Air-Water Flow Measurements with Intrusive, Phase-Detection Probes: Can We Improve Their Interpretation?

H. Chanson[1]

[1]Reader, Fluid Mechanics, Hydraulics and Environmental Engineering, Dept. of Civil Engineering, Univ. of Queensland, Brisbane QLD 4072, Australia.

Introduction

Interest in air-water flows has not diminished in recent years, as evident by the number of associated papers published in the *Journal of Hydraulic Engineering* (ASCE) and other journals, such as the *Journal of Hydraulic Research* (IAHR), the *International Journal of Multiphase Flow* and the *Journal of Fluids Engineering* (ASME). For example, during the period January 1998 to July 2001, the *Journal of Hydraulic Engineering* published nine papers on air-water flow measurements. Approximately twice as many papers appeared in the *International Journal of Multiphase Flow*. The interest is accompanied by frequent citations of very early, sometimes outdated articles. Such citations suggest that little progress has been achieved in past decades. To be sure, some articles are classics: for example, Straub and Anderson (1958). Their work was cited 24 times between 1985 and June 2001. Another classic is Wood (1983). It was cited 10 times between 1985 and June 2001 (source: Science Citation Index Expanded).

The writer believes that a particularly important issue is the often inadequate or incomplete interpretation of air-water flow instrumentation by hydraulic engineers and researchers. The present Forum article briefly comments of the several common techniques for measuring air-water flows by means of intrusive phase detection probes, and it describes a basic data processing method that readily yields expanded information on air-water flow properties.

Intrusive Phase-Detection Probes

In hydraulic engineering, most air-water flows are characterized by large amounts of entrained air. Void fractions are commonly larger than 5–10%, and flows are of high velocity with ratios of flow velocity to bubble-rise velocity greater than 10 or even 20. Classical measurement probes (e.g., pointer gauge, Pitot tube, LDA velocimeter) are affected by air bubbles and can produce inaccurate readings.

When void fraction C exceeds about 10–15%, and when the liquid fraction $(1-C)$ is larger than about 5–10%, the most reliable probes are the intrusive phase detection probes, notably the optical fiber probe and the conductivity/resistivity probe (Jones and Delhaye 1976; Bachalo 1994; Chanson 1997a). Intrusive probes are designed to pierce bubbles and droplets. The principle behind the optical probe is the change in optical index between the two phases (Cartellier 1992; Cartellier and Barrau 1998). The principle behind the conductivity, or electrical probe, is the difference in electrical resistivity between air and water. The resistance of air is 1,000 times larger than that of water, and a needle resistivity probe gives accurate information on the local void fluctuations (Herringe 1973; Serizawa et al. 1975; Chanson 1997a).

Fig. 1 illustrates examples of intrusive probe designs. There are two types: the single tip and dual-tip probes. Their respective purposes are described below. Typical probe signals are shown in Fig. 2. Although a probe signal should be theoretically rectangular, probe response is not exactly square because of the finite size of the tip, the wetting/drying time of the interface covering the tip, and the response time of the probe and electronics.

Basic Measurements and Data Analysis

For both probe types, the probe outputs basically are the void fraction and bubble-count rate. Dual-tip probes also provide air-water velocity, specific interface area, and distributions of chord length. Fig. 3 presents an example of void fraction, bubble-count rate, velocity, and specific interface area distributions measured in a skimming flow down a 16° stepped cascade (step height: 0.1 m; flow rate: 0.188 m^2/s). The data presented in Fig. 2 and subsequently in Figs. 4 and 5 were recorded in the same cross section at $y = 53$ mm. Details are given in Chanson and Toombes (2001a).

The air concentration or void fraction C is the proportion of time that the probe tip is in the air. Past experience shows that the probe orientation with the flow direction has little effect on the void fraction accuracy, provided that the probe support does not affect the flow past the tip (e.g., Sene 1984). The bubble count rate F is the number of bubbles impacting the probe tip. This measurement is sensitive to probe tip size, bubble sizes, velocity, and scanning rate, particularly when sensor size is larger than the smallest bubble sizes. There is an unique relationship between bubble count rate and void fraction as demonstrated by Toombes (2002).

