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Estimation of bubble size distributions and shapes in two-phase bubble column using image analysis and optical probes

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ABSTRACT

A precise estimation of bubble size distributions and shapes is required to characterize the bubble column fluid dynamics at the "*bubble-scale*", and to evaluate the heat and mass transfer rate in bubble column reactors. Image analysis methods can be used to measure the bubble size distributions and shapes; unfortunately, these experimental techniques are limited to resolve bubble clusters and large void fractions, and can not be applied under relevant operating conditions (e.g., high temperature and pressure). On the other hand, needle probes (i.e, optical and conductive probes) can be used to measure bubble sizes in dense bubbly flows and under relevant operating conditions; however, needle probes measure chord length distributions, which should be converted into bubble size distributions by using statistical algorithms. These algorithms rely on correlations—generally obtained for single droplets/bubbles—that predicts the bubble shapes, by relating the bubble equivalent diameter to the bubble aspect ratio. In this paper, we contribute to the existing discussion through an experimental study regarding the bubble sizes and aspect ratio in a large air-water bubble column. The experimental investigation has consisted in gas holdup, image analysis and optical probe measurements. First, the gas holdup measurements have been used to identify the flow regime transition between the homogeneous flow regime and the transition flow regime. Secondly, the homogeneous flow regime has been described at the "*bubble-scale*": chord length distributions and bubble size distributions have been obtained by using an optical probe and image analysis, respectively. Based on the experimental data from the image analysis, a correlation between the bubble equivalent diameter and the bubble aspect ratio has been proposed and has been compared with existing correlations. Finally, the chord length distributions have been converted into bubble size distributions using a statistical method, supported by the aspect ratio obtained through image analysis. The proposed approach has been able to estimate correctly the bubble size distributions at the center of the column then near the wall. We have also demonstrated that the correlations used to predicts the bubble shapes are the main point of improvement in the method.

1. Introduction

Two-phase bubble columns have found many applications in the chemical industries thanks to their simplicity of construction, the lack of any mechanically operated parts, the low energy input requirements, the reasonable prices and high performances (i.e., a large contact area between the liquid and gas phase and good mixing within the liquid phase throughout the column). Despite the simple system arrangement (typically, a vertical pipe with a gas sparger located at the bottom of the column), bubble columns are characterized by extremely complex fluid dynamics interactions between the phases. For this reason, their correct design, operation and scale-up rely on the knowledge of the fluid dynamics at different scales: mainly, the "*bubble-scale*" (i.e., bubble size distributions and shapes, single bubble dynamics, collective bubble dynamics, …) and the "*reactors-scale*" (i.e., flow patterns, mean residence time of the disperse phase, dynamics of mesoscale clusters, …). The knowledge of the fluid dynamics at the different scales can be quantified through the precise estimation of the local (i.e., the bubble size distributions, BSD, and the bubble aspect ratio) and the global (i.e., the gas holdup, ε_G) fluid dynamic properties. In particular, the gas holdup is a dimensionless parameter defined as the volume of the gas phase divided by the total volume of the dispersed phase. It determines the residence time and, in combination with the BSD, the interfacial area for the rate of interfacial heat and mass transfer [1,2]. The global and local fluid dynamic properties are strictly related to the prevailing flow regime, which can be distinguished—considering a large-diameter bubble column—in the homogeneous flow regime, the transition flow regime and the heterogeneous flow regime. A complete description of

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Nomenclature

Non-dimensional numbers

$Eo=\frac{g(\rho_L-\rho_G)d_{eq}^2}{\sigma}$	eötvös number [−]
$Fr=\frac{U^2}{gd_{eq}}$	froude number [−]
$Mo=\frac{g(\rho_L-\rho_G)\mu_L^4}{\rho_L^2\sigma^3}$	morton number [−]
$Re=\frac{\rho_L U d_{eq}}{\mu_L}$	reynolds number [−]
$We=\frac{d_{eq}U^2\rho_L}{\sigma}$	weber number [−]
$N_\mu=\frac{\mu_L}{\mu_G}$	viscosity ratio [−]

