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Airlift bioreactor for biological applications with microbubble mediated transport processes

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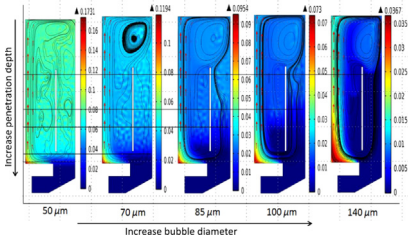
HIGHLIGHTS

- Microbubbles increase the mixing efficiency in airlift bioreactors.
- Dispersal of gas phase throughout the ALR occurs with decreasing the bubble size.
- Phase slip velocity decreases with smaller bubble size as gas rise rate decreases.

GRAPHICAL ABSTRACT

Snapshots of gas concentration at different bubble diameter after steady state



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ABSTRACT

Airlift bioreactors can provide an attractive alternative to stirred tanks, particularly for bioprocesses with gaseous reactants or products. Frequently, however, they are susceptible to being limited by gas–liquid mass transfer and by poor mixing of the liquid phase, particularly when they are operating at high cell densities. In this work we use CFD modelling to show that microbubbles generated by fluidic oscillation can provide an effective, low energy means of achieving high interfacial area for mass transfer and improved liquid circulation for mixing.

The results show that when the diameter of the microbubbles exceeded 200 μm, the "downcomer" region, which is equivalent to about 60% of overall volume of the reactor, is free from gas bubbles. The results also demonstrate that the use of microbubbles not only increases surface area to volume ratio, but also increases mixing efficiency through increasing the liquid velocity circulation around the draft tube. In addition, the depth of downward penetration of the microbubbles into the downcomer increases with decreasing bubbles size due to a greater downward drag force compared to the buoyancy force. The simulated results indicate that the volume of dead zone increases as the height of diffuser location is increased. We therefore hypothesise that poor gas bubble distribution due to the improper location of the diffuser may have a markedly deleterious effect on the performance of the bioreactor used in this work.

1. Introduction

In spite of the accelerated development of bioreactors due to their widespread use, there are still difficulties in maintaining stability and rates of bioprocesses. It is believed that the most important causes of that failure have been poor construction and design, leading to inadequate mixing, which may jeopardize the

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Nomenclature

Cd	viscous drag coefficient (dimensionless)
D	diameter of the bioreactor (m)
d	draught tube diameter (m)
d_b	bubble diameter (m)
g	gravity (m s^{-2})
hd	Height of gas sparger (m)
H	height of airlift bioreactor (m)
M_w	molecular weight of the gas bubble
m_{gl}	mass transfer rate (kg m^{-3} s^{-1})
R	ideal gas constant J (mol^{-1} K^{-1})
Re_b	Reynolds number (dimensionless)
P	pressure (Pa)
u_{slip}	relative velocity between two phases fluid (gas and liquid).
T	temperature of gas (K)
t	time (s)
u_l	velocity of liquid phase (m s^{-1})
u_g	velocity of gas phase (m s^{-1})
$\varnothing_l$	liquid volume fraction (m^3 m^{-3})
$\varnothing_g$	gas volume fraction (m^3 m^{-3})
ρ_l	density of liquid phase (Kg m^{-3})
ρ_g	density of gas phase (Kg m^{-3})
η_l	dynamic viscosity of liquid (Pa s)

Subscript

ALR	airlift bioreactor
CFD	Computational Fluid Dynamics

stability and performance of the process (Karim et al., 2005; Monteith and Stephenson, 1981; Karim et al. 2003).

Mixing in fermentation processes is required to prevent thermal stratification, maintain uniformity of the pH, increase the intimate contact between the feed and microbial culture, and prevent fouling and foaming. The importance of mixing in bioreactor design has encouraged numerous studies for many bioprocesses, including those producing biogas by anaerobic digestion (Stroot et al., 2001; Stafford, 2001; Bello-Mendoza and Sharratt, 1998).

