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Experimental investigation into the impact of sparger design on bubble columns at high superficial velocities

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ABSTRACT

In this work we have quantified the impact of sparger design on the hydrodynamics of a pilot-scale bubble column (0.39 m in diameter and 2 m in height) at superficial velocities between 0.07 and 0.29 m/s. It was found that increasing the sparger orifice diameter from 0.5 mm to 3 mm led to different behaviour in the homogenous flow regime, this being attributed to the different bubble size distributions (BSDs) generated. At higher superficial velocities (i.e., in the heterogeneous flow regime), it was observed that the sparger orifice diameter had little impact on the column behaviour (as characterised by the BSD, overall hold-up, local hold-up profile, liquid velocity profile and mixing time). Changing from a symmetric to an asymmetric sparger design was observed to have a minimal impact on the BSD and overall hold-up, but a large impact on the flow behaviour (i.e., the local hold-up and liquid velocity profiles). The change in flow patterns caused by the asymmetric sparger generally led to a decrease in the mixing time for all measurement locations and tracer addition points. Results from this work are of clear interest in the design of bubble columns.

1. Introduction

Bubble columns are widely used as gas–liquid contactors in the chemical and biochemical industries. This is largely due to their mechanical simplicity and good heat and mass transfer characteristics (Kantarci et al., 2005; Shah et al., 1982). Three flow regimes have been identified in bubble columns; homogenous flow, heterogeneous (churn turbulent) flow and slug flow; the flow regime in a given column is commonly held to be a function of both the column diameter and superficial velocity (Shah et al., 1982). Homogeneous flow generally occurs at low superficial velocities (<0.05 m/s), and is typically characterized by having a relatively narrow Bubble Size Distribution (BSD) with a small mean bubble size. Heterogeneous flow occurs at higher superficial velocities and is characterized by a broader BSD, with a higher level of turbulence in the liquid phase (Kantarci et al., 2005).

It has been noted by others (Chaumat et al., 2006; Kantarci et al., 2005) that the flow-regime occurring inside a bubble column is not just a function of its diameter and the gas superficial velocity; with the design of the sparger also playing a role. For example, Chaumat et al. (2006) observed that changing the sparger orifice diameter (d_o) from 1 to 0.5 mm led to a higher overall hold-up in the homogenous regime, with the transition from the homogenous to the heterogeneous flow regime occurring at a higher superficial velocity. At higher superficial velocities (i.e., in the heterogeneous regime) little difference between the two spargers was observed.

It is generally acknowledged (Kantarci et al., 2005; Shah et al., 1982) that the sparger design influences the size of the

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Nomenclature

Symbol	*Units Description*
a	Interfacial area per unit volume [$m^2\,m^{-3}$]
d_o	Sparger orifice diameter [m]
d_b	Bubble diameter [m]
P	Pressure [Pa]
t	Time [s]
t_m	Mixing time [s]
U_G	Superficial gas velocity [$m\,s^{-1}$]
U_L	Liquid velocity [$m\,s^{-1}$]
x	Distance in x direction [m]
y	Distance in y direction [m]
z	Distance in z direction [m]
α	Overall hold-up [dimensionless]
α_{local}	Local gas hold-up [dimensionless]
ρ_G	Gas density [$kg\,m^{-3}$]
ρ_L	Liquid density [$kg\,m^{-3}$]

bubbles produced, and hence the column behaviour. Recently Rollbusch et al. (2015) have examined bubble columns operating with organic liquid phases with a focus on applications in the chemical industry. They have found that the overall hold-up was dependent on both the properties of the liquid phase (a conclusion in line with that of others (Jamialahmadi et al., 1994; McClure et al., 2014a)) as well as the sparger design, with the sparger design being particularly important in the homogeneous flow regime. Several authors (Akita and Yoshida, 1974; Davidson and Schuler, 1960) have proposed correlations relating the orifice diameter and gas velocity to the size of bubbles produced; generally speaking, increasing the orifice diameter or velocity will lead to the generation of larger bubbles. The influence of the sparger design on the bubble size is thought to extend for 1–2 column diameters above the sparger (McClure et al., 2014c; Polli et al., 2002); above this height, bubbles reach their 'equilibrium' size. Given that bubble columns used in some industries (e.g., bio-processing) typically have aspect ratios of 2–5 (Kantarci et al., 2005) the sparger design may well have a substantial impact on the overall behaviour of the system.

