



The effect of liquid phase properties on bubble column fluid dynamics: Gas holdup, flow regime transition, bubble size distributions and shapes, interfacial areas and foaming phenomena



Giorgio Besagni*, Fabio Inzoli

Politecnico di Milano, Department of Energy, Via Lambruschini 4a, 20156 Milan, Italy

HIGHLIGHTS

- A comprehensive experimental dataset is presented.
- Foaming phenomena in bubble columns with organic compounds are studied.
- The relationship between the “bubble-scale” and the “reactor-scale” is studied.
- Novel correlations for interfacial areas and bubbles shapes are proposed.
- Destabilization of the homogeneous regime is interpreted by the lift force.

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ABSTRACT

The correct design, operation and scale-up of bubble columns rely on the knowledge of the fluid dynamics at the “bubble-scale” and at the “reactor-scale”. This paper contributes to the existing discussion on the multi-scale fluid dynamics of bubble columns, and provides a complete dataset concerning the influence of the liquid phase properties on bubble column fluid dynamics at “bubble-scale” and at the “reactor-scale”. The bubble column is large-diameter and large-scale (5.3 m in height, inner diameter of 0.24 m), it was operated with superficial gas velocities in the range of 0.004–0.20 m/s, and it was tested for different aspect ratios (in the range 5–12.5). Air was used as the dispersed phase and various fluids (tap water, aqueous solutions of NaCl, a water-ethanol mixture and solutions of water-monoethylene glycol of different concentrations) were employed as liquid phases. The gas holdup measurements were used to investigate the global fluid dynamics, the flow regime transition and the foaming phenomena. Subsequently, the image analysis was used to characterize the bubble size distributions and shapes in the homogeneous flow regime. Finally, the gas holdup and image analysis data were used to estimate the interfacial areas. The experimental data were extensively compared with previous studies and correlations and were used to propose novel correlations to estimate the bubble shapes and the interfacial areas, for the different liquid phases tested. It was found that a change in the liquid phase properties affects the bubble interfacial properties at the “bubble-scale”, thus changing the prevailing bubble size distribution because of the reduced/promoted coalescence phenomena. The variation in the prevailing bubble size distribution affects the “reactor-scale” (gas holdup and flow regime transition) and a lift-force-based approach is used to analyze the relationship between the “bubble-scale” and the “reactor-scale”. When the prevailing bubble size distribution shifts towards larger bubbles, because of the promoted coalescence (i.e., high viscous liquid phases), the lift force pushes the larger bubbles towards the center of the bubble column, inducing “coalescence-induced bubbles” and, consequently, destabilizing the homogeneous flow regime and decreasing the gas holdup. Conversely, when the prevailing bubble size distribution shifts towards smaller bubbles, because of the reduced coalescence (i.e., organic and inorganic active compounds, and low viscous liquid phases), the lift force pushes the small bubbles towards the wall, inducing cluster of bubbles and, consequently, stabilizing the homogeneous flow regime and increasing the gas holdup. In addition, foaming phenomena were observed for organic active compounds, in the case of high aspect ratios only: this observation suggests that the validity of the scale-up criteria is not ensured for all binary systems and future studies will be devoted to provide insights in the scale-up criteria.

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* Corresponding author.

E-mail addresses: giorgio.besagni@polimi.it (G. Besagni), fabio.inzoli@polimi.it (F. Inzoli).

Nomenclature

Non-dimensional numbers

$AR = \frac{H_0}{d_c}$ aspect ratio

$Eo = \frac{g(\rho_L - \rho_G)d_{eq}^2}{\sigma}$ Eötvös number

Eo_{\perp} Eötvös number considering the maximum horizontal dimension of the bubble (Eq. (36))

$Fr = \frac{U^2}{gd_{eq}}$ Froude number

$Mo = \frac{g(\rho_L - \rho_G)\mu_G^4}{\rho_L^2 \sigma^3}$ 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

| | |
|------|------------------------------|
| AR | Aspect Ratio |
| BSD | Bubble Size Distribution |
| CMC | Carboxymethyl cellulose |
| DNS | Direct numerical simulations |
| EtOH | Ethanol |
| MEG | Monoethylene glycol |
| NaCl | Sodium chloride |
| PDF | Probability density function |

