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Discussion of "Performance of Intrusive Phase-Detection Probe with Large Sensor Size in Air-Water Flow Measurement and Application to Prototype Hydraulic Jump Study"

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This paper presents a discussion of "Performance of Intrusive Phase-Detection Probe with Large Sensor Size in Air-Water Flow Measurement and Application to Prototype Hydraulic Jump Study" by Rongcai Tang, Ruidi Bai, and Hang Wang. https://doi.org/10.1061/(ASCE)HY.1943-7900.0002022.

Air-water flows are commonly observed in hydraulic structures. While their behavior has been widely investigated at laboratory scale, including hydraulic jumps, spillway flows, breaking bores, and plunging jets, prototype measurements are scarcely available, mostly because air-water flow measurements in the real world are currently hindered by the fragility of phase-detection probes. In this context, the study by the authors provides relevant information and an interesting methodology in support of the development of thicker and sturdier instruments that will bridge the gap between laboratory and prototype.

Some studies have shown that prototype measurements are an ambitious yet reachable goal, with pioneering investigations by Cain and Wood (1981) on the smooth spillway chute of Aviemore Dam (New Zealand), where a void fraction probe ($Ø_1 = 0.05$ mm) and dual-tip probes ($Ø_1 = 1$ mm) withstood velocities up to 21.7 m/s. Chanson (1988) successfully applied a dual-tip phase-detection probe with a 0.2 mm inner electrode and a 0.8 mm outer diameter to self-aerated flows with interfacial velocities up to 20 m/s. Hohermuth et al. (2021) tested air-water flow properties in the smooth tunnel spillway of the Luzzone Dam (Switzerland) with velocities up to 38 m/s using dual-tip conductivity probes with inside/outside diameters of 0.125 and 0.6 mm, respectively. A more comprehensive summary of previous studies with various probe sizes is presented in Table 1. Overall, these studies show that the construction of mechanically resistant probes is an achievable goal, even in high-velocity flows at large Reynolds numbers. While it is acknowledged that all intrusive phase-detection probes affect the measured signal, studies have shown that probe sensor size has a minor influence on the void fraction and interfacial velocity data, in contrast to measurements of bubble count rate, bubble size distributions, and bubble clustering characteristics, for which large differences have been observed. Simply, any discussion of the effect of sensor size on air-water flow properties in hydraulic jumps

Table 1. Summary of selected air-water flow studies, with details on probe sensor size

Type	Reference	F_1	R	d_1 (m)	V_1 (m/s)	Probe type	Needle size (mm)		Flow type
							$Ø_1$	$Ø_2$	
Prototype	Cain and Wood (1981)	—	$2.2–3.2 \times 10^6$	—	18.1–21.7	Conductivity (dual tip)	1.0	6.0	Spillway chute
		—	—	—	—	Conductivity	0.05	—	
	Volkart and Rutschmann (1984)	—	$1.8–2.8 \times 10^6$	—	16.2–18.5	—	0.5	—	Tunnel spillway
	Hohermuth et al. (2021)	—	$1.95–6.0 \times 10^6$	—	23–38	Conductivity (dual tip)	0.125	0.6	Tunnel spillway
Laboratory	Chanson (1988)	—	$2.1–4.8 \times 10^5$	—	9.0–17.9	Conductivity (dual tip)	0.2	0.8	Smooth chute
	Cummings (1996)	7.6–18	$2.4–7.2 \times 10^4$	0.010–0.012	2.4–6.1	Conductivity (dual tip)	0.025	0.2	Plunging jet
	Chanson and Brattberg (2000)	6.3–8.5	$3.28–4.40 \times 10^4$	0.014	2.34–3.14	Conductivity (dual tip)	0.025	0.2	Hydraulic jump
	Murzyn et al. (2005)	2.0–4.8	$4.60–8.85 \times 10^4$	0.021–0.059	1.50–2.19	Optical fiber (dual tip)	0.010	—	Hydraulic jump
	Tang et al. (2022)	15.1	1.4×10^5	0.021	6.8	Conductivity (dual tip)	0.1 1.0	0.8 3.0	Hydraulic jump
	Wüthrich et al. (2022)	2.4	1.9×10^5	0.084	2.21	Conductivity (dual tip)	0.25	0.8	Hydraulic jump
	Present study	2.4	1.9×10^5	0.084	2.21	Conductivity (dual tip)	0.25–0.64	1.0–1.3	Hydraulic jump

