Chemical Engineering Journal 180 (2012) 216–228

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Journal

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

Statistical tool combined with image analysis to characterize hydrodynamics and mass transfer in a bubble column

A. Ferreira[a,b,*], G. Pereira[b], J.A. Teixeira[a], F. Rocha[b]

[a] IBB-Institute for Biotechnology and Bioengineering, Centre of Biological Engineering, Universidade do Minho, Campus de Gualtar, 4710-057 Braga, Portugal
[b] LEPAE-Laboratory for Process, Environmental and Energy Engineering, Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 23 June 2011
Received in revised form
23 September 2011
Accepted 28 September 2011

Keywords:
Bubble column
Mass transfer
Multiphase reactors
Hydrodynamics
Image analysis

ABSTRACT

Image analysis technique has been proved to be very effective in the quantification of particles size and morphology distributions in different work areas. In the present work this technique was combined with the discriminant factorial analysis (DFA) in order to allow the automatic identification of single bubbles (isolated bubbles without influence of surrounded bubbles) in multiphase systems. With the previous methodology it has been possible to distinguish online and automatically among three different classes of bubbles (single bubbles and medium complexity and large complexity bubbles groups), allowing for the first time the computation of the local bubble population complexity in the system. The automatic and correct characterization of the single bubbles allowed the correct determination of bubble size and, consequently, the specific interfacial area a at different experimental conditions. Agreement between automated and manual classification, measured in terms of a performance index, is 98% for single bubbles identification. Further, the present work describes the application of such methodology to the study of temperature, type of gas sparger, and liquid phase properties (viscosity and surface tension) influence on the individual components of volumetric liquid side mass transfer coefficient, k_La. The results show that the different experimental parameters and liquid properties act by a particular way on k_L and a.

1. Introduction

Gas/liquid contactors are used in chemical, biochemical, pharmaceutical, petrochemical and others industries. Bubble column reactors are intensively used as multiphase contactors. Their popularity is essentially related to the simple design and excellent heat and mass transfer properties. The mass transfer from the gas to the liquid is the most important goal of the process in bubble columns reactors. Thus, the characterization of the individual parameters of volumetric liquid side mass transfer coefficient, k_La, at different experimental conditions is an imperative process for the correct characterization of the mass transfer process. The liquid-side mass transfer coefficient k_L can be estimated from correlations [1] or determined, indirectly, when the interfacial area a and k_La are known. The experimental determination of a can be done using chemical and physical methods. The chemical techniques are based on a reaction of known kinetics in which the absorption rate is a function of the interfacial gas–liquid area [1–7], while the physical methods are based on the measurement of a physical property. The physical techniques are usually divided in non-invasive methods that give global, cross-section-averaged or local data, and the intrusive probes adequate to local measurements. An extensive overview of the instrumentation techniques developed for multiphase flow analysis in gas/liquid and gas/liquid/solid reactors can be found in Boyer et al. [8].

Despite all the techniques, the correct determination of a remains a challenge, as the bubble size distribution in the column is not constant, due to bubble–bubble and bubble–particle interactions that can lead to breakage or coalescence [9–13]. Moreover, the bubbles are, usually, not spherical and can vary widely in shape, affecting the reliability of some techniques. The non-invasive technique able to obtain, directly, the bubble size and shape is the one based on image analysis technique. The most common limitations of this technique are associated to problems related to wall transparency, out-of-focus, system illumination and image analysis. Most of these limitations can be experimentally solved, however, in what concerns the image analysis the automatic and correct identification of isolated and overlapping bubbles is one of the biggest challenges on this field. Several works can be found in the literature regarding the image analysis from bubble columns [12,14–16]. However, the automatic identification of isolated and overlapping bubbles remains unsolved. The commercial softwares used by the

* Corresponding author at: IBB-Institute for Biotechnology and Bioengineering, Centre of Biological Engineering, Universidade do Minho, Campus de Gualtar, 4710-057 Braga, Portugal. Tel.: +351 225081678; fax: +351 225081632.
E-mail address: amaf@fe.up.pt (A. Ferreira).

