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The bubble size distribution and O_2 mass transfer in an oscillating, meso-scale tube

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Abstract

This work aims at characterizing bubble size distribution and its control in a small-scale, constricted tube in the presence of an oscillating flow. From previous works, it became clear that the full modelling of the dispersed gas-liquid flow in the constricted tube requires a deeper clarification of the impact of tube geometry and the hydrodynamic parameters on the observed values of the oxygen mass transfer coefficient (k_La). In order to do so, data on the size and shape of the generated bubbles have been obtained with a CCD camera during the steady, continuous operation of a 350 mm constricted tube in the presence of flowing liquid and gas phases, at different combinations of oscillation frequency (f) and amplitude (x_0). These data were used to generate bubble size distribution curves.

The results demonstrated that the operation at smooth oscillatory flow conditions ($f \leq 10$ Hz) leads to a decrease of the bubble size, while for higher values of f (15-20 Hz) the increased oscillatory velocities cause an increase in bubble size. The simultaneous increase of gas hold-up for the same oscillatory flow conditions (f = 15-20 Hz) suggests that the gas hold-up correlates with the bubbles' diameter for this particular geometry. A correlation between the bubbles' diameter and the mass transfer coefficient in the liquid, k_L, with the oscillatory flow mixing conditions is also presented.

Introduction

The development of novel industrial bioprocesses is a major motivation for the design of innovative small-scale bioreactors as a screening tool or simply for fine chemicals manufacturing. Previous studies in the scale-down of oscillatory flow reactors have confirmed the good control of radial mixing and liquid dispersion, allowing for the operation of a 4.4 mm internal diameter constricted tube as a continuous tubular system with improved radial mixing or simply as a novel batch platform for high throughput screening. The obtained high backmixing made possible the successful application of a 350 mm length tube on the batch aerobic and anaerobic yeast growth (Reis et al., 2006b) and on a biotransformation process with *Yarrowia lipolytica* (a strictly aerobic yeast) in a four phase system (Reis et al., 2006a). It became clear that the reversing nature of the oscillatory flow is a valuable meso-scale mixing strategy as it promotes an effective contact of the heterogeneous phases. O_2 mass transfer coefficients, k_La, up to 0.16 s^{-1} were obtained in the constricted tube, for oscillation frequencies, f, and centre-to-peak amplitudes, x_0, up to 20 Hz and 3 mm, respectively, and a mean superficial gas velocity of 0.37 mm/s. This represented an improved k_La value in comparison with the k_La values usually reported for gas-sparged stirred tanks, bubble columns or airlift columns. The experimental measurements of gas hold-up have shown gas volume-fractions below 5 %, but suggested a transient regime for increasing values of f. It became clear that the full modelling of the dispersed gas-liquid flow in the constricted tube requires a deeper clarification of the impact of tube geometry and the hydrodynamic parameters on the observed *kLa* values. Being so, due to its importance in mass transfer, it is fundamental to obtain experimental data on the size and shape of generated bubbles.

Nomenclature

a	Specifica gas-liquid contact area ($m^2.m^{-3}$)
d	Tube internal diameter (mm)
d_c	Free tube diameter in the constriction (mm)
D_{32}	Sauter mean diameter (mm)
f	Oscillation frequency (Hz)
k_L	Liquid-side mass transfer coefficient ($m.s^{-1}$)
k_La	Oxygen mass transfer coefficient (s^{-1})
L	Average inter-constriction spacing (mm)
Q	Flow rate ($ml.min^{-1}$)
x_0	Oscillation amplitude (centre-to-peak) (mm)
Greek letters	
e	holdup (-)
Subsripts	
G	Gas
L	liquid

Experimental Facility

The configuration of the oscillatory meso-tube was previously presented (Reis et al., 2005) and is here illustrated in Figure 1. It consists in a 4.4 mm internal diameter (*d*) tube provided with narrow, smooth-periodic constrictions. The average inter-constrictions spacing (*L*) is ~13 mm and the mean constrictions diameter (d_c) is ~1.6 mm.