Velocity measurement is based upon the successive detection of air-water interfaces by two tips. This technique assumes that the probe tips are aligned along a streamline and that bubbles and droplets are little affected by the leading tip. In turbulent air-water flows, the successive detection of a bubble by each tip is highly improbable, and therefore it is common to use a cross-correlation technique (e.g., Crowe et al. 1998). The time-averaged, air-water velocity equals

$$V = \frac{\Delta x}{T} \tag{1}$$

where Δx is the distance between tips (Fig. 1), and T is the time for which the cross-correlation function is maximum (Fig. 4). The shape of the cross-correlation function provides further information on the velocity fluctuations. The turbulent intensity may be derived from the broadening of the cross-correlation function

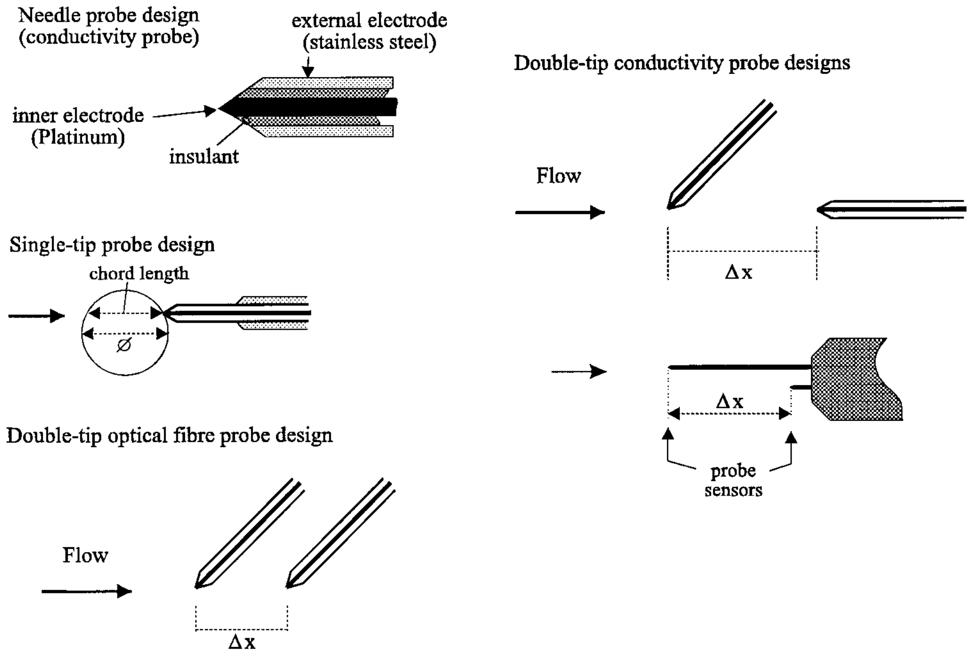

Fig. 1. Intrusive phase detection probes: sketches of probe design

compared to the auto-correlation function (Kipphan 1977; Chanson and Toombes 2001b). Fig. 4 shows an example of auto- and cross-correlation functions for the flow case mentioned above.

The measurement of the air-water interface area is a function of void fraction, velocity, bubble size, and bubble count. Specific air-water interface area, *a*, is defined as the air-water interface area per unit volume of air and water. It may be estimated from the air bubble size in monosize bubbly flows

$$a = 6 \cdot \frac{C}{\varnothing} \tag{2}$$

where $\varnothing$ is the bubble diameter. Measurements with intrusive probes do not provide bubble diameters but bubble chord lengths (Fig. 1). For any bubble shape, size distribution, and chord length distribution, the mean chord length size (i.e., number mean size) equals $C \cdot V/F$ by continuity. The specific air-water interface area may then be estimated as

$$a = \frac{4 \cdot F}{V} \tag{3}$$

Eq. (3) is valid for bubbly flows. In regions of high air content ($C > 0.3-0.4$), the flow structure is more complex, and the result is not exactly the true specific interface area. Then, *a* becomes simply proportional to the number of air-water interfaces per unit length of air-water mixture, i.e., $a \propto 2 \cdot F/V$.

