CHEMICAL ENGINEERING TRANSACTIONS Volume 17, 2009
Editor Sauro Pierucci
Copyright © 2009, AIDIC Servizi S.r.l., ISBN 978-88-95608-01-3 ISSN 1974-9791
DOI: 10.3303/CET0917101

Area-to-volume data translation in the measurement of bubble size distributions *via* laser sheet and image analysis

Antonio Busciglio, Alberto Brucato, Francesca Scargiali and Franco Grisafi
Dipartimento di Ingegneria Chimica dei Processi e dei Materiali
Università degli Studi di Palermo
Viale delle Scienze, Ed.6 – 90128 Palermo (Italy) –grisafi@dicpm.unipa.it

A nov el experimental technique for measuring local bubble size distributions in gas-liquid systems, is proposed. The technique is based on laser sheet illumination of the gas-liquid dispersion and synchronized camera, i.e. on equipment typically available within PIV set-ups. By suitably arranging experiments and subsequent image analysis, bubbles intercepted by the laser sheet are clearly identified. The size distribution of observed intercept areas can therefore be assessed. This is however different from the actual bubble size distribution needed for modelling and interfacial area estimation purposes. In this paper a simple statistical correction procedure able to reconstruct actual bubble size distributions from relevant intercept size distributions is proposed and discussed. Preliminary data obtained in stirred gas-liquid dispersions confirm the technique viability.

1. Introduction

Gas-liquid contactors are widely employed as reactors and bio-reactors in the process industry. Gas-liquid mass transfer is a common rate-determining step in these apparatuses. Local mass transfer areas depend on bubble size and concentration, and vary notably from place to place even in small stirred tanks (Calderbank ,1958; Sridhar and Potter, 1980; Barigou and Greaves, 1992, 1996). Mass transfer area is obtained most reliably from local gas hold-up and bubble size distribution (BSD).
Particle Image Velocimetry techniques (PIV) have been used in recent years for velocity field measurements in gas-liquid systems (Montante et al., 2007; Khopkar et al., 2003; Aubin et al., 2004) and in some cases for measuring BSD (Spicka et al., 2001; Liu et al., 2005; Laakkonen et al., 2005). As a matter of fact, PIV apparatuses, apart from providing information on the flow and turbulence quantities in gas-liquid systems, may be employed for other measurements, taking advantage of the possibility of isolating a well known volume of the systems. However, when trying to do so, the problem arises that the light sheet employed randomly intercepts bubbles at various distances from their centres, therefore resulting in visible intercepts smaller than the actual bubble size and in turn in a *Visible Intercept Size Distribution* (subsequently simply referred VISD) significantly different from the actual *Bubble Size Distribution* (BSD).
The need therefore arises of devising ways for transforming measured VISDs into the relevant BSDs. The problem is akin to that faced in several papers regarding gas-liquid and gas-solid bubbly flows (Herringe and Davis, 1976; Clark and Turton, 1988; Hobbel

Please cite this article as: Busciglio A., Grisafi F., Scargiali F. and Brucato A., (2009), Area-to-volume data translation in the measurement of bubble size distributions via laser sheet and image analysis, Chemical Engineering Transactions, 17, 603-608 DOI: 10.3303/CET0917101

et al., 1991; Liu et al., 1998; Simmons et al., 1999; Langston et al., 2001), by means of different computational and statistical approaches.

In this work a simple statistical correction procedure able to reconstruct actual bubble distributions from relevant intercept size distributions is proposed and discussed. Preliminary data obtained in stirred gas-liquid dispersions are also presented. The intercept sizes were obtained by a novel technique based on laser sheet illumination and synchronized camera (i.e. on typical PIV equipment) in conjunction with a fluorescent liquid phase and a purposely developed image analysis procedure. The technique details are given elsewhere (Busciglio et al., 2009). The preliminary data obtained confirm the technique viability as well as its reliability.

3. Statistical Correction of Visible Intercept Size Distribution (VISD)

VISDs obtained by means of light sheets and image analysis tend to underestimate the actual bubble size distributions (BSD) in gas-liquid systems (Laakkonen et al., 2005), due to light sheet randomly cutting bubbles at planes generally different from the diametrical one. Notably, this leads to a statistical distribution of visible intercept sizes even in the ideal case of single-sized bubbles.