1385-8947/$ – see front matter
doi:10.1016/j.cej.2011.09.117

Nomenclature

A_{proj}	projected bubble area (m^2)
a	gas–liquid interfacial area (m^{-1})
a^*	gas–liquid interfacial area for pure system (m^{-1})
B_{CD}	mean complexity degree of the entire population
B_{CDi}	complexity degree of the bubble i
C	circularity, dimensionless
C	oxygen concentration in the liquid (kg/L)
C_0	oxygen concentration in the liquid at $t = 0$ (kg/L)
C^*	oxygen solubility in the liquid (kg/L)
D_{eq}	equivalent diameter (m)
D_L	diffusivity of gas in the liquid (m^2/s)
d_{10}	bubble average diameter (m)
d_{32}	Sauter mean diameter (m)
F_{max}	maximal Feret diameters (m)
F_{min}	minimal Feret diameters (m)
f	volumetric concentration of the particles, dimensionless
g	acceleration due to gravity (m/s^2)
k_L	liquid-side mass transfer coefficient (m/s)
k_La	volumetric liquid side mass transfer coefficient (s^{-1})
N_i	number of internal zones
n	number of bubbles, dimensionless
P	perimeter (m)
PI	performance index
$Pb_{i,S}$	probability of bubble being single
$Pb_{i,MA}$	probability of bubble belong to a medium complexity bubbles group
$Pb_{i,VA}$	probability of bubble belong to a large complexity bubbles group
S_{in}	surface occupied by the internal zones (m^2)
T	temperature (°C)
t	time (s)
u_G	superficial gas velocity (m/s)
ε_G	gas holdup, dimensionless
α	angle (°)
μ^*	effective viscosity of the particle–fluid mixture (kg/(m s))
μ_l and μ	viscosity of liquid phase (kg/(m s))
Ω_1	particle robustness
σ	surface tension (N/m)

different authors conduct to a manual or semi-manual characterization of the individual bubbles by the operator. Some authors [15] used the concavity index as a criterion to distinguish between isolated and overlapping bubbles: overlapping induces concavities in the object and decreases the concavity index. This criterium seems to not produce significant errors on the bubble size determination for low superficial gas velocity (less than 3×10^{-3} m/s). However, for high superficial gas velocities other criteria need to be found, as a result of bubbles number increase.

A combination of image analysis technique with the discriminant factorial analysis has been proved to be very effective in the quantification of particles size and morphology distributions in crystallization area, as off-line [17] and online [18] techniques.

In the present work, the online technique, developed by Ferreira et al. [18] for characterization of sucrose crystal morphology, was improved in order to allow the automatic identification of single bubbles (isolated bubbles without influence of surrounded bubbles) and bubble groups (medium complexity and large complexity groups) in the bubble column. As this automatic classification is based on several probabilities of each bubble belonging to each of the groups considered [17,18], it was also possible to obtain the complexity or turbulence of the system. This information shows to be very useful in understanding the bubble size distribution and the mass transfer process in the bubble column, mainly in what concerns the influence of the other bubbles on the concentration profiles surrounding individual bubbles, a question that has been recently studied [19,20]. The methodology and image analysis development on the present work aims to open new insights for a better understanding of mass transfer phenomena in the bubble column. The developed tool was applied to the study of the influence of temperature, type of gas sparger, and liquid phase properties (viscosity and surface tension) on the individual parameters of volumetric liquid side mass transfer coefficient, k_La.

2. Experimental

2.1. Mass transfer experiments

2.1.1. Set-up

The contact device used to perform the mass transfer experiments was the bubble column represented in Fig. 1 with the respective dimensions. The device is a perspex cylindrical column covered by a perspex rectangular box to control the temperature through water circulation. At the bottom a gas chamber is located, where the gas enters first and then passes through a steel sparger, with a thickness of 2 mm, where the bubbles are formed. The sparger has a relative free area of 0.02% and 0.05% for an orifice diameter of 0.3 and 0.5 mm, respectively.

2.1.2. Methodology

Oxygen mass transfer experiments were performed in two-phase system at different temperatures (20, 25 and 30 °C), superficial gas velocities (up to 14 mm/s), gas spargers (orifice diameter of 0.3 and 0.5 mm) and liquids (aqueous solutions of alcohol, ethanol (up to 3.43 M), sodium chloride, NaCl (up to 3.54 M) and sucrose (up to 1.41 M)). Air was used as gas phase. The liquid height was $h_0 = 0.32$ m for all experiments (no liquid throughput). Table 1 presents a summary of the experimental conditions used in the present work.

Initially the liquid is deoxygenated by bubbling nitrogen. When the dissolved oxygen concentration is practically zero, humidified air is fed into the column. At this moment the oxygen transfer process from bubbles to the liquid begins and continues

Table 1
Experimental conditions used in the present work.

Liquid phase			Gas phase	Sparger
Type	Concentration	T (°C)	$u_G \times 10^3$ (m/s)	Orifice diameter (mm)
	–	20	Up to 14	
Distilled water	–	25	Up to 14	0.3 and 0.5
	–	30	Up to 14	
Aqueous solutions of alcohol	Up to 3.43 M	25	Up to 12	0.3
Aqueous solutions of NaCl	Up to 3.5 M	25	Up to 12	0.3
Aqueous solutions of sucrose	Up to 1.41 M	25	Up to 12	0.3