Chemical Engineering Science 170 (2017) 91–97

Contents lists available at ScienceDirect

Chemical Engineering Science

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

# Experimental investigation into the drag volume fraction correction term for gas-liquid bubbly flows

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## HIGHLIGHTS

- Volume fraction correction term measured at high superficial velocities.
- Value of the term was observed to depend on bubble size and bubble size distribution.
- New correlations for the volume fraction term have been developed.

## ARTICLE INFO

*Article history:*
Received 28 July 2016
Received in revised form 3 December 2016
Accepted 22 December 2016
Available online 29 December 2016

*Keywords:*
Bubble column
Hydrodynamics
Multiphase flow
Drag
Bubble size distribution

## ABSTRACT

Estimates have been made using data from an instrumented pilot-scale bubble column of the volume fraction correction term over a range of local volume fractions (0.03–0.38) and mean bubble diameters (4–10 mm) for Bubble Size Distributions (BSDs) of varying 'broadness'. The value of this correction term was found to depend on both the mean bubble diameter and the dispersity of the BSD, not simply on the local volume fraction. Using the available experimental data, no hindered bubble rise was observed. The results from this study should assist in the development of more accurate predictive CFD models of bubble columns and other gas-liquid systems operated at high local volume fractions.



## 1. Introduction

Bubble columns are widely used as gas-liquid contactors in a range of applications in both the chemical and bio-processing industries, due to their mechanical simplicity and good heat and mass transfer characteristics (Doran, 1995; Shah et al., 1982). Despite their apparent simplicity, the physics underlying the operation of such systems is complex, particularly at high gas volume fractions. Such complexity creates a considerable challenge from a modelling perspective, as it is necessary to account for a range of possibilities, including inter-phase momentum transfer (e.g. drag, lift, turbulent dispersion and virtual mass), bubble-induced turbulence, as well as the break-up and coalescence of bubbles.

However, it is generally accepted that of the various inter-phase momentum transfer terms, the most significant for buoyancy driven flows is drag. For spherical bubbles the drag force per volume ($\boldsymbol{F}_D$) using the Euler-Euler framework is:

$$\boldsymbol{F}_D = \frac{3C_D}{4d_b}\rho_L\alpha(\boldsymbol{U}_G - \boldsymbol{U}_L)|\boldsymbol{U}_G - \boldsymbol{U}_L| \quad (1)$$

where $d_b$ is the bubble diameter, $\rho_L$ is the liquid phase density and $\boldsymbol{U}_G$ and $\boldsymbol{U}_L$ are the gas and liquid phase velocities respectively. The magnitude of the drag coefficient ($C_D$) is dependent on the size and shape of the bubble (Clift et al., 1978; Ishii and Zuber, 1979), the presence of surface active compounds in the liquid phase (Clift et al., 1978; Jamialahmadi et al., 1994; McClure et al., 2014), as well as the local volume fraction ($\alpha_{local}$) Ishii and Zuber, 1979; Simonnet et al., 2007. To account for this behaviour a common approach (Ishii and Zuber, 1979; Simonnet et al., 2007; Olmos et al., 2003; Rampure et al., 2007; Behzadi et al., 2004; Roghair et al., 2011) is to include a factor $f(\alpha)$ in the calculation of the drag coefficient which accounts for the presence of other bubbles:

$$C_D = f(\alpha)C_{D,\infty} \quad (2)$$

where $C_{D,\infty}$, is the drag coefficient for an isolated bubble. Various correlations for determining the drag of an isolated bubble exist (Clift et al., 1978; Ishii and Zuber, 1979) with each providing comparable predictions. The effect of surface active compounds on the

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http://dx.doi.org/10.1016/j.ces.2016.12.066
0009-2509/

**Nomenclature**

| | | | |
|---|---|---|---|
| $b$ | constant (–) | $U_b$ | bubble velocity (m/s) |
| $C_D$ | drag coefficient (–) | $U_{b,\infty}$ | bubble terminal velocity (m/s) |
| $C_{D,\infty}$ | drag coefficient of an isolated bubble (–) | $\boldsymbol{U}_G$ | gas velocity (m/s) |
| $d_b$ | bubble diameter (m) | $\boldsymbol{U}_L$ | liquid velocity (m/s) |
| $Eo$ | Eotvos number (–) | $U_{slip}$ | bubble slip velocity (m/s) |
| $f(\alpha)$ | volume fraction correction term (–) | $\alpha$ | gas volume fraction (–) |
| $\boldsymbol{F}_D$ | drag force per volume (kg/(m$^2$ s$^2$)) | $\alpha_{local}$ | local volume fraction (–) |
| $H$ | empirical function in Grace drag model (–) | $\mu_L$ | liquid viscosity (Pa·s) |
| $i$ | index (–) | $\mu_{ref}$ | reference viscosity (Pa·s) |
| $j$ | index (–) | $\rho_G$ | gas density (kg/m$^3$) |
| $J$ | empirical function in Grace drag model (–) | $\rho_L$ | liquid density (kg/m$^3$) |
| $Mo$ | Morton number (–) | $\sigma$ | surface tension (N/m) |
| $n_b$ | number of bubbles (–) | | |

drag experienced by bubbles has also been quantified experimentally (McClure et al., 2014; Jamialahmadi and Müller-Steinhagen, 1992), with this knowledge being used to develop CFD models of surfactant containing systems (McClure et al., 2015).

