Chemical Engineering Science 102 (2013) 551–566

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

On the measurement of local gas hold-up, interfacial area and bubble size distribution in gas–liquid contactors *via* light sheet and image analysis: Imaging technique and experimental results

A. Busciglio *, F. Grisafi, F. Scargiali, A. Brucato

Dipartimento di Ingegneria Chimica, Gestionale, Informatica e Meccanica, Universitá degli Studi di Palermo, Viale delle Scienze, Ed. 6 - 90128 Palermo, Italy

AUTHOR-HIGHLIGHTS

- Original data about gas–liquid dispersion properties in stirred vessels are presented and discussed.
- The experimental technique is based on the adoption of a laser plane and a fluorescent liquid phase.
- Highly detailed data can be obtained without affecting the system fluid dynamics.
- Data presented are in agreement with the literature.

ARTICLE INFO

Article history:
Received 13 February 2013
Received in revised form
21 June 2013
Accepted 8 August 2013
Available online 20 August 2013

Keywords:
Bubble
Imaging
Mixing
Multiphase flow
Gas–liquid dispersion
Bubble size distribution

ABSTRACT

In this work a novel experimental technique for measuring local gas hold-up, interfacial area and bubble size distribution, in gas–liquid systems is proposed. The technique is based on advanced Image Processing coupled with experimental set-ups typically available for Particle Image Velocimetry. A fluorescent dye dissolved in the liquid phase allows to identify *in-plane* bubbles among all visible bubbles in the images. To this end, a suitable algorithm is proposed. The raw data so obtained are processed by previously developed statistical methods that result in a reliable reconstruction of actual dispersion properties.

The technique is applied to the case of a gas-dispersed mechanically agitated vessel, and the data obtained are presented and discussed.

1. Introduction

Gas–liquid contactors are widely employed as chemical and biochemical reactors in the process industry. In most of these applications, gas–liquid mass transfer is the main rate-determining step. Significant attention has been devoted in the past to the experimental assessment of k_La_i values in stirred vessels by means of several experimental techniques (*e.g.* Linek et al., 1982, 1989; Scargiali et al., 2007, 2010, 2012). Knowledge of the mass transfer product k_{La} is important for equipment design, even if the separated k_L and a_i values are not known. However, experimental assessment of specific interfacial area is needed for properly modelling fast gas–liquid chemical reactions as well as in the realm of validation of CFD models. Local mass transfer areas depend on gas phase volume fraction as well as on bubble sizes, properties that are known to vary notably from place to place, even in small stirred tanks (Calderbank, 1958; Sridhar and Potter, 1980; Barigou and Greaves, 1992b, 1996; Laakkonen et al., 2005a). In the followings, some of the papers dealing specifically with measurements of bubble size distribution, gas hold-up and specific interfacial area are briefly reviewed.

1.1. Measurement techniques

By exploiting suitably catalyzed chemical reactions the specific interfacial area may be obtained (Hassan and Robinson, 1980; Mandal et al., 2005; Mohanty et al., 2007). These *chemical methods* can only access global (vessel and time averaged) data and are affected by system coalescence alterations due to the presence of the added chemicals.

Apart from these, a number of techniques, able to access local information on dispersion properties has been devised over the

* Corresponding author. Tel.: +39 091 238 63779.
E-mail addresses: antonio.busciglio@unipa.it (A. Busciglio), franco.grisafi@unipa.it (F. Grisafi), francesca.scargiali@unipa.it (F. Scargiali), alberto.brucato@unipa.it (A. Brucato).

0009-2509/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.08.029

years. A comprehensive review of measuring techniques in gas–liquid contactors can be found in Boyer et al. (2002) and is not repeated here for the sake of brevity. In Tables 1 and 2 the most significant references, for non-intrusive and intrusive techniques respectively, that can be adopted for measuring gas–liquid dispersion properties in stirred vessels are reported.

Each technique has its own strengths and weaknesses. Those involving intrusive probes are in general quite robust and simple to use. On the other hand they have intrinsic drawbacks, namely (i) the flow field is bound to be more or less affected by probe presence and (ii) long experimentation times are required to sample data at different vessel locations in order to derive overall data.

In some cases (*Capillary Suction Probes* and *Suction probes with image analysis*) a stream of dispersion is continuously withdrawn from the vessel and brought to some measuring device. In these cases fluid-dynamic sampling effects may undermine the accuracy of results. In fact, apart from probe intrusivity, it is practically impossible to achieve a perfectly *iso-kinetic* sampling and therefore the withdrawn sample has more or less different properties than the dispersion at the probe location. Also, care must be exercised in order to avoid changing dispersion properties along the external measurement circuit, due for instance to bubble break-up and/or coalescence phenomena.