Remarks

Some studies have suggested that interfacial velocities may be measured with a single-tip probe, based upon the voltage rise time associated with a water-air transition (e.g., Cartellier 1992). However, this technique is restricted to specific applications and probe designs. Several studies show that it does not work with most probes, for large void fractions, or high velocities (e.g., Sene 1984; Cummings 1996).

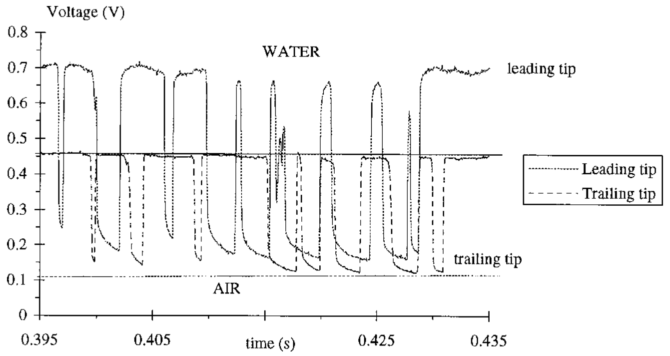

Fig. 2. Voltages across a double-tip conductivity probe (scan rate: 20 kHz per tip). Local air-water flow properties: $C = 0.29$; $V = 3.24$ m/s; $F = 217$ Hz (skimming flow).

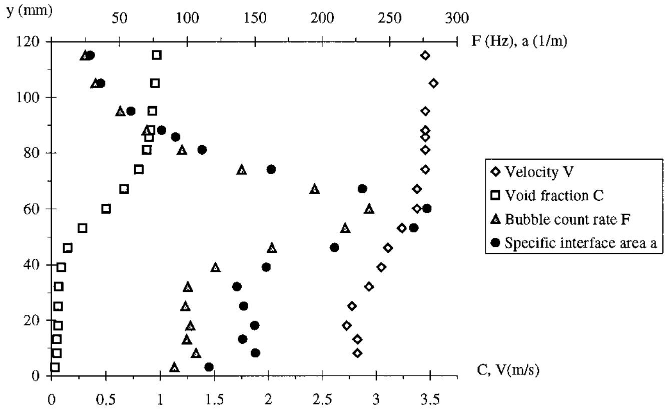

Fig. 3. Distributions of air concentration, bubble-count rate, velocity, and specific interface area. Skimming flow down a 16° stepped chute (0.19 m^2/s; step height: 0.1 m, step edge 8).

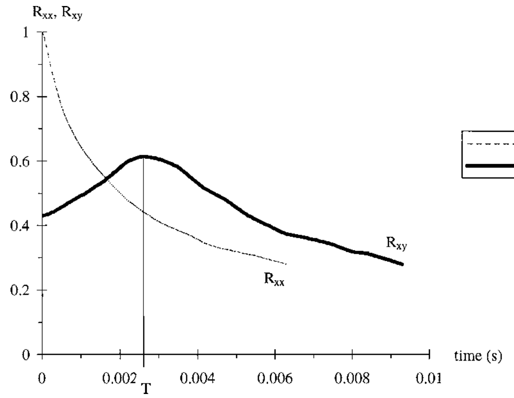

Fig. 4. Normalized auto-correlation and cross-correlation functions. Local air-water flow properties: $C=0.29$; $V=3.24$ m/s; $F=217$ Hz (skimming flow).

