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Oxygen transfer in pilot-scale contactors: An experimental and computational investigation into the effect of contactor design

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HIGHLIGHTS

- Direct comparison made between four different designs of two-phase contactor.
- Bubble column (with three different sparger designs) and airlift compared.
- Measured OTR between 4.0 and 10.2 $\mathrm{kg\,m^{-3}\,h^{-1}}$ increasing with superficial velocity.
- Contactor design had minimal impact on the OTR for systems examined.

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ABSTRACT

Oxygen transfer is a key parameter in many industrial bioprocesses, however there are few direct comparisons between different reactor designs and their effect on the Oxygen Transfer Rate (OTR), particularly at high superficial velocities (i.e. greater than 0.1 $\mathrm{m\,s^{-1}}$). In this work, we have directly compared four different designs: a bubble column with a sparger having 0.5 mm diameter orifices, a bubble column with a sparger having 3 mm diameter orifices, a bubble column having an asymmetric sparger (with 0.5 mm orifices) and an airlift configuration. For the range of superficial velocities examined (0.11–0.31 $\mathrm{m\,s^{-1}}$), the OTR was between 4.0 and 10.2 $\mathrm{kg\,m^{-3}\,h^{-1}}$ with values increasing with the superficial velocity; however, the OTR was not a strong function of column design. We also examined a Computational Fluid Dynamics (CFD) model of the system; predictions were in satisfactory agreement with experimental data for the symmetrical bubble column while under-predicting the OTR for the bubble column with the asymmetric sparger and the airlift. Results from this work have clear implications in the design and operation of aerobic two-phase contactors as widely used in the bioprocess industries.

1. Introduction

Bubble columns and airlifts are used in the bio-processing industry to perform aerobic fermentations [1,2]. Of the two designs, bubble columns are the simpler, consisting of a tank with a sparger at the base where gas is introduced. Airlifts can be divided into those configurations that have internal structures (e.g. the split cylinder design having an internal baffle, or the draft tube type design) and external loop reactors where the liquid is circulated through an external circuit. Compared with other reactor designs (e.g. stirred tanks) bubble columns and airlifts have the advantage of mechanical simplicity while retaining good heat and mass transfer characteristics [3,4]. Additionally, bubble columns may be advantageous for large-scale processes as they have a lower cost of oxygen delivery [5].

A key parameter in bioprocessing is the Oxygen Transfer Rate (OTR) as this is strongly related to reactor productivity. The OTR is determined by the interfacial area for mass transfer (a), the liquid film mass transfer coefficient (k_L) and the difference between the saturation oxygen concentration (C^*) and the dissolved oxygen concentration (C):

$$OTR = k_L a (C^* - C) \qquad (1)$$

Typical values of C^* are low (of the order 8 $\mathrm{g\,m^{-3}}$ [3]) meaning that it is necessary to have high values for k_L and a to ensure sufficient oxygen transfer. Due to its importance in a wide range of biotechnological applications, oxygen transfer in both bubble columns and airlifts is a topic that has been extensively reviewed in the literature [1,2,4,6,7], while several authors [8–11] have examined the application of CFD to large-scale bio-processes.

The interfacial area is related to the hold-up (α) as well as the bubble diameter (d_b); for spherical bubbles, the relationship is:

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Nomenclature

Symbol	description
a	interfacial area per unit volume [m^2 m^{-3}]
C	dissolved oxygen concentration [kg m^{-3}]
C_{IN}	inlet oxygen concentration [kg m^{-3}]
C_{OUT}	outlet oxygen concentration [kg m^{-3}]
$C_{SO_3^{2-}}$	sulphite concentration [kg m^{-3}]
$C*$	saturation dissolved oxygen concentration [kg m^{-3}]
C^*_{IN}	saturation dissolved oxygen concentration at inlet [kg m^{-3}]
C^*_{OUT}	saturation dissolved oxygen concentration at outlet [kg m^{-3}]
D_L	oxygen diffusivity in the liquid phase [m^2 s^{-1}]
d_b	bubble diameter [m]
f	volume fraction of oxygen in gas phase [−]
H	Henry's law constant [Pa m^3 mol^{-1}]
k_L	liquid film mass transfer coefficient [m s^{-1}]
k_La	volumetric liquid film mass transfer coefficient [s^{-1}]
M_{w,O_2}	molecular weight of oxygen [kg mol^{-1}]
P	pressure [Pa]
Q_{IN}	inlet flow rate [m^3 s^{-1}]
Q_{OUT}	outlet flow rate [m^3 s^{-1}]
t	time [s]
U_G	superficial gas velocity [m s^{-1}]
V_L	liquid volume [m^3]
V_{slip}	bubble slip 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 [−]
ρ_G	gas density [kg m^{-3}]
ρ_L	liquid density [kg m^{-3}]

$$a = \frac{6\alpha}{d_b} \tag{2}$$

The value of the overall hold-up depends on the superficial velocity, the physical properties of the gas and liquid phases, as well as the presence of any surface active compounds in the liquid [1].

