Chemical Engineering Science 62 (2007) 858–866

Chemical Engineering Science

www.elsevier.com/locate/ces

Experimental determination of the drag coefficient in a swarm of bubbles

M. Simonnet, C. Gentric*, E. Olmos, N. Midoux

Laboratoire des Sciences du Génie Chimique, UPR 6811, CNRS-ENSIC-INPL, 1 rue Grandville, BP 20451, 54001 Nancy Cedex, France

Received 24 June 2005; received in revised form 24 July 2006; accepted 16 October 2006
Available online 26 October 2006

Abstract

Simultaneous measurements of liquid velocity by laser Doppler velocimetry and bubble velocity, diameter, and void fraction by a double optical probe are performed in a bubble column to study the influence of the void fraction on the relative velocity of a swarm of gas bubbles. Bubble diameters d_b vary from 2 to 10 mm and local void fractions α_{loc} can reach 35%. It is found that, for $\alpha_{\mathrm{loc}} < 15\%$, the relative bubble velocity is determined by the hindrance effect and consequently decreases with the void fraction. Beyond this critical value, the aspiration of bubbles in the wake of the leading ones dominates the hindrance effect and the relative velocity thus increases suddenly. The contribution of the bubble diameters to this evolution is also determined. Finally, a drag correlation, valid for the whole range of void fraction and for pure water–air systems, is proposed.

Keywords: Bubble; Multiphase flow; Bubble columns; Hydrodynamics; Drag formulation; Local void fraction

1. Introduction

Multiphase reactors are encountered in several industrial processes, for instance, in the chemical, biochemical, environmental, pharmaceutical, or petrochemical industries and are therefore of practical importance. Among multiphase reactors, bubble columns are widely used for several reasons: simple construction (no mechanically moving part), low maintenance cost, good mass and heat transfer (Deckwer, 1992). The complexity of their hydrodynamics explains why so many experimental and numerical studies have been conducted over the last decades. Computational fluid dynamics (CFD) theoretically offers the capability of simulating the behavior of this type of reactor, to investigate the influence of design or operating parameters, without the construction of experimental setup. However, it requires the knowledge of the closure terms in the Navier–Stokes equations such as the turbulence Reynolds stresses or the interaction forces between the bubbles and the liquid phase: drag, lift, added mass, or Basset forces. To close these last terms, empirical correlations giving drag or lift coefficients for an isolated bubble rising in a quiescent liquid (Clift et al., 1978) are generally used. But many authors (Jakobsen, 2001; Grienberger and Hofmann, 1992; Behzadi et al., 2004) emphasize the fact that those coefficients are no more appropriate as soon as the bubble is surrounded by other bubbles. In this study, the experimental variation of the drag coefficient with the local void fraction is investigated.

Several papers in the literature already deal with this topic; examples of dependence laws of the relative velocity (directly linked to the drag coefficient) with the global void fraction (α_{glob}) in the homogeneous regime are given below:

- $V_{\mathrm{rel}} = V_\infty/(1-\alpha_{\mathrm{glob}})$ by Davidson and Harrison (1966).
- $V_{\mathrm{rel}} = V_\infty(1-\alpha_{\mathrm{glob}})$ by Griffith and Wallis (1961).
- $V_{\mathrm{rel}} = V_\infty(1-\alpha_{\mathrm{glob}})^{1.39}$ by Bridge et al. (1964).
- $V_{\mathrm{rel}} = V_\infty(1-\alpha_{\mathrm{glob}})/(1-\alpha_{\mathrm{glob}}^{5/3})$ by Marrucci (1965).

All these correlations have been inspired by the pioneering work of Richardson and Zaki (1954) who established the dependence of the relative velocity of solid particles in batch fluidization and sedimentation experiments, in the form:

$$V_{\mathrm{rel}} = V_\infty(1-\alpha_{\mathrm{glob}})^n, \tag{1}$$

* Corresponding author. Tel.: +33 3 83 17 53 38; fax: +33 3 83 32 29 75.
E-mail address: caroline.gentric@ensic.inpl-nancy.fr (C. Gentric).

0009-2509/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2006.10.012

where n is often referred to as "the Richardson and Zaki exponent" and is a function of the particle Reynolds number. V_∞ is the velocity of an isolated bubble in a quiescent liquid and can be calculated using, for instance, the correlation of Jamialahmadi et al. (1994):

$$V_\infty = \frac{V_{b1}V_{b2}}{\sqrt{V_{b1}^2 + V_{b2}^2}}, \tag{2}$$

with

$$V_{b1} = \frac{1}{18}\frac{\Delta\rho}{\mu_l} g d_b^2 \frac{3\mu_l + 3\mu_g}{3\mu_g + 2\mu_l}$$

and

$$V_{b2} = \sqrt{\frac{2\sigma}{d_b(\rho_l + \rho_g)} + \frac{g d_b}{2}}.$$

Correlation (2) will thereafter be used to calculate the slip velocity of an isolated bubble.

