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Letter to the Editor

Experimental analysis of local void fraction measurements for boiling hydrocarbons in complex geometry – Discussion

Hubert Chanson *

Division of Civil Engineering, The University of Queensland, Brisbane, QLD 4072, Australia

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The discusser congratulates the authors for their significant contribution. They presented some challenging gas–liquid flow measurements with three different gases in a complex geometry using some interesting signal-processing. Herein the discusser aims to complement the discussion on local void fraction, especially in terms of the second statistical moment and signal correlation analyses.

With a phase-detection intrusive probe, the time-variation of the voltage output has a "square-wave" shape. Each steep rise of the signal corresponds to a gas bubble pierced by the probe sensor. The signal is theoretically rectangular, but the probe response is not square because of the finite size of the tip, the wetting/drying time of the interface on the sensor and the response time of the probe electronics. The signal-processing may be conducted on the raw signal output and on a thresholded "square-wave" signal (like the authors). A thresholded signal analysis relies upon some arbitrary discrimination between the two phases. The technique may be based upon single or multiple thresholds, or some signal pattern recognition The resulting square-wave signal yields the instantaneous void fraction ε' with $\varepsilon' = 0$ in liquid and $\varepsilon' = 1$ in gas. It is used to calculate the time-averaged void fraction, bubble count rate, the air/water chord times, the bubble/droplet chord lengths and their statistical moments (mean, median, std, skewness, kurtosis), and the streamwise particle grouping analysis. Some simple considerations show that the variance of the bi-modal distribution of instantaneous void fraction equals:

$$\varepsilon_{\text{rms}}^2 = \frac{1}{N}\sum_{1}^{N}(\varepsilon' - \bar{\varepsilon})^2 = \bar{\varepsilon} \times (1 - \bar{\varepsilon}) \tag{1}$$

where N is the number of samples and $\bar{\varepsilon}$ is the time-averaged void fraction. Eq. (1) is a parabolic equation observed experimentally by the authors (Aprin et al., 2007, Fig. 13). The second statistical moment of the void fraction (Eq. (1)) is linked with the gas bubble count rate F, defined as the number of bubbles impacting the probes. It is a quantity that is easily measurable with any phase-detection probe. The bubble count rate is proportional to the fluctuations of instantaneous void fraction and hence to $\bar{\varepsilon} \times (1 - \bar{\varepsilon})$. Experimental data in air–water flows showed a parabolic relationship between the time-averaged void fraction and bubble count rate:

$$\frac{F}{F_{\max}} = 4 \times \bar{\varepsilon} \times (1 - \bar{\varepsilon}) \tag{2}$$

where $F_{\max}$ is the maximum bubble count rate in a cross-section. Eq. (2) was obtained in high-velocity free-surface flows on smooth chute and in stepped spillway flows (e.g. Chanson, 1997; Chanson and Toombes, 2002; Gonzalez and Chanson, 2004; Kokpinar, 2005). Some experimental data are shown in Fig. 1. The data were obtained in supercritical open channel flows above a stepped invert for five dimensionless discharges d_c/h at several cross-sections above step edges. Toombes (2002) demonstrated the theoretical validity of Eq. (2) and proposed a more general extension.

The authors used the results of a signal correlation analysis to select the window duration of their PDF data analysis. The signal correlation analyses were further extended recently (Chanson, 2007). A simple auto-correlation analysis give the auto-correlation integral time scales T_{xx}:

$$T_{xx} = \int_{\tau=0}^{\tau=\tau(R_{xx}=0)} R_{xx}(\tau) \times \mathrm{d}\tau \tag{3}$$

where R_{xx} is the normalised auto-correlation function and τ is the time lag. The auto-correlation time scale T_{xx} represents the integral time scale of the longitudinal bubbly flow structure. It is a characteristic time of the eddies advecting

