rate is 120 Hz, i.e. 120 bubbles per second as in Fig. 2A, and the minimum number of bubbles per window is $N_p = 5$, the 'pseudo sampling frequency' would be 24 Hz, that is very low compared to typical sampling rates in wind tunnels and water channels (200 Hz to 1,000 Hz).

The selection of an optimum window size is based upon the concept of 'bubbles', something highly questionable when the void fraction exceeds 0.3. The AWCC technique is physically based upon a detection of a number of interfaces, with substantial physical differences between air surrounded by water, water surrounded by air or an intermediate region where $C \approx 50\%$. This is illustrated in Fig. 2, showing the probe response signals in three very different air-water regions of a stepped spillway flow. Such physical differences are intrinsically smoothed during the brutal application of the AWCC technique to the entire air-water flow, e.g. the whole air-water column, without moderation and adjustments.

In free-surface air-water flows, the detected 'bubbles' are not uniformly distributed nor randomly distributed (ELPERIN et al. 1996, CHANSON and TOOMBES 2002). (See also Figure 2A.) In particular, some particle clustering may occur and the level of clustering provides some quantitative measure of bubble-turbulence interactions, self-excitation of fluctuations of the bubble concentration and associated turbulent dissipation (CALZAVARINI et al. 2008, CHANSON 2013). The application of the AWCC technique can only provide physically meaningful data in regions of high bubble count rates and high clustering rates. Elsewhere, i.e. the majority of air-water flow, the AWCC data outputs are irregularly distributed in time.

The implementation of the AWCC method to real air-water flows, e.g. a stepped spillway, showed a very-substantial amount of rejected data (KRAMER et al. 2019). At many measurement locations, the rejected data exceeded 50% of the entire signal when the void fraction C was less than 0.5 (Fig. 3). Fig.3A presents the dimensionless distribution of void fraction and interfacial velocity, with Y_{90} the normal distance where the void fraction is $C = 0.9$ and V_{90} is the characteristics velocity at $y = Y_{90}$. For the same data set, Figure 3B shows the dimensionless bubble count rate and data rejection rate in percentage. The large amount of rejected data is linked to a combination of physical limitations and intrinsic limitations of the processing technique. In particular, the AWCC assumes that bi-modal velocity (OMF) distributions are "non-physical", in contradiction to the existence of physical instabilities in non-linear air-water systems as shown theoretically (LEZZI, and PROSPERETTI 1991) and experimentally (CHANSON and BRATTBERG 1998, RENSEN and ROIG 2001).

Finally, the dual-tip phase detection probe signal analyses assume inherently an one-dimensional flow, although transverse fluctuations can be very large and rapid, as shown in hydraulic jumps by WANG and CHANSON (2019). The adverse impact on any sub-sampled techniques, like the AWCC, is implicitly ignored.

3. Concluding remarks

Air-water free-surface flows are extremely complicated to model physically and numerically, because of the uncontrolled exchanges of air and water through the free-surface, the large