Lockett and Kirkpatrick (1975) suggested a modification to the Richardson and Zaki correlation (Eq. (1)) to take the bubble deformation into consideration. For a swarm of bubbles with $d_b = 5$ mm, and $\alpha_{glob} < 66\%$, they obtained:

$$V_{rel} = V_\infty(1 - \alpha_{glob})^{1.39} \times (1 + 2.55\alpha_{glob}^3). \tag{3}$$

Ishii and Zuber (1979) proposed correlations, still based on the global void fraction, but depending on the particle regimes, namely the Stokes, viscous, distorted particle, and churn turbulent flow regimes. The drag formulation obtained has been tested by Grienberger and Hofmann (1992) in an Eulerian CFD code but no improvement in the model predictions, compared to those achieved with a drag coefficient based on the radial position in the column, was found.

The problem of all the preceding correlations is that the relative velocity should be based on the local void fraction, rather than on the global one since the bubble behavior is governed by local phenomena. They can, however, be used to simulate the flow hydrodynamics in the homogeneous regime of the bubble column, when local and global gas hold-ups are equal, since bubbles are uniformly distributed over the column volume.

More recently, Garnier et al. (2002) measured the relative velocity in a highly controlled system, namely a cylindrical bubble column where the bubble size is uniform and without transverse gradients of liquid velocity and of local void fraction. For bubble diameters smaller than 5.5 mm, they found the following relationship:

$$V_{rel} = V_\infty(1 - \alpha_{loc}^{1/3}) \tag{4}$$

for $\alpha_{loc} < 35\%$. This correlation has been checked for another experimental system by Guet et al. (2004) for $\alpha_{loc} < 20\%$, and only for $d_b < 6$ mm.

The present experimental study aims at testing the applicability of the above-mentioned correlations to bubble columns operated over a wide range of void fraction and to propose a reliable and continuous drag correlation.

2. Experiments

2.1. Experimental setup

The experimental setup (Fig. 1) consists of a square bubble column with a $0.1 \times 0.1\,m^2$ cross-sectional area and a total height h of 1 m. A pump is used to circulate the liquid phase (demineralized water), at a superficial velocity J_l up to 10 cm/s. Before reaching the test section, water passes through a convergent and across two grids which ensure uniform profiles of water velocities. The gas phase (air) is injected through 133 capillaries (18 cm long and 0.44 mm internal diameter). Before entering these capillaries, air passes through a calming chamber containing a porous plate, allowing all the needles to be supplied uniformly with the gas. With this particular injection system, a uniform and monodisperse population of bubbles can be formed (Garnier et al., 2002). It can moreover be modified, for example, to cut off the supply of air in a capillary, independent of the others. The superficial gas velocity J_g can be varied from 0 to 8 cm/s, corresponding to a global void fraction between 0% and 35% approximately. Liquid and gas volumetric flowrates are fixed by means of rotameters. The origin of the coordinates system is at the center of the cross-section and at the top of the capillaries; the measurements, unless specified otherwise, are performed at the point of coordinates $x/L = 0$, $y/L = 0$, and $z/h = 0.32$.

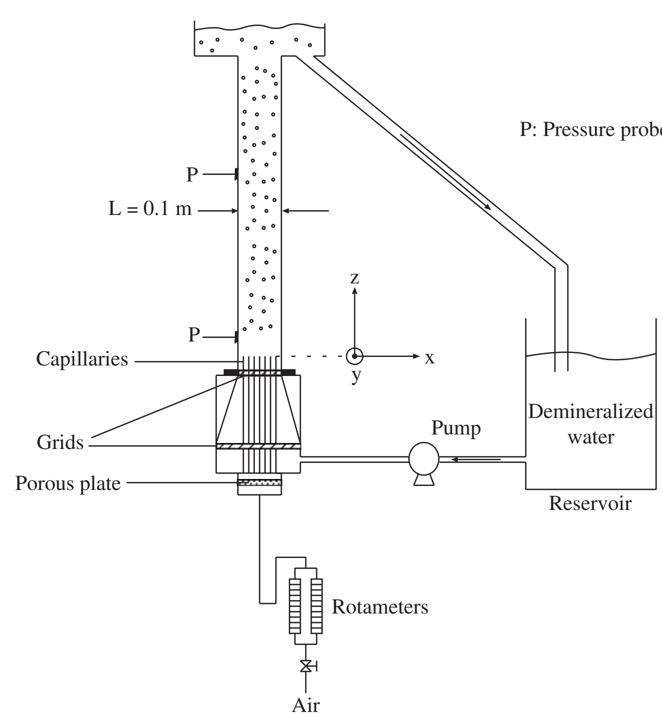

Fig. 1. Experimental device.