The probe signals may be analyzed to provide bubble and droplet chord size distributions (e.g., Chanson 1997b, 1999), although the amount of data processing is significant. Fig. 5 presents the probability distribution functions of bubble chord sizes and water chord sizes in 0.5 mm intervals. The data were measured at the same location and for the same flow conditions as those in Figs. 2 and 4. Bubble chord sizes are indicated in white, and water chord sizes in black. The last column indicates the probability of chord size exceeding 20 mm. Further signal processing may yield information on air-water structures, including bubble/droplet clusters (e.g., Chanson and Tombes 2001a).

Application to Air-Water Mass Transfer

Air-water flows in hydraulic structures have great potential for aeration enhancement of flow because of the large interfacial area generated by entrained bubbles, as inferred by Fig. 3. This consideration is worthy commenting on in the context of using intrusive probes for measuring air-water flow.

The mass transfer rate of a chemical across an interface varies directly as the coefficient of molecular diffusion, the negative gradient of gas concentration, and the interface area. If the chemical of interest is volatile (e.g., oxygen), the transfer is controlled by the liquid phase, and the gas transfer of the dissolved chemical may be expressed as

$$\frac{\partial}{\partial t} C_{\text{gas}} = k_L \cdot a \cdot (C_{\text{sat}} - C_{\text{gas}}) \tag{4}$$

where k_L is the liquid film coefficient; a is the specific surface area; C_{gas} is the local dissolved gas concentration; and C_{sat} is the concentration of dissolved gas in water at equilibrium (e.g., Gulliver 1990). Eq. (4) accounts for the effect of air bubble entrainment and the drastic increase in interfacial area. Many studies have assumed implicitly that the term $(k_L \cdot a)$ is a constant. For example, this assumption is made by all but one relevant papers published in the *Journal of Hydraulic Engineering* and the *Journal of Environmental Engineering* (ASCE) during the period January 1998 to July 2001. The assumption is incorrect. Detailed studies showed that the mass transfer coefficient k_L in turbulent gas-liquid flows is almost constant regardless of bubble sizes and flow situations (e.g., Kawase and Moo-Young 1992), but the interface area varies greatly along a hydraulic structure as a function of the air-water flow properties, as explained above. If the air-water interface area is measured, the integration of the mass transfer equation may provide a genuine, accurate estimate of aeration performances (e.g., Toombes and Chanson 2000).

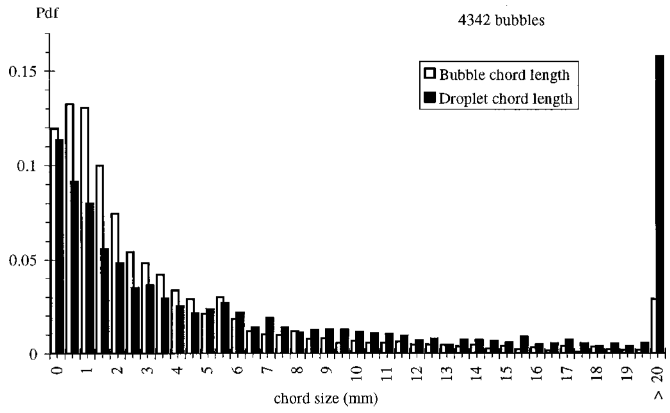

Fig. 5. Probability distribution functions of bubble and droplet chord sizes in 0.5 mm intervals. Local air-water flow properties: $C=0.29$; $V=3.24$ m/s; $F=217$ Hz (skimming flow).

Concluding Comment

During the period January 1998 to July 2001, the *Journal of Hydraulic Engineering* published nine papers on air-water flow measurements. All but one paper presented only void fraction data, although some papers presented velocity data as well. The writer's intent with this Forum article is to point out that the probes and techniques customarily used for obtaining air-water properties can readily provide substantially more information than most papers present. With relative ease, intrusive phase-detection probes may provide detailed additional information on bubble count rate, specific interface area, and bubble chord sizes. Such information is essential to gain a better understanding of air-water mass transfer in hydraulic engineering applications. It will further assist comprehension of the interactions between turbulence and entrained air: interactions actively researched by multiphase flow experts, including hydraulic engineers.

Acknowledgment

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