The position of the sparger orifices will obviously influence the column behaviour, as any flow patterns are entirely driven by the air introduced into the column. Hence, it would be reasonable to think that by modifying the sparger design it could be possible to change the flow patterns and the hence mixing within the column. Li et al. (2009) have examined this issue using Computational Fluid Dynamics (CFD), with their model predicting that the mixing time is reduced for more asymmetrical sparger designs. Haque et al. (1986) investigated this issue experimentally at relatively low superficial velocities ($U_G < 0.06$ m/s), finding that the use of a single ring type sparger led to the smallest mixing time. However, very little work examining the impact of the sparger design on mixing at high superficial velocities has been identified in the open literature.

Knowledge of how the sparger design impacts column behaviour such as mixing and hold-up (which is related to mass transfer) is of obvious interest in the design of bubble columns. In our previous work (McClure et al., 2013, 2014c, 2015a) we have experimentally investigated the performance of bubble columns at a range of conditions and scales, however, we have not examined the impact of the sparger design.

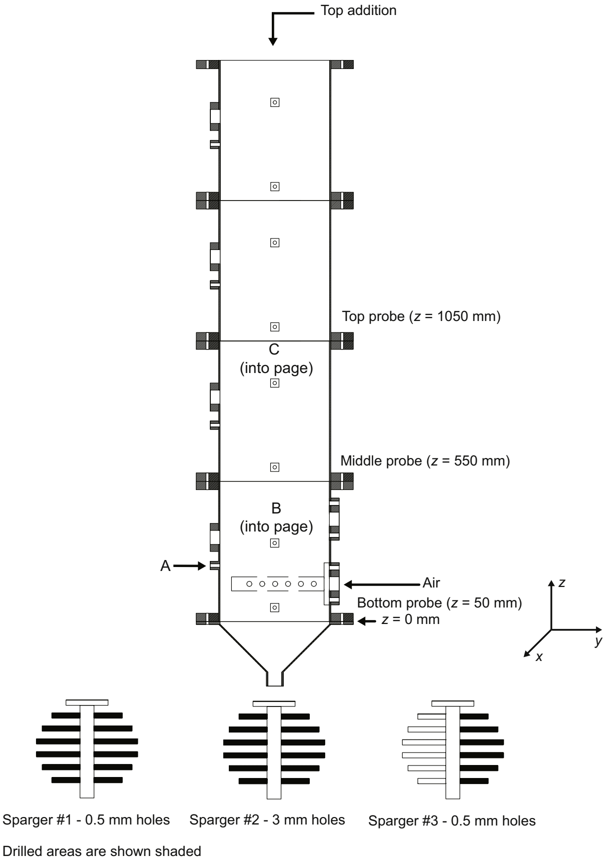

Fig. 1 – Schematic showing the column as well as the sparger designs used. Areas of the sparger which have holes are shown as black.

Hence, the aim of this present study is to quantify the impact of changing the sparger design (both in terms of the orifice diameter and the symmetry with which air is introduced) on the bubble column behaviour, particularly at high superficial velocities (conditions for which relatively few data are available in the open literature).

This work fits into an overall programme of research undertaken over the past five years to generate detailed data sets at the pilot-scale to validate a Computational Fluid Dynamics (CFD) model for bubble column bioreactors. Previous work has concentrated on validation of the model against experimental data for hold-up, gas and liquid velocity profiles (McClure et al., 2014c), mixing times (McClure et al., 2015a) and oxygen transfer rate (McClure et al., 2015b) using the mean bubble size as an input. Results are extremely encouraging, being able to reproduce the data to a sufficient degree to make the model suitable for industrial design and operation studies. Therefore, a key objective for this paper is to provide the data required to explicitly investigate the impact of the sparger design; data that will be used in on-going extension and validation of the model.

2. Method

Experiments were conducted using a pilot-scale bubble column 2 m in height and 0.39 m in diameter. The column was constructed from clear acrylic and is shown schematically in Fig. 1. Further details about the column design are available elsewhere (McClure et al., 2014c). In this work 'tree' type spargers were used, located such that the midpoint of the sparger was 135 mm above the base of the column. Two different