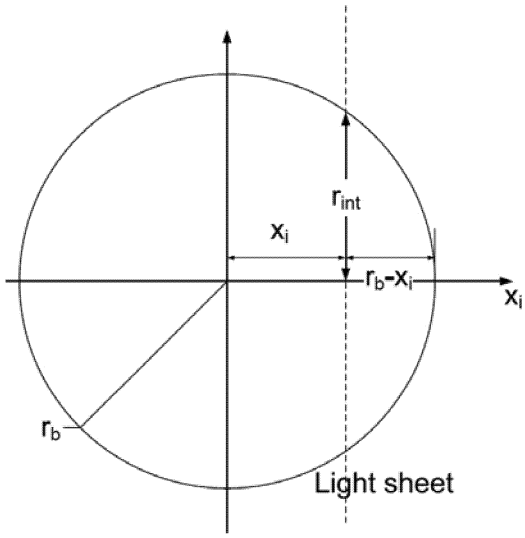

Fig. 1. Schematical representation of a bubble cut by "thin" laser sheet.

In the simplest case of univariate BSD and "thin" light sheet (thickness ideally equal to zero) the analytical form of VISD can be directly obtained from geometrical considerations, based on the hypothesis of cut planes randomly equidistributed over bubble radius, i.e. on the realistic assumption that each position of the light plane with respect to bubble centre has the same probability of occurrence.

For each x_i distance of the light plane from bubble centre, the cumulative probability of finding intercept radii smaller or equal to the relevant intercept radius r_{int} is equal to the ratio between the number of stochastic planes in the range $x_i < x < r_b$ and the total number of planes. In other words, the probability of finding intercept radii smaller than or equal to the intercept radius r_{int} (the cumulative Visible Intercept Size Distribution, cVISD) is simply proportional to the relevant geometrical segments:

$$cVISD(r_b) = \frac{N(r \le r_{\text{int}})}{N_{tot}} = \frac{r_b - x_i}{r_b} = 1 - \cos\left[\arcsin\left(\frac{r}{r_b}\right)\right] \quad (1)$$

by differentiating Eqn.1, the intercept size probability density function is obtained:

$$VISD(r_b) = \frac{d(cVISD(r_b))}{dr} = \frac{r}{r_b^2\left(1 - \frac{r^2}{r_b^2}\right)^{1/2}} \quad (2)$$

Once the VISD for each bubble size class is known, it is possible to tackle the problem of reconstructing BSD from the relevant VISD

To this end, the probability density function of actual bubble sizes is discretised by suitably defining N equispaced discrete bubble radius classes and associating statistical weights w_i to each class, proportional to the number of bubbles in each class. It is self evident that, if each bubble size class gives its VISD independently of every other bubble size classes, the overall VISD can be computed as the sum of all VISDs (each one associated to an actual bubble size class), weighted on the basis of the relevant w_i :

$$\overline{VISD} = \sum_{i=1}^{N} w_i \cdot \overline{VISD(r_{b,i})} \quad (3)$$

In order to increase numerical stability, it is better to consider the relevant cumulative (integral) density function, by simple integration:

$$\overline{cVISD} = \sum_{i=1}^{N} w_i \cdot \overline{cVISD(r_{b,i})} = \overline{w_i} \bullet \begin{bmatrix} \overline{cVISD(r_{b,1})} \\ \overline{cVISD(r_{b,2})} \\ \ldots \\ \overline{cVISD(r_{b,N})} \end{bmatrix} \quad (4)$$

where the bullet indicates a scalar product between the two vectors. Since the cumulative density function of intercepts is assumed to be known, the problem becomes that of finding the values of w_i that satisfy Eqn. 4. This is clearly a closed linear system, with the vector w_i as unknown, that can be easily solved by any standard procedure. As a result, the weights w_i of the actual BSD are obtained.

2. Experimental set-up and image analysis

The experimental system here investigated was a fully baffled cylindrical vessel (diameter T = 0.19 m) with a flat base, stirred by a standard six-bladed Rushton turbine (diameter D = T/3) offset by T/3 from vessel bottom. The liquid phase was deionised water in which a fluorescent dye (Rhodamine-B, at 0.486 kg/m^3) had been dissolved. The gas phase (air) was supplied through a 6 mm ID open-ended pipe, centrally placed 10 mm below the turbine. Further details on experimental set-up and technique are given elsewhere (Busciglio et al. 2009). Gas flow rate of Q_g = 0.5 lt/min and at a rotational speed equal to 300 rpm were adopted for this work.
A typical image of the lower part of the vessel obtained by the above described apparatus is shown in Fig.2a, where the right border coincides with the vessel axis and the impeller region is digitally shielded in order to avoid spurious results in the subsequent image analysis. The laser sheet entered from the left side of the image and travelled towards the right side on a vertical plane at 45° between subsequent baffles. All the light observable in Fig.2b is that re-emitted by the fluorescent dye, that practically turns the laser sheet into a planar (fluoresced) light source.