Tomographic techniques are in general able to investigate systems with high gas hold up values without affecting system fluid dynamics. However, the apparatuses are generally quite expensive and results often show a somewhat poor spatial resolution.

Table 1
Intrusive experimental techniques.

Method	Notes
Transmitted light probes	Calderbank (1958)
Imaging probes	Honkanen et al. (2010)
Suction probes and image analysis	Kamiwano et al. (2003), Parthasarathy and Ahmed (1994)
Capillary suction probe	Greaves and Kobbacy (1984), Barigou and Greaves (1992a,b), Alves et al. (2002a,b), Laakkonen et al. (2005b,c)
Pressure probes	Linek et al. (1996)
Conductivity probes	Gao et al. (2001), Kim et al. (2000)
Impedance probes	Paglianti and Pintus (2001)
Resistivity probes	Bombac et al. (1997), Bombac and Zun (2000)
Wire mesh sensors	Lucas et al. (2005), Manera et al. (2005)
Hot-film anemometry	Lo and Ju (1987)

Table 2
Non intrusive experimental techniques.

Method	Notes
Transmitted light techniques	Calderbank (1958)
Scattered light techniques	Aslan et al. (2006)
Computed tomography	Wang et al. (2000), Toye et al. (2005), Khopkar et al. (2005), Hampel et al. (2007), Ford et al. (2008), Boden et al. (2008)
Photographic techniques	Machon et al. (1997), Bouaifi and Roustan (1998), Bouaifi et al. (2001), Winterton and Munaweera (2001), Bailey et al. (2005), Horn et al. (2007), Montante et al. (2008), Sommerfeld and Broder (2009), Lau et al. (2013)
Laser sheet	Laakkonen et al. (2005a)
Laser doppler anemometry	Laakkonen et al. (2005c)

Photographic techniques have the potential to result in very accurate BSD measurements, but are generally unable to sharply identify the volume over which the measurements are made. Attempts to overcome this drawback have been made by means of cameras equipped with macro-lenses sporting very small depths of field. This however does not fully resolve the problem; as a consequence quantities dependent on precise control volume definition (such as gas hold-up and specific interfacial area) can be only approximately estimated. Moreover, when no intrusive probes are involved, only low gassing conditions and highly transparent fluids can be dealt with, in order to guarantee optical accessibility. Though this limitation may partially be narrowed by advanced image analysis techniques (Lau et al., 2013), this is obtained at the cost of somewhat widening results uncertainty. Another way of circumventing the optical accessibility limit is that of resorting to imaging probes (Honkanen et al., 2010), but this is clearly done at the cost of system intrusion and related data loss of accuracy.

A more effective way to overcome the above mentioned control volume definition limitations is that of resorting to laser blades with known thicknesses. Laakkonen et al. (2005a) developed a laser sheet based technique aimed at obtaining quantitative simultaneous data on dispersion properties and liquid phase flow field. Unfortunately, with this technique not all visible bubbles belong to the directly illuminated volume, yet the authors did not attempt to discard all out-of plane bubbles from data analysis, so leading to somewhat biased measurements. Clearly, in order to get quantitative results, a way of discarding out-of-plane bubbles has to be devised.

A comparison of bubble size distributions obtained in the same system with three different techniques (Digital Image Analysis, Capillary Suction Probes and Phase Doppler Anemometry) can be found in Laakkonen et al. (2005c). According to the authors, all three adopted techniques gave rise to measurements in qualitative agreement with each other. However significant mismatches between quantitative data were found, allegedly due to the different range of detectable bubble sizes. Authors noted that optical techniques have the potential to provide more detailed information, but need more expertise then capillary suction probes, though these last can result in biased data.

1.2. Experimental assessment of bubble size distribution in stirred tanks

Average bubble sizes were first measured in stirred vessels by Calderbank (1958), who measured interfacial area (based on a light attenuation technique) and gas volume fractions (based on suction probe results or, as regards the overall voidage, on vertical pressure gradient assessments). From these, bubble Sauter mean diameter was easily derived. By integration of the local data obtained to the entire vessel volume, Calderbank was able to propose the following correlation:

$$D_{32} = 4.15 \frac{\sigma^{0.6}}{\left(\frac{P_g}{V}\right)^{0.4} \rho_l^{0.2}} \epsilon^{0.5} \left(\frac{\mu_g}{\mu}\right)^{0.25} + 9 \times 10^{-4} \quad (1)$$

that predicts a decreasing D_{32} when increasing agitation power consumption, as expected. Gas flow rate dependence is implicitly introduced by the relevant dependence of ϵ on the same parameter.

Also Bouaifi et al. (2001), working with a dual-impeller system and a photographic technique, found that the average Sauter diameter decreases while increasing power consumption (with a power law exponent of -0.2), but it was found to be unaffected by gas flow rate.