Various authors (Ishii and Zuber, 1979; Simonnet et al., 2007; Olmos et al., 2003; Rampure et al., 2007; Behzadi et al., 2004; Roghair et al., 2011) have examined the effect of bubble-bubble interactions on the drag force. One approach extends a methodology first suggested by Richardson and Zaki for fluidisation of solids (Richardson and Zaki, 1997), where the magnitude of the volume fraction correction term $f(\alpha)$ is proportional to the local volume fraction raised to an index $n$:

$$f(\alpha) = (1 - \alpha_{local})^n \tag{3}$$

The value of $n$ is typically determined to lie in the range 2–4 for bubbly flow with the best-fit value increasing with superficial gas velocity, and hence local volume fraction, (Ishii and Zuber, 1979; Olmos et al., 2003; Rampure et al., 2007). For example, Rampure et al. (2007) used a value of $n = 4$ at superficial velocities above 0.20 m/s, while Olmos et al. (2003) set $n$ based on both the superficial velocity and bubble size. Such an empirical approach predicts a reduction in drag for all local volume fractions, i.e. there is no situation in which bubbles experience hindered rise.

As an alternative to this power-law approach, other researchers (Ishii and Zuber, 1979; Simonnet et al., 2007; Behzadi et al., 2004; Roghair et al., 2011; Lockett et al., 1975) have developed more complex correlations for the volume fraction correction term, some of which are compared in Fig. 1. It is clear that as yet there is no agreement in the literature on how best to account for the drag experienced by a bubble swarm; with some authors predicting hindered rise (i.e. $f(\alpha) > 1$) at all volume fractions, others authors predicting no hindered rise, and yet others predicting hindered rise up to a critical volume fraction. Definitive work in this area is complicated by the fact that experimentally determining the value of $f(\alpha)$ is very challenging, particularly at high local volume fractions. Such challenges are related to the transient nature of the system and the fact that many widely used measurement techniques (i.e. high speed photography and laser Doppler velocimetry) have difficulties being applied at high gas volume fractions (Boyer et al., 2002). Certainly one of the key challenges in the present study was in developing an estimation methodology that could be meaningfully employed based on the experimental data that could be obtained.

Simonnet et al. (2007) observed hindered bubble rise up to a local volume fraction of ~0.15 using mono-disperse bubbles with diameters ($d_b$) between 6 and 10 mm. Garnier et al. (2002) also observed hindered rise, but up to a local volume

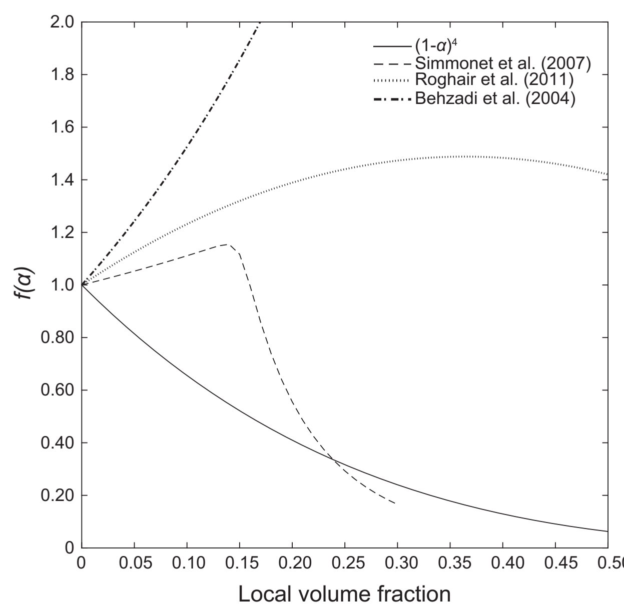


**Fig. 1.** Comparison of published volume fraction correction terms for a swarm of 6 mm air bubbles in water (Simonnet et al., 2007; Rampure et al., 2007; Behzadi et al., 2004; Roghair et al., 2011).

fraction of ~0.4, again using mono-disperse bubbles of relatively small size ($d_b$ < 5.5 mm). Similarly, Colombet et al. (2015, 2011) observed hindered rise for local volume fractions up to 0.35, again using mono-disperse BSDs of relatively small mean size ($d_b$ = 2–5 mm).

By comparison, Rabha and Buwa (Rabha and Buwa, 2010) did not observe hindered rise for a range of mono-disperse distributions ($d_b$ = 1.5, 3.3 and 4.75 mm). However, they did note that above a certain local volume fraction (around 0.06–0.1), the value of $f(\alpha)$ did not change with any further increase in local volume fraction. This 'constant' $f(\alpha)$ value fell in the range 0.12–0.32 depending on the bubble size, with smaller values found at smaller bubble diameters. Rabha and Buwa did examine a poly-disperse system, finding large drag reductions at low volume fractions (e.g. $f(\alpha) = 0.65$ for $\alpha_{local} = 0.03$).

As an alternative to experimental work it is possible to use computational fluid dynamics, in which Direct Numerical Simulation (DNS) is used to resolve all flow details including the bubbles, to estimate the value of the volume fraction correction term. For example, Roghair et al. (2011, 2013) applied this technique and observed hindered rise for both monodisperse and bi-disperse sys-