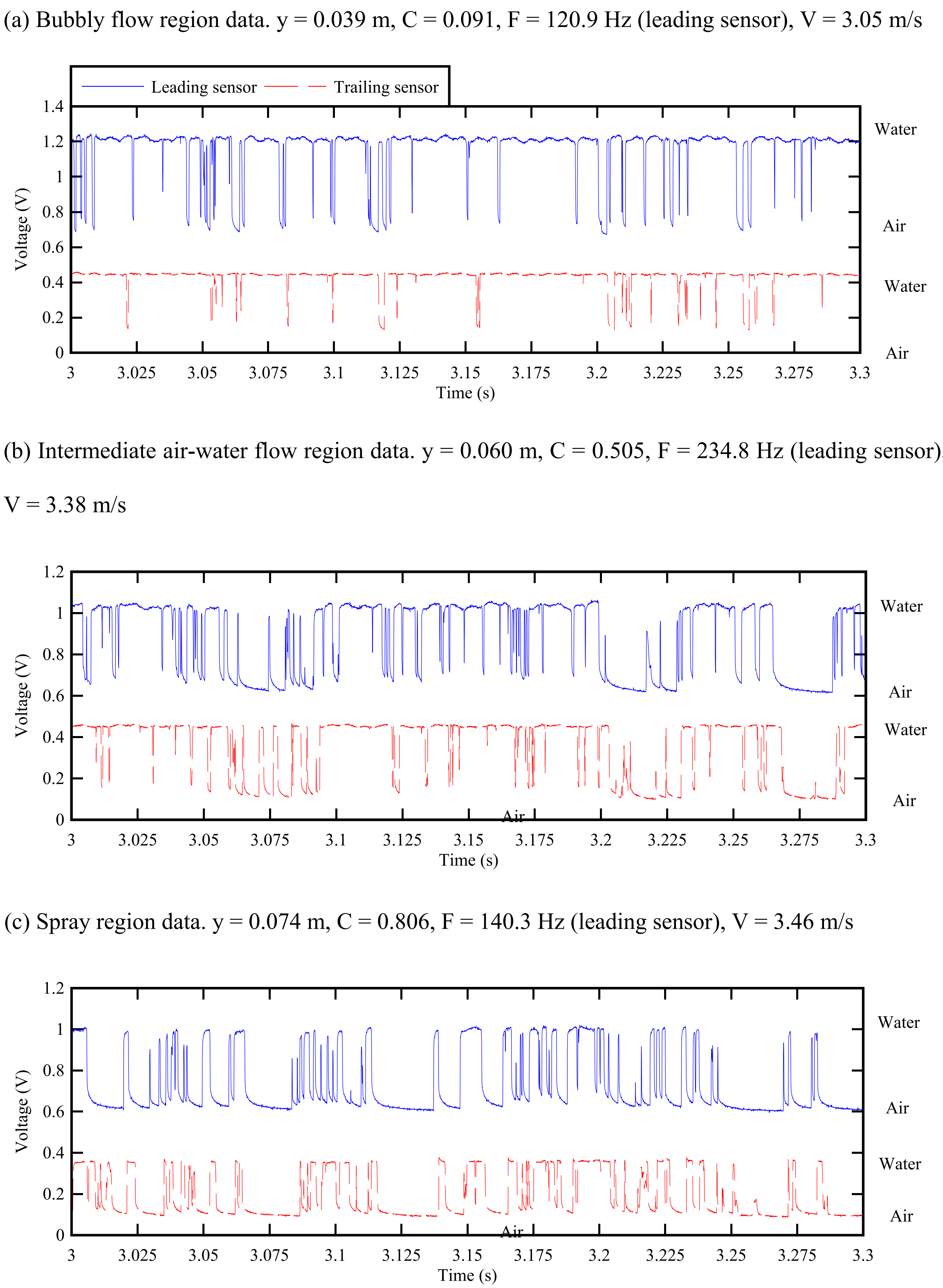

Fig. 2. Instantaneous voltage signals of dual-tip phase-detection probe signal in a rough-wall boundary layer (stepped chute: h = 010 m, θ = 15.9°) - Data set: CHANSON and TOOMBES (2002), d_c/h = 1.53, Re = $\rho_w q_w/\mu_w$ = 1.9 × 10^5, step edge 8, probe sensor size: 0.025 mm, sampling rate: 20 kHz - The high voltage is Water and the low voltage is Air (same legend for all graphs). (a) Bubbly flow region data. y = 0.039 m, C = 0.091, F = 120.9 Hz (leading sensor), V = 3.05 m/s. (b) Intermediate air-water flow region data. y = 0.060 m, C = 0.505, F = 234.8 Hz (leading sensor), V = 3.38 m/s. (c) Spray region data. y = 0.074 m, C = 0.806, F = 140.3 Hz (leading sensor), V = 3.46 m/s.