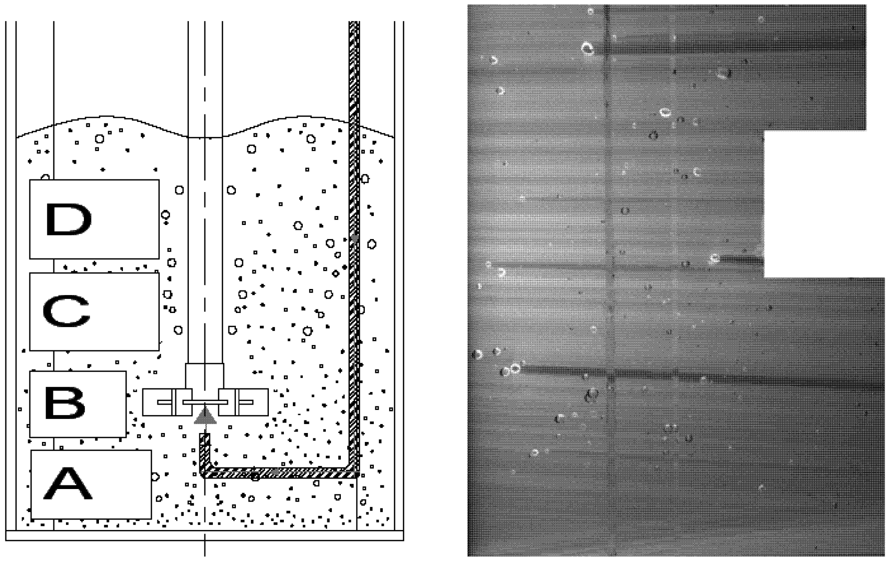

Fig. 2. From left to right, a) schematic representation of the vessel, with macro areas investigated; b) typical raw image of the lower part of the vessel.

In this image gas bubbles can be clearly observed. As it can be seen there are “dark bordered” bubbles, clearly placed beyond the light sheet, and “white bordered” bubbles. These may be either in front of the light plane or right on the light plane. These last are however easily identified as they are the only ones that give rise to a neat straight “shadow” in the image, caused by the fact that the laser light intercepted is diverted in many directions and fails to excite the dye on the light path rear the bubble (the vertical dark and white lines in Fig.2b is are image disturbances from baffle borders).

For each in-plane bubble, its area, equivalent intercept diameter and centroid coordinates can be computed and stored, so allowing the reconstruction of local as well as overall intercept size distributions.

4. Results and Discussion

The procedure viability was checked by processing 2000 images obtained with the previously described experimental apparatus. It should be noted that, although the technique can in principle provide very detailed local bubble distribution information, the 2000 images adopted here were sufficient to obtain statistically significant BSD information only over fairly large vessel macro-areas, as those indicated with A,B,C and D in Fig.2a. The (non-parametric) BSD and relevant average bubble sizes (D_{10}, D_{21}, D_{32}, D_{43}) were computed in these macro areas of the vessel.
Some of the results obtained are shown in Fig 3. As it can be seen in Fig. 3.a, all BSDs in the region are positively skewed. The comparison between apparent and actual average diameter (Fig.3b) highlights the effect of the statistical correction, especially on higher moments, as in could have been expected.

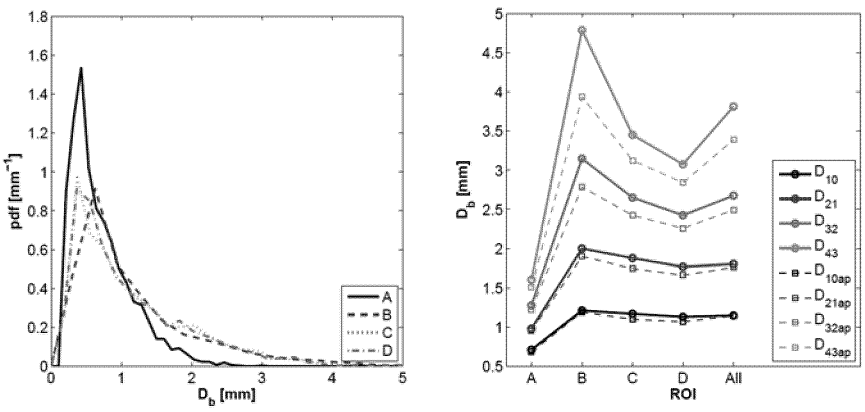

Figure 3. Local BSDs (left) and statistical moments of the distribution (right, actual and intercept values)

