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Global and local hydrodynamics of bubble columns – Effect of gas distributor

Safa Sharaf [a], Maria Zednikova [b], Marek C. Ruzicka [b], Barry J. Azzopardi [a,*]

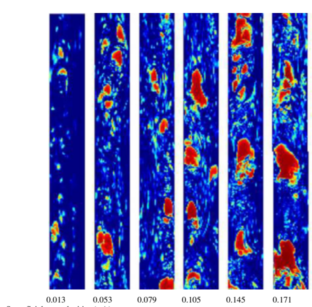
[a] Manufacturing and Process Technologies Research Division, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom
[b] Department of Multiphase Reactors, Institute of Chemical Process Fundamentals, Czech Academy of Sciences, Rozvojova 135, Prague 6 165 02, Czech Republic

HIGHLIGHTS

- Global and local hydrodynamics of bubble columns: level swell and WMS.
- Flow regimes in bubble column and their transitions: effect of gas distributor.
- Critical review of current modelling strategies.
- New data on gas–liquid interfacial area.

GRAPHICAL ABSTRACT

Time history of phase across a diameter of the bubble column blue is liquid, red is gas. Earliest time at top, later time below.



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ABSTRACT

Global (level swell) and local (WMS – Wire Mesh Sensor) measurements were made on waters of different purities and air, in a cylindrical laboratory bubble column (2 m tall, 0.127 m dia) using two different gas distributors: a perforated plate (to produce homogeneous flow) and a spider sparger (to produce heterogeneous flow). The level swell method provided the steady space-averaged gas holdup/gas flow rate data. The WMS method provided the actual gas holdups and bubble sizes resolved in time and space at one cross-sectional horizontal plane (1 m above distributor), whose integration yields the time-averaged data. The following results were obtained: The global and local data agree relatively well; there are distinct differences between the radial profiles and bubble size distributions between the two main flow regimes; the local information identifies why the predictions of published models, which account for the smaller and larger bubbles in the flow, may not perform well; the modelling approaches based on the hindrance and enhancement concepts prove to be suitable for the flow regime identification and description, including the transition range between the homogeneous and heterogeneous flows; based on the hydrodynamics, the specific interfacial area is obtained, together with the mass transfer coefficient.

1. Introduction

In this section, two aspects of bubble columns are considered: (i) the experimental findings regarding the key features of the columns behaviour relevant to the present study, and (ii) the mathematical modelling especially related to the description and interpretation of the measured data. The formulas introduced in here below (Section 1.2) are then applied to the present data (Section 3.4).

* Corresponding author.
E-mail address: barry.azzopardi@nottingham.ac.uk (B.J. Azzopardi).

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Nomenclature

a	constant in Eq. (5)
a'	specific interfacial area (m^2/m^3)
C_0	term accounting for profile effects
C_1	critical point marking end of homogeneous regime
C_2	critical point marking boundary between transition and heterogeneous regimes
D_B	large bubble size (m)
D_{32}	Sauter mean diameter of bubbles (m)
g	gravitational acceleration (m^2/s)
H_f	height of aerated column (m)
H_i	initial or clear height of liquid (m)
j	drift flux (m^3/m^2 s)
k	constant in Eq. (4)
k_L	liquid side mass transfer coefficient (m/s)
k_La	volumetric liquid side mass transfer coefficient (1/s)
n	power in Richardson and Zaki relationship, Eq. (4)
p	weighting function
u	bubble velocity (m/s)
u_d	drift velocity (m/s)
u_{gs}	superficial gas velocity (m/s)
u_{Tr}	velocity at upper boundary of homogeneous flow
u_o	constant in Eq. (5)
V_g	volume of gas in aerated column (m^3)
V_l	volume of liquid in aerated column (m^3)
$\Delta\varepsilon_g/\Delta D_B$	
ε_g	gas holdup
$\langle\varepsilon_g\rangle$	volume average gas holdup
ε_B	gas holdup in large bubbles
ε_{Tr}	gas holdup at upper boundary of homogeneous flow
ρ_l	liquid density (kg/m^3)

Subscripts

He	heterogeneous
Ho	homogeneous
1	at boundary between homogeneous and transition
2	at boundary between transition and heterogeneous

Abbreviations

ECT	Electrical Capacitance Tomography
EIT	Electrical Impedance Tomography
MRI	Magnetic Resonance Imaging
WMS	Wire Mesh Sensor

1.1. Experimental findings

Bubble columns are gas/liquid contactors which are often used as chemical reactors. They do not employ moving parts to produce mixing but achieve this purely by the hydrodynamics. Their background, geometries and characteristics are described in texts [1–4]. However, in spite of the plentiful literature on the topic there is still a need for improved understanding.