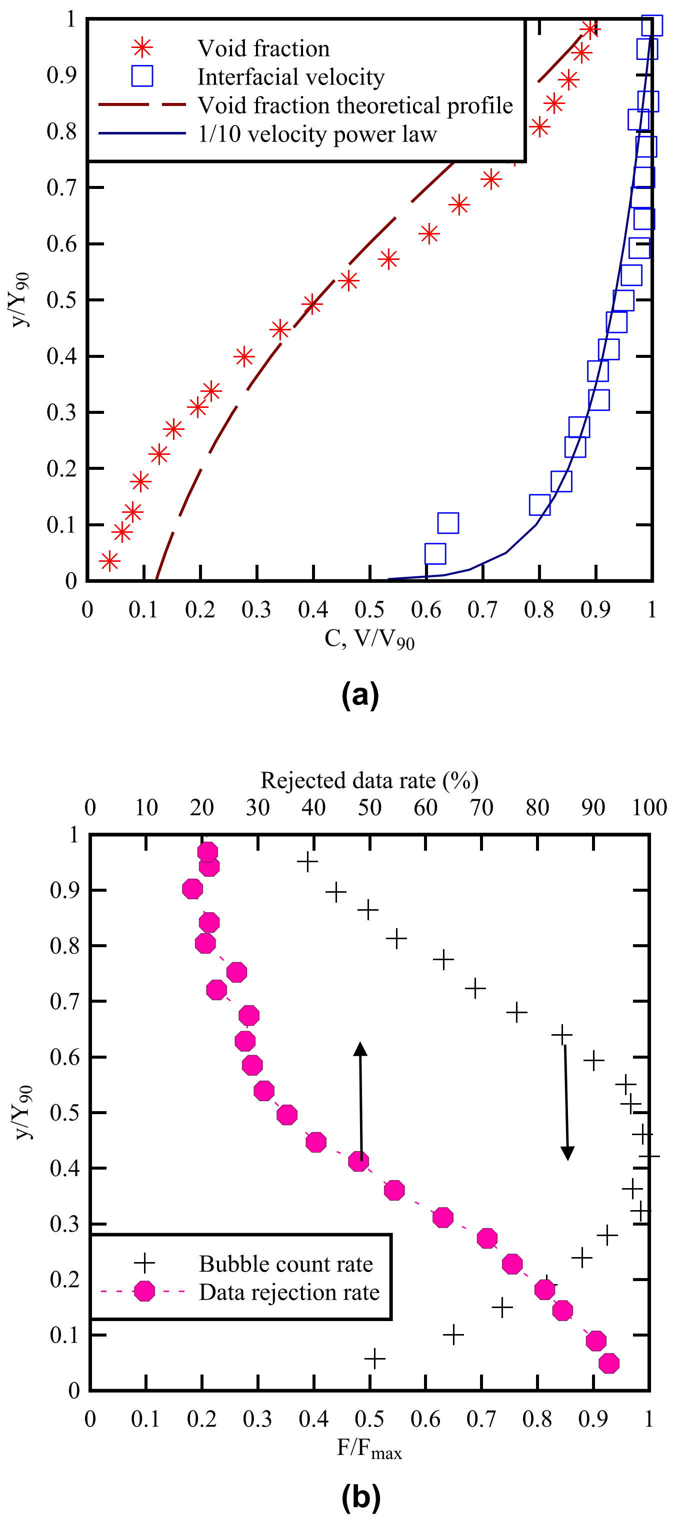

Fig. 3. Rejection rate with the AWCC method in free-surface air-water flow - Data set: KRAMER et al. (2019), $d_c/h = 1.1$, $Re = \rho_w q_w/\mu_w = 1.13 \times 10^5$, step edge 8, $Y_{90} = 0.0674$ m, $C_{mean} = 0.44$, $F_{max} = 144$ Hz (leading sensor), $V_{90} = 3.4$ m/s, sensor size: 0.35 mm, sampling rate: 20 kHz. (A) Void fraction and interfacial data - Comparison with theoretical solution of advective diffision of air and 1/10th velocity power law (B) Bubble count rate data and data rejection rate.

amounts of entrained air and the bubble-turbulence interactions including turbulence modulation and interfacial deformations. For the last five decades, phase-detection needle probes have been successfully used for both laboratory and field measurements in high-turbulence air-water flows (Fig. 1). The signal processing is not trivial, even in simple steady one-directional flows. Many phase-detection probe signal processing techniques rely upon some cross-correlation approach, although all the implementations have some degree of imperfections.