The initial bubble diameter (i.e. on leaving the sparger) depends on

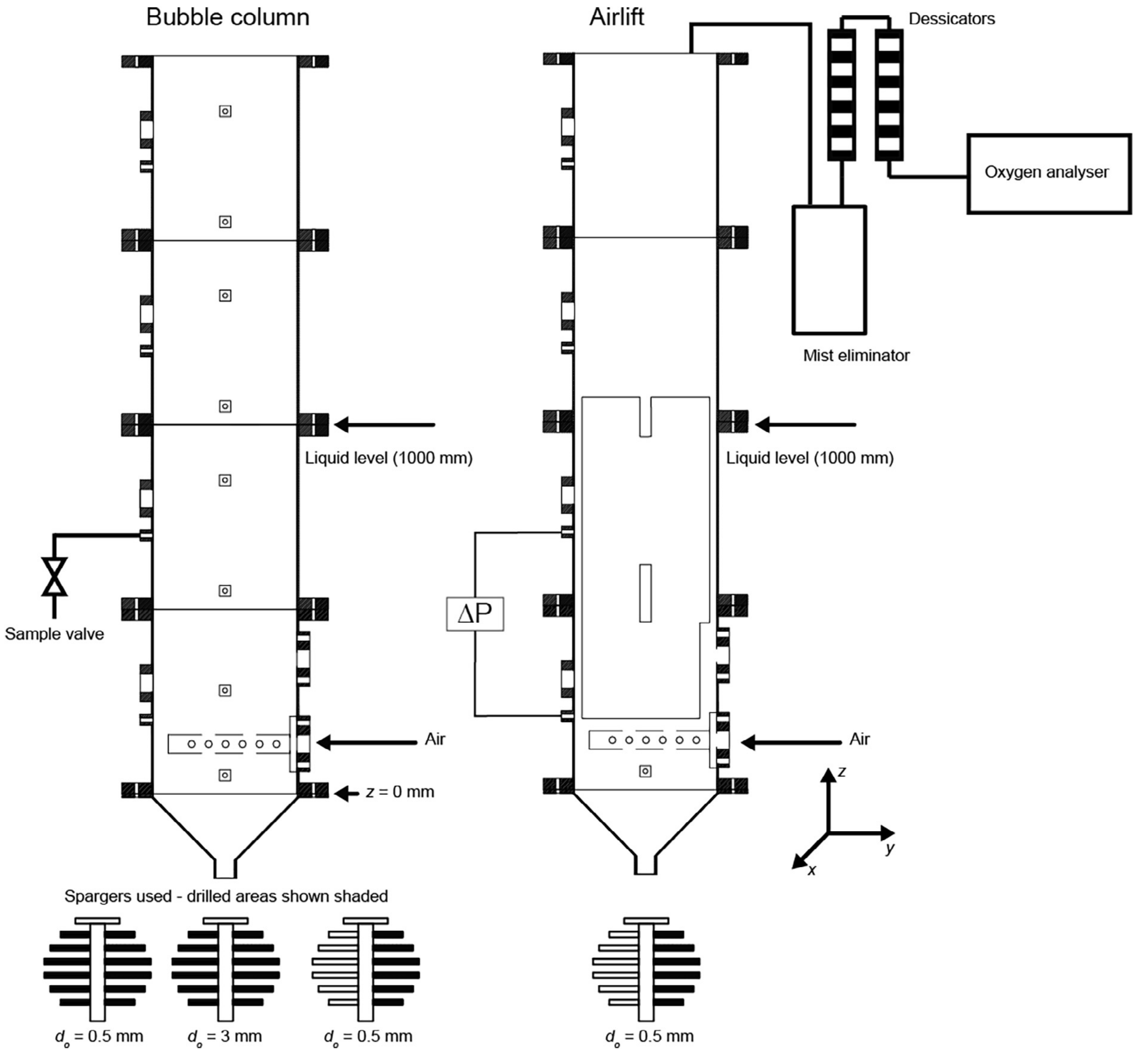

Fig. 1. Schematic diagram of the experimental column systems used, showing both the sparger designs and the layout of the baffle used for the airlift configuration.