Note: F_1 = Froude number for hydraulic jumps and plunging jets, defined as $\mathsf{F}_1 = V_1/(gd_1)^{0.5}$, where d_1 = initial depth and V_1 = initial flow velocity; $Ø_1$ = diameter of inner conductor filament; $Ø_2$ = diameter of outer stainless needle; and R = Reynolds number defined as $\mathsf{R} = \rho V_1 d_1/\mu$ for hydraulic jumps and $\mathsf{R} = \rho V_1 R_h/\mu$ for spillway chutes, where R_h = hydraulic radius (i.e., approximately the clear water depth).

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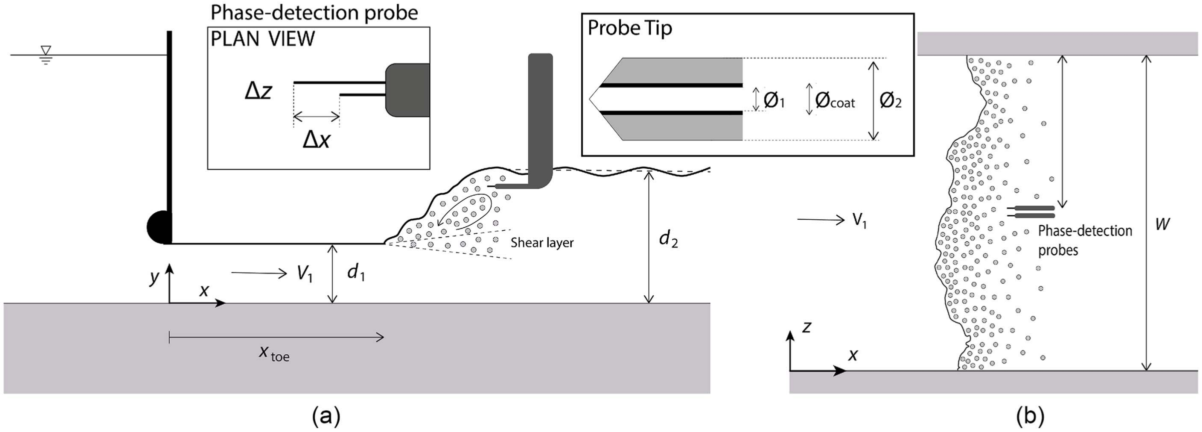

Fig. 1. Experimental facility and instrumentation at University of Queensland: (a) side view; and (b) top view. Details of dual tip conductivity probes are also provided.

must be closely associated with the air-water flow property under consideration.

In addition to the authors' valuable contribution, the discussers would like to present some results of experiments that were recently conducted at the University of Queensland (Australia). Here, a hydraulic jump was induced in a horizontal channel with a rectangular section 3.2 m long, 0.5 m wide, and 0.4 m deep (Shi et al. 2021). The study used dual-tip conductivity probes with two identical needle sensors having a longitudinal separation distance Δx, mounted with a transverse separation distance Δz (Fig. 1). The probe had an inner conductor filament with a diameter $Ø_1$, covered with coating material with a diameter $Ø_{coat}$, isolating the conductor from an outer needle, which was made of stainless steel with a diameter $Ø_2$, as detailed in Fig. 1. Altogether, four double-tip phase-detection conductivity probes were tested, with their details summarized in Table 2. Note that Probes 1 and 2 were tested side by side, as well as Probes 3 and 4 (Fig. 1). In line with Tang et al. (2022), the probes were sampled at 20 kHz for 45 s. Tested flow conditions, provided in Table 2, resulted in a Froude number $\mathsf{F}_1 = V_1/(gh_1)^{0.5} = 2.4$, as also tested by Wüthrich et al. (2022).

The probe signal was post-processed using a single threshold technique at 50% of the voltage difference ΔV between air (V_{min}) and water (V_{max}), in line with the authors and with the literature. At two elevations ($y/d_1 = 1.13$ in the shear layer and $y/d_1 = 1.67$ in the recirculation zone), the probability distribution functions (PDFs) of the raw signal are presented in Fig. 2, showing that the probes tested by the discussers had differences in behavior in line with the ones presented by the authors. More specifically, at both selected locations most differences were observed for higher voltages, in the range $0.5 < (V–V_{min})/\Delta V < 1$, which confirms the authors' theory that increasing probe diameters is likely to result in incomplete voltage drops in the phase-detection signal.