The recently-introduced adaptive window cross-correlations (AWCC) method was developed to be applied to the signals of dual-tip phase-detection probe in steady air-water flows (KRAMER et al. 2019). While original, the technique includes a number of inherent limitations, which can lead to very poor data retention rates (Fig. 3B) and does not guarantee better data quality and bias-free outputs. The air-water phase detection probe signals processed with the AWCC method are implicitly smoothed, and the data outputs deliver a much lesser resolution than many other systems, e.g., total pressure probe, hot-film probe. The implications are serious because the air-water flow features are intrinsically ignored during a blunt application of the technique to the entire air-water column, unless empirical and artificial moderation and adjustments.

Moving forwards, unbiased signal processing must be based upon newer methods based upon the entire signal processing, as attempted in ZHANG and CHANSON (2019). Further research into air-water free-surface flows needs to combine experimental, theoretical and numerical modelling, as well as composite approaches embedding more than two or more methodologies, e.g. hybrid modelling. This is not trivial, especially when the industrial applications are large hydraulic structures, e.g. dam spillways and dropshafts, operating at Reynolds numbers in excess of 10^7 to 10^8, sometimes with strong three-dimensional flow features.

Declaration of Competing Interest

None.

CRediT authorship contribution statement

Hubert Chanson: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijmultiphaseflow.2020.103330.

Appendix A. Interfacial velocity and turbulence intensity in air-water flows

When the velocity is measured with a dual-tip phase-detection probe, the time-averaged interfacial velocity is equal to:

$$V = \frac{\Delta X}{T} \tag{A1}$$

where V is the interfacial velocity in the longitudinal direction aligned with the two tips, Δx is the separation distance between the two tips, and T is the travel time for which the cross-correlation function is maximum (CROWE et al. 1998). The dimensionless standard deviation of the interfacial velocity equals:

$$Tu = \frac{V'}{V} = \frac{\sqrt{\sigma_{XY}^2 - \sigma_{XX}^2}}{T} \tag{A2}$$

where σ_{xy} is the standard deviation of the cross-correlation function and σ_{xx} is the standard deviation of the autocorrelation function (KIPPHAN 1977, CHANSON and TOOMBES 2002). Assuming that the successive detections of bubble interfaces by the probe sensors is a true random process, the cross-correlation function is a Gaussian distribution, and Equation (A-2) becomes:

$$Tu = \frac{\sqrt{2}}{\sqrt{\pi} \times T} \times \sqrt{\left(\frac{T_{XY}}{(R_{XY})_{\max}}\right)^2 - T_{XX}^2} \tag{A3}$$

where T_{xy} is the cross-correlation integral time scale, T_{xx} is the auto-correlation time scale, and $(R_{xy})_{max}$ is the maximum cross-correlation when the time lag equals T (FELDER and CHANSON 2014).

If the cross-correlation function is a Gaussian distribution and defining $\tau_{0.5}$ the time scale for which: $R_{xy}(T+\tau_{0.5})=R_{xy}(T)/2$, and $T_{0.5}$ is the characteristic time for which the normalised autocorrelation function equals 0.5, Equation (A-3) may be approximated as:

$$\frac{V'}{V} = 0.851 \times \frac{\sqrt{\tau_{0.5}^2 - T_{0.5}^2}}{T} \tag{A4}$$

With all above equations, the calculations become indeterminate when the time-averaged velocity V tends to zero.

References

ANDRE, S., BOILLAT, J.L., SCHLEISS, A., 2005. Two-phase flow characteristics of stepped spillways. discussion. J. Hydraulic Eng. ASCE 131 (5), 423–427.

BUNG, D.B., VALERO, D., 2016. Optical flow estimation in aerated flows. J. Hydraulic Res. IAHR 54 (5), 575–580. doi:10.1080/00221686.2016.1173600.

CARTELLIER, A., ACHARD, J.L., 1991. Local phase detection probes in fluid/fluid two-phase flows. Rev. Sci. Instrum. 62 (2), 279–303.

CALZAVARINI, E., BERG, T.H., van der, TOSCHI, F., LOHSE, D., 2008. Quantifying microbubble clustering in turbulent flow from single-point measurements. Phys. Fluids 20 (4), 6 pages. doi:10.1063/1.2911036, Paper 040702.

CHANG, K.A., LIM, H.J., SU, C.B., 2003. Fiber optic reflectometer for velocity and fraction ratio measurements in multiphase flows. Rev. Scientific Inst. 75 (1), 284–286 Vol. 74, No. 7, pp. 3559-3565Discussion: 2004.

