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A new method of relating a chord length distribution to a bubble size distribution for vertical bubbly flows

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ABSTRACT

Measurements of a bubbly flow using an intrusive probe give a set of random chord length values whose distribution differs considerably from the actual bubble size distribution (BSD). Considering the interaction of bubbles in groups of different sizes and shapes with the probe, a new method of relating the measured chord length distribution (CLD) to the BSD is proposed. The CLD is decomposed into simple distributions, which are considered as the CLDs of individual bubble groups and translated into BSDs using a developed analytical transformation. Entire BSD is constructed statistically from the obtained BSDs. The new method is applied to analyzing the CLDs measured by a five-sensor conductivity probe for a vertical bubbly flow in a narrow rectangular channel at different flow conditions. The results show a good agreement between the predicted BSDs and the experimental distributions measured simultaneously by a high-speed video camera. Valuable information on the statistical characteristics estimated from the CLDs and BSDs, including the chord length, bubble size and shape, and bubble population fraction, are evaluated and discussed in detail.

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Introduction

For multiphase flow systems, such as fluidized beds or bubble columns, in which bubbles take a vital role in the exchange processes of the mass and energy between phases, the bubble size distribution (BSD) is imperatively essential information for the design and management of the system performance. Regarding the measurement of the bubble size and BSD, many experimental techniques are available, but their applicability is somewhat limited in practice. Non-intrusive photography techniques, e.g. X-ray, γ-ray, or magnetic resonance imagining, provide good visual observation of the bubble fields, but often lack information on the local system behavior and require a compatible measurement environment (Liu et al., 1998; Sobrino et al., 2009). To obtain the local flow information about bubble velocity, void fraction, BSD, etc., an analysis of subsequent frame-by-fame bubble images, which is time consuming and laborious, is required. This analysis can be performed using a high-speed video camera but only with small transparent facilities and low bubble densities (Euh et al., 2006). Another technique like intrusive wire–mesh sensors can be used to measure directly the bubble size with high precision, but a disturbance to some degree might be introduced to the downstream flow (Lucas et al., 2005).

In the open literature, many experimental studies of bubbly flows have preferred to use intrusive conductivity/optical multi-sensor probes (Gunn and Al-Doori, 1985; Kalkach-Navarro et al., 1993; Dias et al., 2000; Euh et al., 2001). In comparison with the aforementioned techniques, the intrusive probe technique is much simpler and has a highly comparable accuracy in the local measurements of interfacial area concentration, void fraction and velocity (Euh et al., 2006; Manera et al., 2009). Unfortunately, the probe measurements provide a set of random chord length values, which are typically smaller than the diameter of pierced bubbles. Moreover, larger bubbles are more likely pierced by the probe than smaller bubbles. Consequently, the distribution of the measured chord length values differs considerably from the actual size distribution (Rüdisüli et al., 2012).

A lot of efforts have been made to derive BSDs from measured CLDs for bubbly flows. Uga (1972) and Werther (1974) first introduced a statistical relationship between a CLD and a BSD based on a geometrical relation between the chord length and bubble size. Since then several methods have been proposed to determine the BSD through this relationship. Clark and Turton (1988) and Turton and Clark (1989) developed a numerical backward

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transformation, which converts the statistical relationship into a triangular matrix form by means of a discretization. Liu and Clark (1995) and Clark et al. (1996) proposed an analytical backward transformation, in which a closed form of the CLD obtained by a nonlinear fitting method or by an optimization using Pazen window estimator is required (Liu et al., 1996, 1998; Santana and Macías-Machín, 2000). Lately, Santana et al. (2006) and Sobrino et al. (2009) introduced a maximum entropy method, which calculates the unknown BSD with minimum amount of a priori knowledge by maximizing the so-called Shannon's entropy function subject to a given number of known raw-moment constraints of the CLD. In general, these methods concentrated a lot on the development of a mathematical algorithm rather the physical aspect related to the bubble dynamics and bubble–probe interactions, and were shown to be numerically unstable and difficult to apply to actual bubbly flows (Rüdisüli et al., 2012).

The weakness of the foregoing methods is mainly concerned with the assumption of homogenous bubble shape and the use of simple and well-shaped CLDs. The simplistic considerations are usually unrealistic and do not expose important physical phenomena about the bubbles. In fact, bubbles look quite different in both size and shape, and their characteristics vary significantly under the influence of dynamic processes, for example bubble coalescence and breakup. The formation and destruction of bubbles induced by bubble–bubble interactions are able to form multiple bubble classes of different sizes and shapes (Krepper et al., 2005; Jo and Revankar, 2010). Furthermore, a real CLD does not always have a fine shape as considered previously. It is a fact that the probe can touch anywhere on the bubble surface, not always at the centerline, and large bubbles are more likely hit by the probe than smaller bubbles. Hence, the chord length value depends on the size and lateral motion of bubbles. A wide range of the chord length value is seen by large bubbles while it is narrow with small bubbles. Thus, the CLD looks like a superposition of small distributions of different bubble classes. If so, separating the CLD into well-shaped distributions, which a backward transformation can work with, can be suggested as a solution of the problem of translating the CLD to the BSD.