Based on these data, the void fraction C was computed as the cumulative time that each tip spent in air over the sample duration. The bubble count rate F was defined as the average number of bubbles encountered by each sensor per second. For the present data, Fig. 3 showed negligible differences in terms of void fraction for the profiles measured with Probes 1 to 4 ($Ø_1 = 0.25$–0.64 mm; $Ø_2 = 1$–1.3 mm), compared with data measured with Probe 5 ($Ø_1 = 0.25$ mm and $Ø_2 = 0.8$ mm) by Wüthrich et al. (2022). This suggests that despite the difference in signal PDFs (Fig. 2), a small increase in outer probe diameter (0.8–1.3 mm) was not responsible for any substantial difference in void fraction. Contrarily, the maximum bubble count rate showed a decreasing trend for larger probe diameters, with probe 3 ($Ø_1 = 0.64$ mm) detecting 80% and 86% of the bubbles compared with Probes 1 and 2 ($Ø_1 = 0.25$ mm) at $x_{toe}/d_1 = 1.19$ and 3.57, respectively. These differences become more important for the thicker probes with $Ø_1 = 1$ mm and $Ø_2 = 3$ mm, as shown by the authors (Tang et al. 2022). This suggests that for probes up to $Ø_1 = 0.64$ mm and $Ø_2 = 1.3$ mm, traditional signal processing techniques can be applied to compute the void fractions, while an adapted technique introduced by the authors might only be necessary for larger probes ($Ø_1 = 1$ mm and $Ø_2 = 3$ mm) to enable detection of smaller air bubbles and therefore more reliable bubble characteristics.

It is worthwhile to point out that, for a hydraulic jump with the same Froude number $\mathsf{F}_1 = 2.4$, Murzyn et al. (2005) reported values of $F_{max} \times d_1/V_1 < 1$, despite the small diameter $Ø_1 = 10$ μm of their optical fiber probe. While many factors might affect such a difference (including the type of probe), the authors believe that it is linked to the lower Reynolds number used in the experiment by Murzyn et al. (2005), $\mathsf{R} = 7.54 \times 10^4$, leading to a lesser aeration of the hydraulic jump which must be considered for any comparison between laboratory and prototype environments, as recently discussed by Estrella et al. (2022).

In conclusion, the discussers agree with the authors that more research is needed to identify the influence of probe size on obtained air-water flow properties, in support of the development of thicker and sturdier instruments that will bridge the gap between laboratory and prototype.

Table 2. Technical details of double-tip phase-detection conductivity probes used in the present study

References	Probe No.	$Ø_1$ (mm)	$Ø_2$ (mm)	$Ø_{coat}$ (mm)	Δx (mm)	Δz (mm)	Conductor material	Manufacturer of conductor
Wüthrich et al. (2022)	5	0.25	0.80	0.298	5.10	1.80	silver	Goodfellow, UK
Present study	1	0.25	1.00	0.298	7.5	2.47	silver	Goodfellow, UK
	2	0.25	1.00	0.330	7.8	2.20	silver	SDR Scientific, UK
	3	0.38	1.10	0.480	7.0	2.22	silver	SDR Scientific, UK
	4	0.64	1.30	0.760	6.8	3.23	silver	SDR Scientific, UK