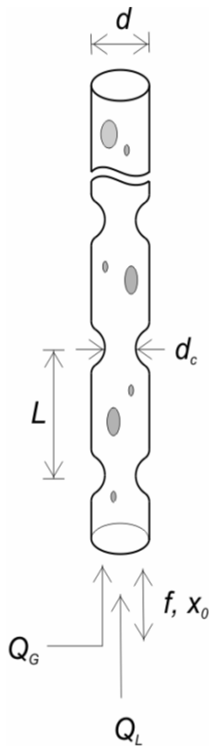


Figure 1: Geometry and gas-liquid flow in the oscillatory meso-tube, where *d* is the internal tube diameter, *L* is the constriction spacing and d_c is the free tube diameter in the constriction.

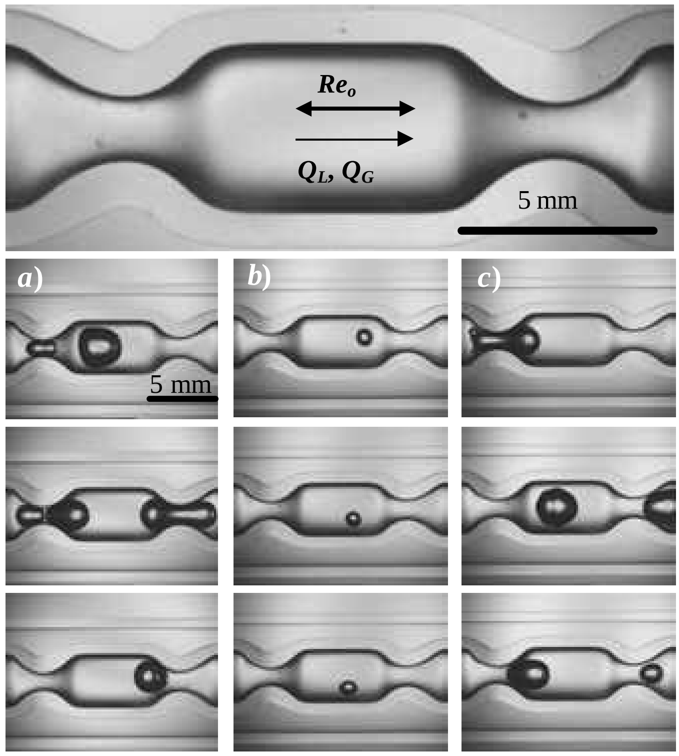
The bubble size and the bubble size distribution (BSD) were determined using image analysis and for different combinations of fluid oscillation frequency, *f*, and centre-to-peak amplitude, x_0. Bubbles images were obtained with a CCD camera for steady, continuous operation of a 350 mm tube with a liquid phase (Q_L = 1.58 ml/min) and a gas flow phase (Q_G = 0.28 ml/min), at different combinations of *f* and x_0 (0-20 Hz, 0-3 mm, respectively). Images were post-processed with image analysis software, allowing the calculation of the equivalent circular bubble's diameter. Bubble size distribution curves were then generated by the bubble number fraction. Image analysis of bubbles was carried out with a Visilog 5.4, a Graphical User Interface based image processing packaging available from Noesis, Velizy, France. Image analysis procedure started with the individual subtraction of the "background" to each TIF image, resulting in a binary image. After a series of thresholds, filters and dilations/erosions, bubbles geometry was analysed by Visilog and saved to a TXT file. The volume fraction of the gas phase (gas hold-up, e_G) was measured in experiments carried out at the same combinations of *f* and x_0, by recording the changes in the liquid height in a fine scaled (± 0.5 mm) plain pipe with 6 mm internal diameter fitted to the outlet of the tube. The precision of this setup allowed an estimation of e_G in most experiments with a final error ± 5 %.
The specific gas-liquid contact area (*a*) can be easily determined from the gas hold-up and the Sauter mean diameter (D_{32}) as

$$a = 6\frac{e_G}{D_{32}}$$

Values of *a* ($m^2\ m^{-3}$) were afterwards used for estimating the liquid-side mass transfer coefficient (k_L) from the volumetric oxygen mass transfer coefficient (product k_La), using previously obtained k_La values (Reis et al., 2004).

