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Gas hold-up distribution and mixing time in gas–liquid stirred tanks

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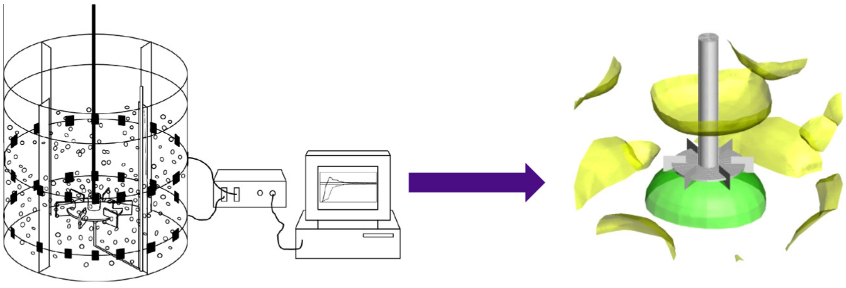
HIGHLIGHTS

- ERT allows the analysis of gas–liquid systems without limitation on the gas loading.
- The local distribution of gas hold-up in sparged stirred tanks is measured.
- The effect of bubbles on the liquid mixing time is assessed.
- The mixing quality is quantitatively related to the flow regimes.
- Data interpretation shows the relationship with a modified Peclet number.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, the gas–liquid dispersion in a stirred tank equipped with different impellers is investigated by Electrical Resistance Tomography (ERT). The main goal of the study is to provide detailed information on the spatial distribution of the gas phase and on the effect of bubbles on the liquid homogenisation dynamics. The analysis is carried out under variable gas flow rates and impeller speeds, thus covering different regimes of gas–impeller interaction, as obtained by Rushton Turbines, Pitched Blade Turbines pumping upwards and Lightnin A310. The experimental technique allows us to overcome the typical limitations of optical methods and to gain insight into the complex behaviour of sparged stirred tanks without restriction on the upper value of overall gas hold-up, that is of great interest for several chemical and biochemical processes. Besides, the experimental data can be adopted as a benchmark for advanced modelling techniques based on CFD methods, whose scant validation is often due to limited information on the local dispersion features.

The analysis of experimental results allows us to suggest simple correlations for the prediction of the prevailing flow regime based on the dimensionless Froude and flow numbers. Finally, the definition of a modified Peclet number is also suggested, as a simple parameter for the interpretation of both the gas hold-up distribution and the dimensionless mixing time.

1. Introduction

The gas dispersion in stirred tanks is a widespread operation in the chemical and biochemical industry, whose effective accomplishment importantly affects mixing, heat and mass transfer and ultimately the chemical/biochemical reactions involved in the overall industrial processes. Several aspects of the complex hydrodynamics of the two-phase turbulent flow in stirred gas–liquid contactors have been investigated in the past decades [1], moving over the years from the overall characteristics of systems of different geometries under variable operation conditions (such as power consumption [2,3], overall gas hold-up [2–5], gas dispersion regimes [4,5], liquid mixing time under gassed conditions [2,3,6,7]) to, more recently, local variables based on advanced

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Nomenclature

C	clearance, m
D	impeller diameter, m
D_{er}	relative axial dispersion coefficient, $\mathrm{m}^2\,\mathrm{s}^{-1}$
Fl	flow number, $\mathrm{Fl} = Q_G/(ND^3)$, dimensionless
Fr	Froude number, $\left(\mathrm{Fr} = \frac{N^2D}{g}\right)$, dimensionless
g	gravity acceleration, $\mathrm{m\,s}^{-2}$
H	vessel height, m
H_{L}	liquid height, m
MI	mixing index, dimensionless
$\overline{\mathrm{MI}}$	mean mixing index, dimensionless
N	impeller speed, s^{-1}
N_{fl}	impeller speed at flooding, s^{-1}
Pe^*	modified Peclet number, dimensionless
Q_{G}	gas flow rate, m^3/s
q	number of measurement planes
Re	impeller Reynolds number $\left(\mathrm{Re} = \frac{\rho N D^2}{\mu}\right)$, dimensionless
T	vessel diameter, m
U_{b}	bubble rise velocity, $\mathrm{m\,s}^{-1}$
t_{95}	mixing time, s
z	axial coordinate, m