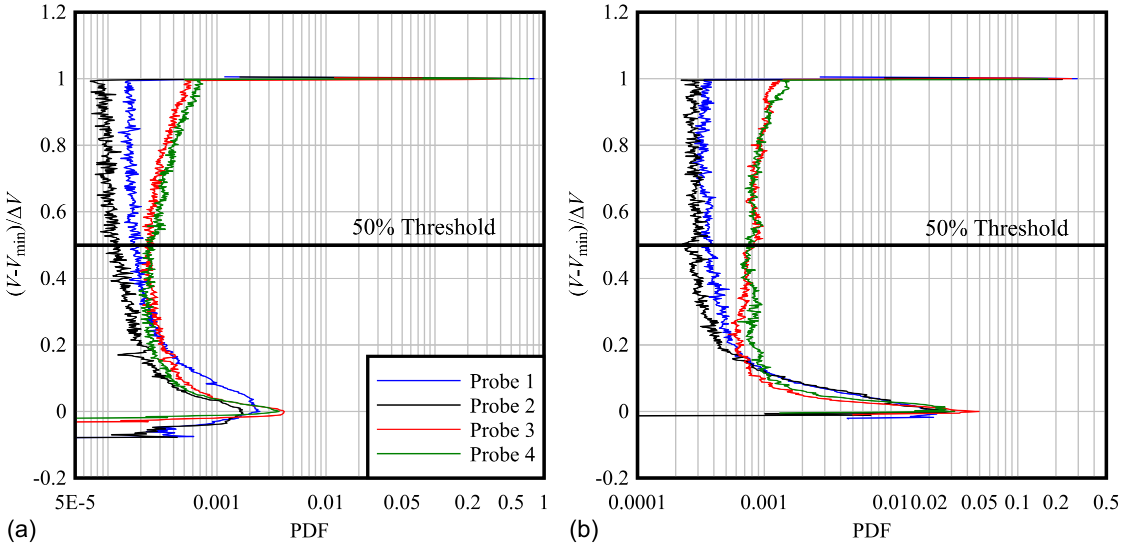

Fig. 2. Probability distribution functions (PDFs) of raw signal collected with all tested probes at $x - x_{toe}/d_1 = 1.19$: (a) in the shear layer at $y/d_1 = 1.13$, where $F = F_{max}$ in Fig. 3(b); and (b) in the recirculating zone at $y/d_1 = 1.67$, where $C \sim 0.5$. Same legend applies to both graphs.

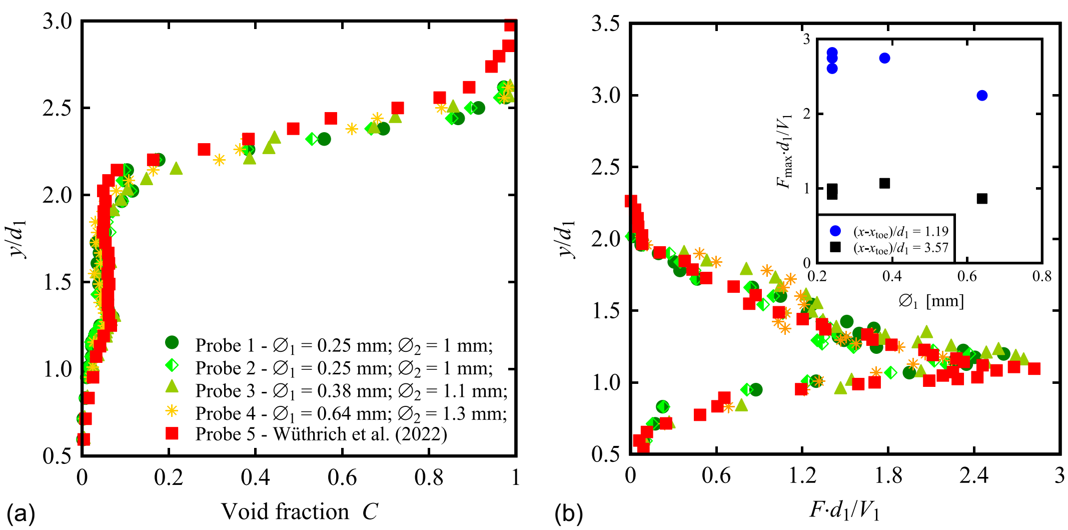

Fig. 3. Air-water properties measured with different probe sizes in hydraulic jump with Froude number $\mathsf{F}_1 = 2.4$: (a) void fraction at $(x - x_{toe})/d_1 = 3.57$; and (b) bubble count rate at $(x - x_{toe})/d_1 = 1.19$, with zoom-in on the behavior of F_{max} as a function of probe inner diameter $Ø_1$. Present data were compared with those by Wüthrich et al. (2022) with $\mathsf{F}_1 = 2.4$ and $\mathsf{R} = 1.9 \times 10^5$ (Table 1); Legend applies to both graphs.

Data Availability Statement

Some or all data, models, or code that support the findings of this discussion are available from the corresponding author upon reasonable request.

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