Results and Discussion

The results demonstrate that bubbles' size depends on the oscillatory flow conditions (Figure 2). The operation at smooth oscillatory flow conditions (*f* = 10 Hz) leads to a decrease of the bubble size, while for higher values of *f* (15-20 Hz) the increased oscillatory velocities cause enhancing bubble sizes.



f = 1 mm, x_0 = 3 Hz *f* = 2 mm, x_0 = 10 Hz *f* = 3 mm, x_0 = 20 Hz

Figure 2: Bubble sizes at increasing oscillation frequencies (*f*) and centre-to-peak amplitude (x_0): a) 1 mm and 3 Hz; b) 2 mm and 10 Hz, c) 3 mm and 20 Hz. Re_o = 2p $f x_0$? d/μ; Q_L = 1.58 ml/min; Q_G = 0.28 ml/min..

A bimodal distribution of bubble size was in general observed (one example is shown in Figure 3). The first mode corresponds to micro-bubbles (with an average size of 0.2 mm approximately), while the second mode is relative to larger bubbles with an average size of 2-3 mm. The number of micro-bubbles is remarkable, its fraction reaching a value around 0.60.

The large amount of micro-bubbles will have a strong impact on the interfacial area of the reactor, whose values were calculated from the gas hold-up (ranging from 0.01 to 0.05, and increasing for higher values of f (15-20 Hz), and from the Sauter mean diameter. The liquid side mass transfer coefficient, k_L, was, then, determined using values of the volumetric mass transfer coefficient, k_La, previously obtained (Reis et al., 2004). The k_L improved with increasing fluid mixing intensities (Figure 4) suggesting a decrease in the liquid side film thickness, and showing the positive influence the oscillatory flow conditions may have on the mass transfer phenomena occurring in an oscillatory meso-tube reactor.

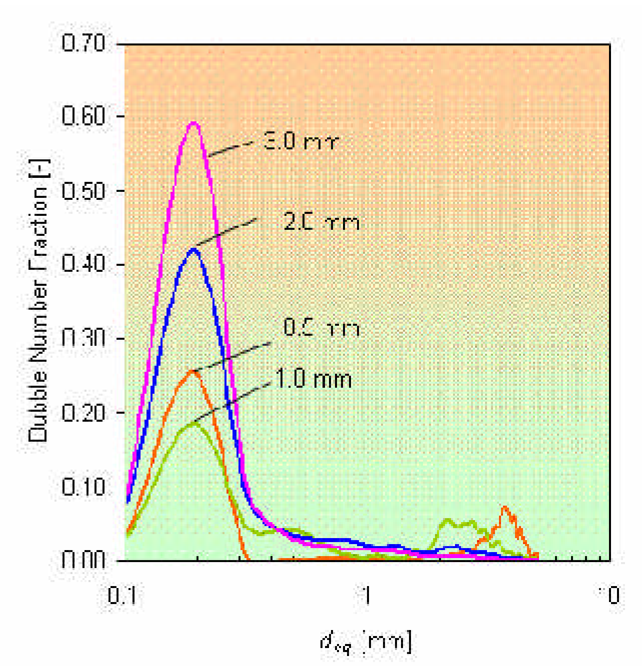


Figure 3: Bubble size distribution in the constricted meso-tube (for $f = 15\ s^{-1}$).

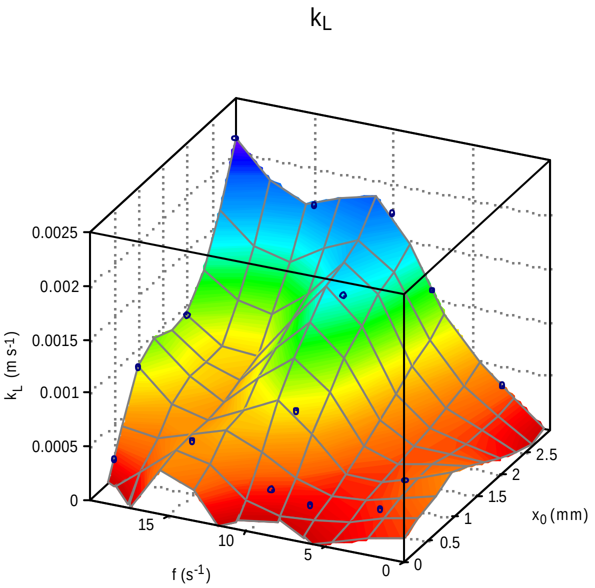


Figure 4: Liquid side mass transfer coefficient (k_L) for the different operating conditions.

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