Greek letters

ε	parameter proportional to the gas hold-up, dimensionless
ρ	liquid density, $\mathrm{kg\,m}^{-3}$
μ	liquid viscosity, Pa s
σ	dimensionless conductivity
σ_{i}	dimensionless conductivity of pixel i
$\overline{\sigma}$	mean dimensionless conductivity
θ	dimensionless time

Abbreviations

CFD	Computational Fluid Dynamics
ERT	Electrical Resistance Tomography
L33	large cavities
PBTU	up-pumping 6-bladed Pitched Blade Turbine
RT	Rushton Turbine
S33	small cavities
VC	vortex clinging cavities

Subscripts

fl	flooding point
1	lower measurement plane
2	upper measurement plane
g	gas phase

techniques (liquid and gas velocity fields [8–10], bubbles size distribution [11,12], local gas hold-up [13–17]).

The development of experimental techniques enabling the collection of local velocity, size and concentration distribution of the dispersed phase, together with the relevant variable of the continuous liquid phase, has provided a significant contribution to the enhancement of both the geometrical design and the modelling of gas–liquid stirred tanks [8,11,18–20].

Among the numerous aspects which still deserve further investigation, the gas hold-up distribution and the liquid mixing time in sparged stirred tanks are those considered in this work. The local determination of the gas volume fraction in stirred tanks has been mainly based either on optical or conductivity probes and more recently on the application of Electrical Resistance Tomography (ERT). One of the first contributions to the determination of the local void fraction in aerated stirred tanks is due to Bombac et al. [13], who based their measurements on a point-wise resistivity probe providing novel maps of gas distribution under different gassed regimes. Recently, Kong et al. [15] have applied a γ-CT scan method to the analysis of the impeller region of a standard geometry gassed stirred tank finding consistent results with those published by Bombac et al. [13] and adding further insight into the effect of operating conditions on the local gas distribution. Among others, the local gas hold-up was also determined by an impedance method by Paglianti and Pintus [21] and by a novel optical technique by Busciglio et al. [14]. A recent contribution of Lee and Dudukovic [16] has shown the capability of a novel technique based on the analysis of optical fibre probe data to identify the flow regime transition from the flooding to the loading regimes in a standard geometry stirred tank. The suitability of ERT for the investigation of gas–liquid stirred tanks has been demonstrated among the first by Wang et al. [22] and it has been lately applied also to three phase systems [23]. A recent review on the application of ERT to chemical engineering apparatuses, including gas–liquid systems and stirred tanks has been performed by Sharifi and Young [24]. Overall, the local characterisation of the gas distribution in sparged stirred tanks with high gas hold-up by non-intrusive methods has been performed in a limited number of cases. As for the ERT investigations, the results have been mainly presented as qualitative tomograms, rather than by quantitative methods. Further experimental information on different impellers and deeper insight into the system characteristics, based on suitable parameter estimations, is expected to provide a useful contribution to improve design and modelling of aerated reactors and bioreactors.

As for the liquid mixing time in gassed stirred tanks, depending on the relative importance of the energy transfer from the gas phase and the power drawn from the impeller, different effects of aeration can be observed [25]. For known stirred tank configurations, the usual correlation suitable for ungassed systems can be adopted, by accounting for the real power consumption [2] and specific methods have been developed [7], while for unconventional geometries and multiple impeller systems, modifications to the standard correlation are required even in ungassed systems [26], and specific investigation are necessary for the identification of reliable correlations based on parameter fitting procedures [17]. The successful prediction of mixing time in gas–liquid stirred tanks by advanced modelling technique has been recently reported among others by Zhang et al. [27]. Nevertheless, the capability of the current modelling techniques in the prediction of all the complex features of gas–liquid systems, including the bubble size distribution and the impeller–bubble interaction regimes, which in turn affect the liquid flow patterns and the macro-mixing characteristics, still requires extensive validation. On the experimental side, the techniques based on conductivity probes for single phase systems require appropriate modifications in aerated conditions [28], the optical methods are limited to very low gas hold-up, while in principle the application of ERT does not suffer of any limitation. Indeed, it has been successful adopted for the dynamic characterisation of single-phase stirred tanks [29–31], as well as for