CHANSON, H., 2005. Air-water and momentum exchanges in unsteady surging waters: an experimental study. Exp. Thermal Fluid Sci. 30 (1), 37–47.

CHANSON, H., 2013. Hydraulics of aerated flows: qui pro quo? J. Hydraulic Res. 51 (3), 223–243. doi:10.1080/00221686.2013.795917, IAHR, Invited Vision paper.

CHANSON, H., BRATTBERG, T., 1998. Air entrainment by two-dimensional plunging jets: the impingement region and the very-near flow field. Proc. 1998 ASME Fluids Eng. Conf. FEDSM'98, Washington DC, USA, June 21-25, Keynote paper, Paper FEDSM98-4806, 8 pages (CD-ROM).

CHANSON, H., TOOMBES, L., 2001. Experimental investigations of air entrainment in transition and skimming flows down a stepped chute. application to embankment overflow stepped spillways. Dept. of Civil Engineering *Research Report No. CE158*. The University of Queensland, Brisbane, Australia July, 74 pages.

CHANSON, H., TOOMBES, L., 2002. Air-water flows down stepped chutes: turbulence and flow structure observations. Int. J. Multiphase Flow 28 (11), 1737–1761. doi:10.1016/S0301-9322(02)00089-7.

CROWE, C., SOMMERFIELD, M., and TSUJI, Y. (1998). "Multiphase Flows with Droplets and Particles." CRC Press, Boca Raton, USA, 471 pages.

CUMMINGS, P.D., 1996. Aeration due to Breaking Waves. In: Dept. of Civil Engineering. University of Queensland, Brisbane, Australia, p. 523 pages. doi:10.14264/uql.2015.70.

DELHAYE, J.M. (1968). "Measurement of the local void fraction in two-phase air-water flow with a hot-film anemometer." *Report CEA-R-3465(E)*.

EHRENBERGER, R., 1926. Wasserbewegung in steilen Rinnen (Susstennen) mit besonderer Berucksichtigung der Selbstbelüftung." ('Flow of Water in Steep Chutes with Special Reference to Self-aeration.'). Zeitschrift des Österreichischer Ingenieur und Architektverein 15/16 (17/18).

ELPERIN, T., KLEEORIN, N., ROGACHEVSKII, I., 1996. Self-excitation of fluctuations of inertial particle concentration in turbulent fluid flow. Phys. Rev. Letters 77 (27), 5373–5376.

FELDER, S., CHANSON, H., 2014. Triple Decomposition Technique in Air–Water Flows: Application to Instationary Flows on a Stepped Spillway. International Journal of Multiphase Flow 58, 139–153. doi:10.1016/j.ijmultiphaseflow.2013.09.006, & 3 videos.

HALBRONN, G., 1952. Etude de la Mise en Régime des Ecoulements sur les Ouvrages à Forte Pente. Applications au problème de l'Entraînement d'Air." ('Study of the Setting up of the Flow Regime on High Gradient Structures. Application to Air Entrainment Problem.'). Jl La Houille Blanche 1, 21–40 No. 3, pp. 347-371; No. 5, pp. 702-722 (in French).

HERRINGE, R.A., DAVIS, M.R., 1974. Detection of Instantaneous Phase Changes in Gas-Liquid Mixtures. Jl. of Physics E: Scientific Instruments 7, 807–812.

HERRINGE, R.A., DAVIS, M.R., 1976. Structural Development of Gas-Liquid Mixture Flows. J. Fluid Mech 73, 97–123.

JONES, O.C., DELHAYE, J.M., 1976. Transient and Statistical Measurement Techniques for two-Phase Flows: a Critical Review. Int. J. Multiphase Flow 3, 89–116.

KIPPHAN, H., 1977. Bestimmung von Transportkenngrößen bei Mehrphasenströmungen mit Hilfe der Korrelationsmeßtechnik. Chemie Ingenieur Technik 49 (9), 695–707 (in German).

KRAMER, M., VALERO, D., CHANSON, H., BUNG, D.B., 2019. Towards Reliable Turbulence Estimations with Phase-Detection Probes: an Adaptive Window Cross-Correlation Technique. Exp. Fluids 60 (1), 6. doi:10.1007/s00348-018-2650-9, Paper 2pages.