Symbols

| | |
|-------------------------|-----------------------------------------------------------------------------|
| a | major axis of the bubble [m] |
| a_i | interfacial area [1/mm] |
| b | minor axis of the bubble [m] |
| c | molar concentration of NaCl [mol/l] |
| c_t | molar transition concentration of NaCl [mol/l] |
| $c_i (i = 1, \dots, 5)$ | coefficient in the ellipse equation (Eq. (15)) [-] |
| $c_{MEG,wt}$ | mass concentration of MEG [%] |
| $c_{EtOH,wt}$ | mass concentration of EtOH [%] |
| c_L | lift coefficient in Eq. (37) [-] |
| d_{Bi} | diameter of bubbles of size class i [mm] |
| d_{23} | Sauter mean diameter (Eq. (16)) [mm] |
| d_o | gas sparger holes diameter [mm] |
| d_c | diameter of the bubble column [m] |
| d_{cr} | bubble diameter for the change of the sig of the lift force coefficient [m] |
| d_{eq} | bubble equivalent diameter [mm] |
| d_{\perp} | maximum horizontal dimension of the bubble as defined in Eq. (37) [mm] |
| D_H | hydraulic diameter [m] |
| D^*_H | non-dimensional diameter (Eq. (1)) [-] |
| $D^*_{H,Cr}$ | critical non-dimensional diameter [-] |
| f | function [-] |
| F_{lift} | lift force [$\text{kg}/\text{m}^2 \text{ s}^2$] |
| g | acceleration due to gravity [m/s^2] |
| h | height along the bubble column [m] |

| | |
|-------------------------|---------------------------------------------------------------|
| H_c | height of the bubble column [m] |
| H_D | height of the free-surface after aeration [m] |
| H_0 | height of the free-surface before aeration [m] |
| J | drift-flux [m/s] |
| $k_i (i = 1, 2)$ | coefficients in the aspect ratio correlation (Eq. (26)) [-] |
| N | number of classes used in Eq. (19) [-] |
| $S_i (i = 1, 2, 3)$ | parameters in the swarm velocity method (Eq. (8)) [-] |
| T | temperature [K] |
| t_G | mean residence time of the dispersed phase [s] |
| U_b | parameter in the drift-flux method (Eq. (11)) [m/s] |
| u_{∞} | terminal velocity of an isolated bubble (Eqs. (11)(13)) [m/s] |
| U | superficial velocity [m/s] |
| \underline{u} | mean rise velocity [m/s] |
| \underline{u}_G | local gas phase velocity [m/s] |
| \underline{u}_L | local liquid phase velocity [m/s] |
| u_b | bubble terminal velocity through the Clift diagram [m/s] |
| $z_i (i = 1, \dots, 5)$ | coefficients in the aspect ratio correlation (Eq. (31)) [-] |
| V | volume [m^3] |
| x | coordinate in ellipse equation (Eq. (15)) [m] |
| y | coordinate in ellipse equation (Eq. (15)) [m] |

Greek symbols

| | |
|---------------|------------------------------------------------------|
| α | proportionality coefficient in Eqs. (3) and (21) [-] |
| β | exponent in Eq. (21) [-] |
| γ | volume fraction contribution (Eq. (38)) [-] |
| ε | holdup [-] |
| v | bubble terminal velocity [m/s] |
| ρ | density [kg/m^3] |
| σ | surface tension [N/m] |
| ϕ | aspect ratio [-] |

Subscripts

| | |
|---------------------|-----------------------------------------------------------|
| c | parameter related to the bubble column |
| <i>correlation</i> | correlation parameter |
| <i>experimental</i> | experimental parameter |
| <i>Slug-bubble</i> | parameter related to slug-bubbles |
| L | liquid phase |
| <i>Local</i> | local parameter |
| G | gas phase |
| T, E | subscripts in the drift-flux formulation (Eqs. (10) (12)) |
| <i>trans</i> | transition point |
| <i>swarm</i> | swarm velocity |
| <i>Wallis</i> | Wallis plot method |
| <i>wt</i> | mass concentration |

1. Introduction

Two-phase bubble columns are multiphase reactors/contacting devices where a gas phase is dispersed into a continuous phase (i.e., a liquid phase—the subject of this study—or a suspension—matter of our future research) in the form of “non-coalescence-induced” bubbles or “coalescence-induced” bubbles. The simplest configuration consists in a vertical cylinder with no internals,¹ in

which the gas enters through a gas sparger located at the bottom, and the liquid phase is supplied in the batch mode or it may be led in either co-currently or counter-currently to the upward gas stream. Two-phase bubble columns are widely used in chemical, petrochemical and biochemical industries because of a number of advantages they provide in both design and operation: (a) the simplicity of construction, (b) the lack of any mechanically operated parts, (c) the low energy input requirements, (d) the large contact area between the liquid and gas phases, and (e) the good mixing within the liquid phase (see references Leonard et al. (2015) and Rollbusch et al. (2015a)). In particular, the large contact area between the phases ensures high interfacial heat and mass transfer

¹ Eventually, internal devices may be added to control the heat transfer, to limit the liquid phase back-mixing or to foster the bubble break-up rate: these elements have significant effects on the fluid dynamics. We have discussed this topic in reference Besagni and Inzoli (2016b).

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