From the viewpoint of the multiple bubble classes, a new method of relating a CLD measured by an intrusive probe to the BSD for vertical bubble flows is developed in this paper. Together with the CLD decomposition and bubble shape estimation, an analytical relationship between the CLD and BSD is formulated. And then, an experiment of a bubbly flow in a narrow rectangular channel is conducted to validate the proposed method.

Proposed method

The whole procedure of the new method, illustrated in Fig. 1, consists of the CLD decomposition, analytical transformation, estimation of the bubble shape factor, and BSD combination. Details of the procedure are presented in the following.

Decomposition of measured CLDs

Firstly, the probability density function (PDF) of measured chord length values, $P_c(y)$, is estimated following the procedure suggested by Bendar and Piersol (1971). The probability densities are obtained digitally by dividing the full range of the chord length into an appropriate number of equal width class intervals, tabulating the number of chord lengths in each class interval, and dividing by the product of the class interval width and the total number of sample chord lengths. To make sure that the estimated PDF is stable in shape and approaches the true PDF of the chord length, the number of class intervals must be chosen so that the class interval width is approximately 0.4 times of the standard deviation of the measured chord length. In this study, the measured CLDs were built from about 590–1900 experimental data points with 15 chord length class intervals.

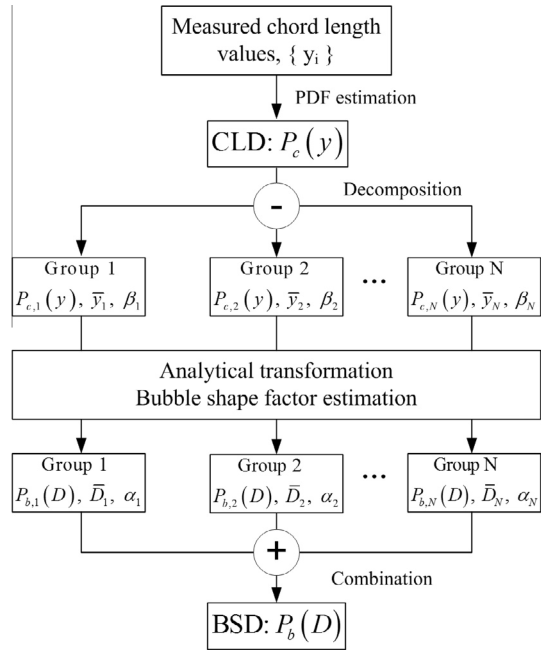

Fig. 1. Conversion procedure.

The estimated CLDs are then inputted to a divider to decompose into N small distributions, as described in Fig. 1. Average chord lengths $\bar{y}_i$ and group fractions β_i (defined as the ratio of the area under each distribution to the area under the initial CLD) accompanying these distributions are calculated. The divider used in this study is a Gaussian fitting function, which is built in the MATLAB program and given by:

$$P_c(y) = \sum_{i=1}^{N} A_i \exp\left[-\left(\frac{y-\bar{y}_i}{w_i}\right)^2\right], \qquad (1)$$

where A_i, $\bar{y}_i$ and w_i are the fitting parameters. To ensure that the separated distributions are non-negative and finite like a true PDF, the fitting parameters must be positive and finite too. Since the interaction between bubbles and a probe is a random process and the distribution of chord lengths generated by this interaction is usually complicated (e.g. multiple peaks), the Gaussian function, which is frequently used to represent such a random process, is chosen to describe the CLD. Other functions, such as Gamma and Rayleigh functions, which were previously adopted to find the closed form of entire CLDs and BSDs, might not be suitable for the CLD separation because of their asymmetry (Liu and Clark, 1995; Rüdisüli et al., 2012). In addition, it is noted that the number of separated distributions is chosen according to each problem, provided that these distributions can be considered as CLDs of independent bubble groups. The selection of the number of separated distributions will be discussed in detail in the results and discussions section.

Analytical relationship between CLD and BSD

To relate a measured CLD to a BSD, the analytical relationship derived by Liu and Clark (1995) for ellipsoidal and vertically raised bubbles is employed.

$$P_b(R) = \alpha[P_c(y) - yP_c'(y)], \qquad (2)$$

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