In their simplest form, bubble columns are cylindrical vessels which can sometimes contain tube banks or coils for heat transfer control. There can be more complicated versions with internal or external down-comers to provide recirculation of the liquid and hence a larger liquid residence time. Here consideration will be focused on the simplest type without any inserts.

Many of the equations published for bubble column design are empirical correlations and, therefore, their applications should be limited to interpolation. For the important parameter of gas holdup (also called: voidage, porosity, void fraction, etc.), published correlations have been reviewed by Ribeiro and Lang [5]. They found 37 sources, most with many empirical constants. Computational Fluid Dynamics has been applied to bubble columns and can give good results. Though, in expert hands they can give valuable information, they are not so useful for initial, first-design calculations. For such applications, simpler models with a sound physical basis are much more appropriate. However, the current versions of these models need to be strengthened and improved. Important geometric parameters in the design of a bubble column are column height, diameter, and the distribution, type and size of holes in the gas injector. These need to be considered along with the gas and liquid densities, the liquid viscosity and the presence and concentration of chemicals particularly those which can inhibit bubble coalescence, e.g., salts, alcohols and other surfactants.

In simple bubble columns and bubbly flows, the following basic flow regimes have been identified: homogeneous or bubble flow; heterogeneous or churn-turbulent flow, and slug flow [6]. At low gas flow rates, with carefully designed 'fine' gas distributors, homogeneous flow is produced. This takes the form of small bubbles that are uniformly dispersed within the column. At higher gas velocities, when it transits into the heterogeneous flow, larger bubbles appear that are interspersed between the small ones. With 'coarse' distributors, heterogeneous flow is produced at all gas inputs. In small diameter columns (⩽100 mm), at higher gas velocities, the large bubbles are stabilised by the column walls and the flow becomes slug flow. Mudde et al. [7] noted that a majority of industrial bubble columns operate in the heterogeneous flow regime region. In lab scale columns, we can typically have the three following flow regimes: *homogeneous*, *heterogeneous*, *transition*, which are also considered in this study.

An important parameter in bubble column design is the gas holdup as, together with bubble size, it determines the gas–liquid interfacial area, which is crucial for mass transfer between the phases [4]. The volumetric gas holdup, ε_g, is defined as the ratio of the volume of the gas phase V_g to the total volume of the dispersion ($V_g + V_l$). The volume averaged gas holdup, $\langle\varepsilon_g\rangle$, can be calculated using "level swell", i.e., the relative difference between the aerated liquid height, H_f, and its unaerated height, H_i, and is given by $\langle\varepsilon_g\rangle = (H_f - H_i)/H_f$.

From experiments on columns with diameters of 0.15, 0.225 and 0.4 m, Groen [8] showed that there is little effect of the column diameter on the overall gas holdup/superficial gas velocity relationship. The clear liquid height was shown [9] to decrease the gas holdup as the height of the two-phase mixture increased. In contrast, in the heterogeneous regime, little difference is seen between the data of Letzel et al. [10] (1.2 m tall bubble column with 200 × 0.5 mm diameter holes) and that of Cheng et al. [11] (10 m high column with measurements made at the 5 m level and having 6 mm diameter holes for air entry). It is generally agreed that the main effect of increasing liquid viscosity is to reduce the gas holdup [12]. However, in some cases, particularly in the homogeneous regime, a 'dual effect' of the viscosity can occasionally be reported: first to enhance the holdup and then to reduce it, with a maximum occurring somewhere within 1–10 mPa s, say (e.g. Ruzicka et al. [13], Olivieri et al. [14]). Anderson and Quinn [15] measured the gas holdup in a bubble column with water at different levels of purity. Impurities suppress bubble coalescence and hence increase its gas holdup. As tap water has more impurities than deionised or distilled water, it is not surprising that its gas holdup was higher than that in the other two. In a similar