* Tel.: +61 7 33653516; fax: +61 7 33654599.
E-mail address: h.chanson@uq.edu.au

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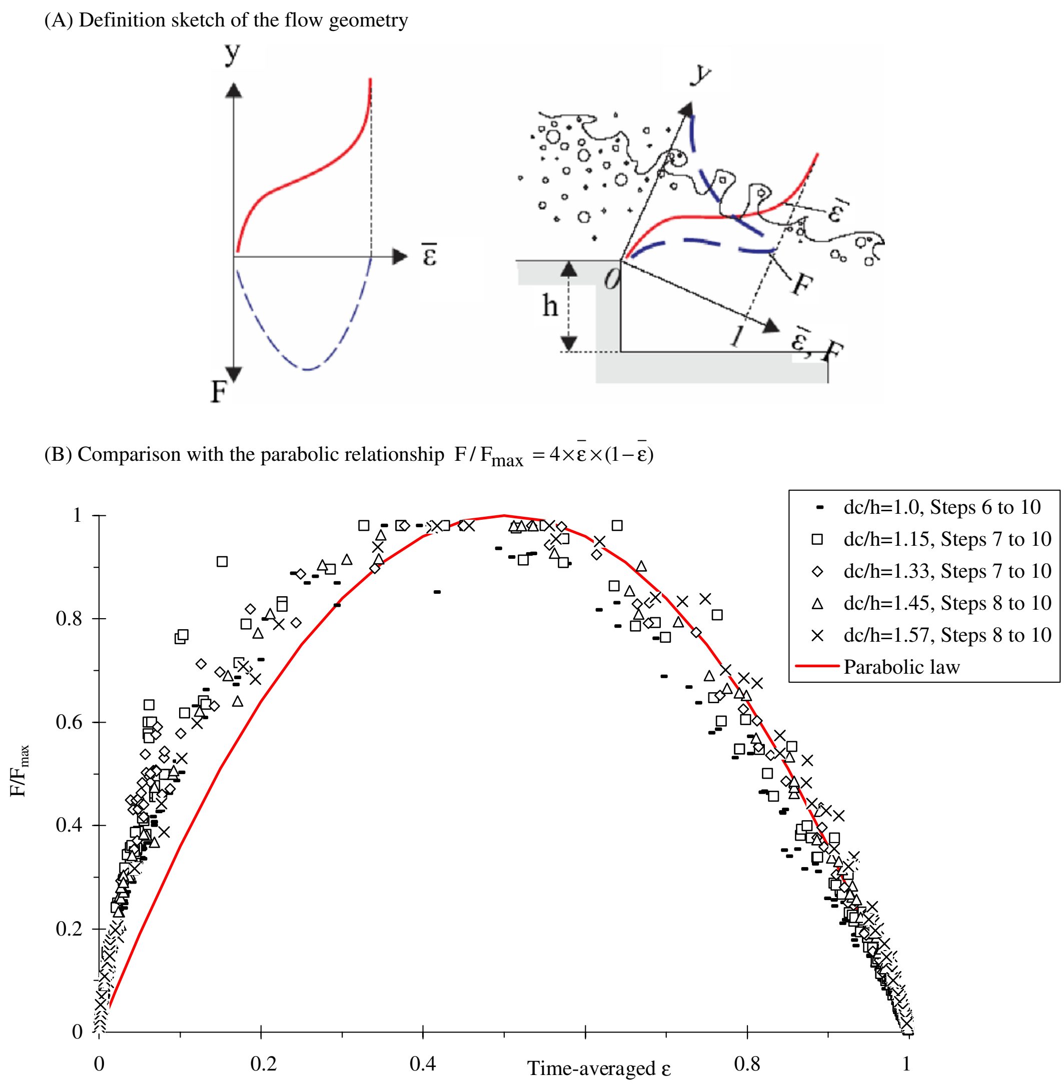

Fig. 1. Dimensionless relationship between bubble count rate F and time-averaged void fraction $\bar{\varepsilon}$ in skimming flows on a stepped chute (Data: Chanson and Carosi, 2007).

the air–water interfaces in the longitudinal direction. The corresponding turbulent integral length scale is

$$L_{xx} = \overline{U} \times \int_{\tau=0}^{\tau=\tau(R_{xx}=0)} R_{xx}(\tau) \times \mathrm{d}\tau \tag{4}$$

where $\overline{U}$ is the advective velocity.

When two (or more phase) detection probe sensors are simultaneously sampled, their signals may be analysed in terms of the cross-correlation function R_{xy}. A basic correlation analysis results include the maximum cross-correlation coefficient $(R_{xy})_{\max}$, and the cross-correlation integral time scale T_{xy}:

$$T_{xy} = \int_{\tau=0}^{\tau=\tau(R_{xy}=0)} R_{xy}(\tau) \times \mathrm{d}\tau \tag{5}$$

where R_{xy} is the normalised cross-correlation function between the two probe output signals separated by a distance Y. The cross-correlation time scale T_{xy} is a characteristic time of the vortices with a length scale Y advecting the air–water flow structures. The length scale Y may be a transverse separation distance Δz or a streamwise separation Δx (e.g. Chanson and Carosi, 2007). When identical experiments with two probes are repeated using different separation distances Y, an integral turbulent length scale may be calculated:

$$L_{xy} = \int_{Y=0}^{Y=Y((R_{xy})_{\max}=0)} (R_{xy})_{\max} \times \mathrm{d}Y \tag{6}$$