KRAMER, M., HOHERMUTH, B., VALERO, D., FELDER, S., 2020. Best practices for velocity estimations in highly aerated flows with dual-tip phase-detection probes. Int. J. Multiphase Flow 126 (103228), 14. doi:10.1016/j.ijmultiphaseflow.2020.103228, Paperpages.

LANCE, M., BATAILLE, J., 1991. Turbulence in the Liquid Phase of a Uniform Bubbly Air-Water Flow. J. Fluid Mech. 222, 95–118.

LEZZI, A.M.PROSPERETTI, 1991. The Stability of an Air Film in a Liquid Flow. J. Fluid Mech. 226, 319–347.

LIU, T.J., BANKOFF, S.G., 1993. Structure of Air-water Bubbly Flow in a Vertical Pipe - II. Void Fraction, Bubble Velocity and Bubble Size Distribution. Intl J. Heat Mass Transf. 36 (4), 1061–1072.

RENSEN, J., ROICG, V., 2001. Experimental study of the unsteady structure of a confined bubble plume. Int. J. Multiphase Flow 27, 1431–1449.

RENSEN, J., LUTHER, S., LOHSE, D., 2005. Hot-film anemometry in bubbly flow i: bubble-probe Interaction. Int. J. Multiphase Flow 31, 285–301.

RESCH, F.J., LEUTHEUSSER, H.J., 1972. Reynolds stress measurements in hydraulic jumps. J. Hydraulic Res. IAHR 10 (4), 407–429.

ROIG, V., SUZANNE, C., MASBERNAT, L., 1998. Experimental investigations of a turbulent bubbly mixing layer. Intl J. Multiphase Flow 24 (1), 35–54.

SENE, K.J., 1984. Aspects of Bubbly Two-Phase Flow. Trinity College, Cambridge, UK *Ph.D. thesis*Dec..

SERIZAWA, A., 1974. Fluid-Dynamic Characteristics of Two-Phase Flow. Institute of Atomic Energy, Kyoto University, Japan *Ph.D. thesis*.

STRAUB, L.G., KILLEN, J.M., LAMB, O.P., 1954. Velocity Measurements of Air-Water Mixtures. Trans. ASCE 119, 207–220.

VIPARELLI, M., 1953. The Flow in a Flume with 1:1 Slope. In: Proc. 5th IAHR Congress. IAHR-ASCE, Minneapolis, USA, pp. 415–423.

WANG, H., CHANSON, H., 2019. Characterisation of transverse turbulent motion in quasi-two-dimensional aerated flow: application of four-point air-water flow measurements in hydraulic jump. Exp. Thermal Fluid Sci. 100, 222–232. doi:10.1016/j.expthermflusci.2018.09.004.

WANG, H., SLAMET, N.S., ZHANG, G., CHANSON, H., 2018. Intrusive measurements of air-water flow properties in highly turbulent supported plunging jets and effects of inflow jet conditions. Chem. Eng. Sci. 177, 245–260. doi:10.1016/j.ces.2017.11.030.

ZHANG, G., CHANSON, H., 2018a. Application of local optical flow methods to high-velocity free-surface flows: validation and application to stepped chutes. Exp. Thermal Fluid Sci. 90, 186–199. doi:10.1016/j.expthermflusci.2017.09.010.

ZHANG, G., CHANSON, H., 2018b. Application of local optical flow methods to high-velocity free-surface flows: validation and application to stepped chutes. Exp. Thermal Fluid Sci. 90, 186–199. doi:10.1016/j.expthermflusci.2017.09.010.

ZHANG, G., CHANSON, H., 2019. On void fraction and flow fragmentation in two-phase gas-liquid free-surface flows. Mech. Res. Commun. 96, 24–28. doi:10.1016/j.mechrescom.2019.01.001, & Digital Appendix pp. S1-S6.

ZHANG, G., CHANSON, H., WANG, H., 2016. Total pressure fluctuations and two-phase flow turbulence in self-aerated stepped chute flows. Flow Meas. Instrum. 51, 8–20. doi:10.1016/j.flowmeasinst.2016.08.007.