Acronyms

BSD	bubble size distribution
CLD	chord length distribution

Symbols

a	major axis of the bubble [m]
b	minor axis of the bubble [m]
c_i *(i=1, ..., 5)*	coefficient in the ellipse equation (Eq. (13)) [−]
c_L	lift coefficient in Eq. (B.1) [−]
D_H^*	non-dimensional diameter [−]
$D_{H,\ Cr}^*$	critical non-dimensional diameter [−]
d_{23}	sauter mean diameter [mm]
$d_b{}^{max}$	critical bubble diameter according in Eq. (26) [mm]
d_{cr}	critical diameter (accordingly to the lift force) [mm]
d_c	diameter of the column [m]
d_{eq}	bubble equivalent diameter [mm]
d_o	gas sparger holes diameter [mm]
e	eccentricity [m]
f	bubble frequency [1/s]
g	gravity acceleration $[m/s^2]$
h	height along the column [m]
H_O	height of the free-surface before aeration [m]
H_D	height of the free-surface after aeration [m]
H_c	height of the column [m]
H_D	height of the free-surface after aeration [m]
J	drift-flux [m/s]
$n_{algorithm}$	number of bubbles generated by the CLD to BSD conversion algorithm [−]
n	exponent in Eq. (11) and (12) [−]
N	number of classes used [−]
$P_c(C)$	probability density function of the chord length [−]
$P_p(a)$	probability density function describing the distribution of the bubbles detected by the probe [−]
$P_s(a)_{(m,s)}$	probability density function of the bubble major axis [−]
S_i *(i=1,2,3)*	parameters in the swarm velocity method (Eq. (6)) [−]
T	temperature [°C]
U	superficial velocity [m/s]
u_b	bubble velocity [m/s]
u_∞	terminal velocity of an isolated bubble (Eq. (11) and (12)) [m/s]
U_b	parameter in the drift-flux method (Eq. (9)) [m/s]
u_{bb}	ubble velocity [m/s]
$\Delta t_{sampling}$	optical probe sampling time [s]
ε	holdup [−]
$\varepsilon_{G,\ Local}$	local gas fraction [−]
ξ	generic variable [−]
ρ	density [kg/m^3]
σs	surface tension [N/m]
C	chord length $[m]$
m, s	parameters in the log-normal probability density function [−]
x	horizontal axis [−]
x_c	horizontal coordinate of the bubble center $[m]$
x	vertical axis [−]
x_c	vertical coordinate of the bubble center $[m]$
z, k, i, l	coefficients in the aspect ratio correlation [−]
α	volume fraction [−]
μ	dynamic viscosity $[Pa \bullet s]$
φ	aspect ratio [−]

Subscripts

exp	*experimental*
predicted	*computed from algorithm*
G	*gas phase*
L	*liquid phase*
T, E	*subscripts in the drift-flux formulation* (Eqs. (6)–(8))
trans	*transition point*
swarm	*swarm velocity*

these flow regimes has been proposed by Besagni et al. [3] and is summarized in the following. The homogeneous flow regime—generally associated with small gas superficial velocities, U_G—is referred as the flow regime where only "*non-coalescence-induced*" bubbles exist (e.g. as detected by the gas disengagement technique, ref. [4]). The homogeneous flow regime can be further distinguished into "*pure-homogeneous*" (or "*mono-dispersed homogeneous*") flow regime and "*pseudo-homogeneous*" (or "*poly-dispersed homogeneous*") flow regime, depending on the BSD and the change of sign of the lift force coefficient (see, for example, ref. [3]). The transition flow regime has been identified by the appearance of the "*coalescence-induced*" bubbles and is characterized by large flow macro-structures with large eddies and a widened bubble size distribution due to the onset of bubble coalescence. At high gas superficial velocities, a fully heterogeneous flow regime is reached [5]; it is associated with high coalescence and breakage rates and a wide variety of bubble sizes. To design and optimize bubble column processes (i.e., when chemical reactions have to be considered in practical applications), it is essential to recognize the prevailing flow regime and, subsequently, estimate the local and the global fluid dynamic properties. In this respect, a complete knowledge of the global fluid dynamics of the bubble column relies on the complete knowledge of the "*bubble-scale*". Indeed, the bubble motion and bubble dynamics characterize and influence the medium-scale circulation (i.e., eddies that transport the dispersed phase) and large-scale circulation (i.e., the liquid phase flowing upward in the center of the column and downward in the region near the wall). Moreover, the size and shape of the interface of the dispersed phase characterize the heat and mass exchange. In this respect, beside experimental investigations to obtain analytical relations for the gas holdup curve (the relation between the gas holdup and the gas superficial velocity), reliable methods to estimate BSDs are needed, which is the main subject of this paper. In the following, in order to discuss the role of the present paper in the literature, a brief literature survey on the experimental methods to estimate the BSDs and shapes is proposed.

In the last decades, different intrusive and non-intrusive experimental techniques have been proposed to measure bubble sizes and shapes [6]. Non-intrusive techniques (i.e., image analysis) are generally preferred over intrusive methods, since the flow conditions are not disturbed. However, these techniques are limited to resolve large bubble clusters and large void fractions; in this respect, the reader may refer to the literature survey proposed in our previous paper [7]. In addition, image analysis may not be used under relevant operating