5. Conclusions

A novel technique has been developed for measuring local dispersion properties in gas liquid contactors. The technique is based on the use of a fluorescent liquid phase coupled with a laser sheet and a purposely developed digital image analysis routine. An efficient routine for converting the raw intercept area distributions so obtained into the relevant bubble size distributions was devised and validated. The preliminary results obtained were found to be in good agreement with expectations.

5. References

Aubin J., Le Sauze N., Bertrand J., Fletcher D.F., and Xuereb C. PIV measurements of flow in an aerated tank stirred by a down- and an up-pumping axial flow impeller. Experimental Thermal and Fluid Science, 28:447–456, 2004.

Barigou M. and Greaves M. Bubbles size distributions in a mechanically agitated gas-liquid contactor. Chem. Eng. Sci., 47(8):2009–2025, 1992.

Barigou M. and Greaves M. Gas holdup and interfacial area distributions in a mechanically agitated gas-liquid contactor. Chem. Eng. Res. Des., 74:397–405, 1996.

Busciglio A., Brucato A., Scargiali F. and Grisafi F. (2009), A novel technique for measuring local bubble size distribution, Proceedings of the 8th World Congress of Chemical Engineering (WCCE8), Montreal, Canada, August 23–27.

Calderbank P.H. Physical rate processes in industrial fermentation. Part 1. the interfacial area in gas-liquid contacting with mechanical agitation. Trans. Inst. Chem. Engrs., 36:443–463, 1958.

Khopkar A.R., Aubin J., Xuereb C., Le Sauze N., Bertrand J., and Ranade V.V. Gas-liquid flow generated by pitched-blade turbine: particle image velocimetry measurements and computational fluid dynamics simulations. Ind. Eng. Chem. Res., 42:5318–5332, 2003.

Laakkonen M., Honkanen M., Saarenrinn P., and Aittamaa J. Local bubble size distributions, gas-liquid interfacial areas and gas holdups in a stirred vessel with particle image velocimetry. Chemical Engineering Journal, 109:37–47, 2005.

Liu Z., Zheng Y., Jia L., and Zhang Q. Study of bubble induced flow structure using PIV. Chemical Engineering Science, 60:3537–3552, 2005.

Montante G., Magelli F., and Paglianti A. Experimental analysis and computational modelling of gas-liquid stirred vessels. IChemE, 85(A5):647–653, 2007.

Spicka P., Dias M.M., and Lopes J.S.B. Gas liquid flow in a 2D column: Comparison between experimental data and CFD modelling. Chem. Eng. Sci., 56:6367–6383, 2001.

Sridhar P. and Potter O.E. Interfacial areas in gas-liquid stirred vessels. Chem. Eng. Sci., 35(3):683–695, 1980

Herringe R.A., Davis M.R. (1976), Structural development of gas-liquid mixtures flows, J. Fluid Mech. 73(1):97-123.

Clark N.N., Turton R. (1988), Chord length distributions related to bubble size distributions in multiphase flow, Int. J. Multiphase Flow, 14(4):413-424.

Hobbel E.F., Davies R., Rennie F.W., Allen T., Butler L.E., Waters E.R., Smith J.T., Sylvester R.W., (1991), Modern methods of on-line size analysis for particulate process streams, Part. Part. Syst. Charact., 8:29-34.

Liu W., Clark N.N., Karamavruc A.I., (1998), Relationship between bubble size distributions and chord-length distribution in heterogeneously bubbling systems, Chem. Eng. Sci., 53(6):1267-1276.

Simmons M.J.H., Langston P.A., Burbidge A.S., (1999), Particle and droplet size analysis from chord distribution, Powder Technol., 102:75-83;

Langston P.A., Burbidge A.S., Jones T.F., Simmons, (2001), Particle and droplet analysis from chord measurements using Bayes' theorem, Powder Technol., 116:33-42.