The length scale L_{xy} represents a length scale of the large vortical structures advecting the air bubbles and air–water packets. The associated turbulent integral time scale is

$$T = \frac{1}{L_{xy}} \times \int_{Y=0}^{Y=Y((R_{xy})_{\max}=0)} (R_{xy})_{\max} \times T_{xy} \times \mathrm{d}Y \tag{7}$$

T represents the integral time scale of the large eddies advecting air bubbles.

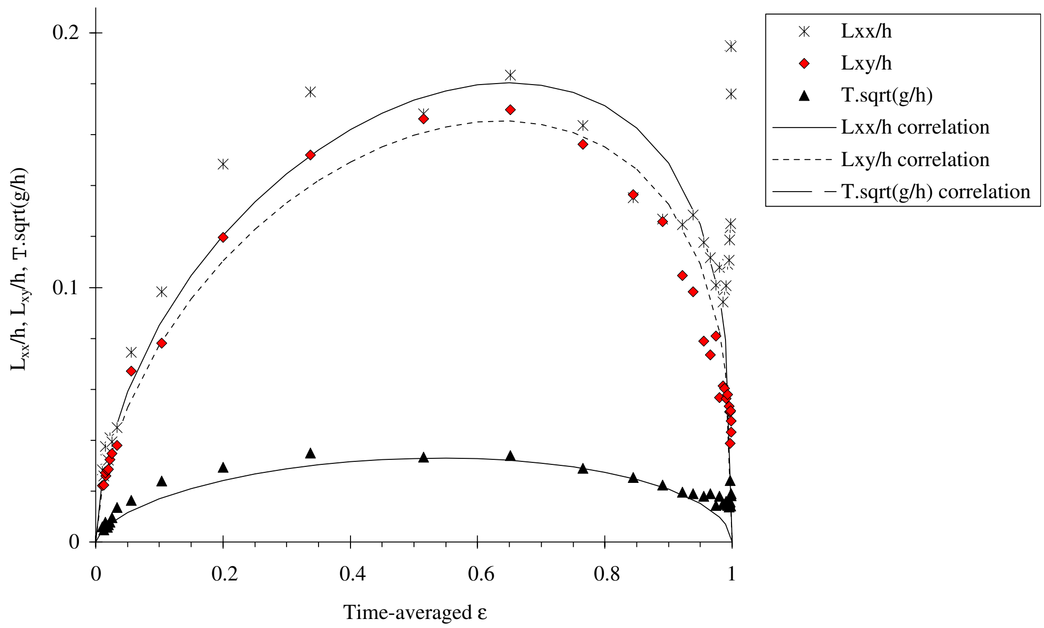

Fig. 2. Dimensionless relationship between advection length scale L_{xx}, transverse integral length scale L_{xy} and transverse integral time scale T in skimming flow on a stepped chute (Data: Chanson and Carosi, 2007) – $d_c/h = 1.45$, $Re = 6.4E+5$, Step 10.

Fig. 2 presents some experimental results obtained in a skimming flow on a stepped channel. Two identical probes were separated by a transverse distance Y. Each probe was sampled at 20 kHz for 20 s and the experiments were repeated with several transverse separation distances Y ($0 \leqslant Y \leqslant 56$ mm). The experimental data highlighted that the relationships between the integral turbulent length scales L_{xy} and L_{xx} and integral time scale T, and the void fraction had a "skewed parabolic shape" with a maxima occurring for time-averaged void fractions between 0.6 and 0.7 (Fig. 2). Note that the turbulent length scales were closely related to the step cavity height h: i.e., $L_{xx}/h \approx L_{xy}/h \approx 0.02$ to 0.2. The result was irrespective of the dimensionless flow rate d_c/h and Reynolds numbers (Chanson and Carosi, 2007).

In summary, it is shown that the parabolic relationship between the second statistical moment of void fraction and the time-averaged void fraction may be derived analytically, and it is valid for a broad range of gas–liquid flow situations. Some basic correlation analyses of the probe signal outputs may lead further information on the turbulent length and timescale of the gas–liquid flow. While the technique was validated in high-velocity free-surface flows, it is applicable to other gas–liquid flow situations.

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