Bello-Mendoza and Sharratt, 1998 concluded that the insufficient mixing can cause a remarkable decrease in both the efficiency of the fermentation process as well as the amount of biogas it produces. More importantly, efficient mixing can speed up reaction rates and therefore reduce the hydraulic retention times required (i.e. reduce the size of the reactor) or increase the throughput of medium (Monteith and Stephenson, 1981).

In bio-hydrogen production processes, for example, liquid mixing plays an important role according to Lay (2000, 2001). This author reported that the hydrogen produced from anaerobic fermentation of microcrystalline cellulose increased with increasing the agitation speed. Therefore, the mixing process in bioreactors is an important and critical factor in determining the efficiency of fermentation process and the nature of design which plays an active role in providing a suitable environment for micro-organisms.

The mechanism by which increased liquid circulation leads to improved reaction rates in three phase fermenter systems is due to it keeping cells and other solids in suspension (i.e. not settling out). This minimises resistance for mass transfer of dissolved non-gaseous species (nutrients, enzymes etc.) from the liquid phase to the surface of cells or solid substrates. It is highly likely that this effect, rather than improved gas transfer between bubble and bulk liquid is the most important explanation for the benefits of improved liquid circulation on fermenter performance. Indeed the work of Lewis and Davidson (1985) showed that there is no difference in gas–liquid mass transfer coefficient when the liquid velocity in an external loop reactor was doubled. i.e., K_L is constant with regard to the liquid velocity and the volumetric mass transfer coefficient K_La is only affected by gas void fraction and bubble size. It is generally recognized that K_L is a wake function of turbulence intensity and the work of Yawalkar et al. (2002) explains the effect of mixing and gas flow on gas–liquid mass transfer very well. However, the laminar regime and simulation used in the present paper is different from the turbulent bubble flows used by Lewis and Davidson (1985).

It should also be stressed that the major advance in micro-bubble injection into air-lift reactors (Zimmerman et al. 2009) is that the cloud of bubbles is injected with very low Reynolds numbers (10–100), just above the threshold for the onset of bubble formation. It was reported in that paper that microbubble clouds were generated with up to 18% less energy dissipation than steady flow, consistent with the observation that the onset pressure difference for bubble formation is ~20% less than steady flow with fluidic oscillation. In this low energy consumption regime, the boundary layer flow around the bubble is laminar and K_L is likely much lower than in conventional turbulent wakes.

Traditional mixing using stirred tanks may give better biogas yields but, when the process energy requirement is weighed against the extra energy obtained, these processes become economically unviable. Therefore, the reduction of the energy required for mixing is one the most challenging targets that is faced in large-scale bioenergy production.

The present study proposes the use of an airlift bioreactor as an alternative to stirred tanks for bioprocess applications. The airlift reactor (ALR) has been used in several industrial applications requiring gas–liquid contacting. ALRs can be classified into two main types: the external airlift loop reactor, in which the circulation takes place in separate conduits; and the internal airlift loop reactor, which is has a tube or a plate to create the conduit (channel) inside a single reactor for circulating the liquid inside the reactor (Chisti, 1989; Mudde and Van Den Akker, 2001) (Fig. 1).

In addition to good mixing, ALRs have long times for gas–liquid contacting and do not cause shear damage to cells. This has seen their widespread use in various biological processes, for example: biomass from yeast, vinegar, bacteria, etc. These advantages can be considerably further improved by equipping the ALRs with a fluidic oscillator for generating micro-bubbles which, compared to traditional stirred tanks, can dramatically increase the interfacial area between gas and liquid phases (Ying et al., 2014, 2013a, 2013b; Zimmerman et al., 2011a, 2011b).

2. Micro-bubble generated by fluid oscillation

Traditionally, enhancement of mass and heat transfer rates in gas–liquid contacting have always been accomplished by increasing the interfacial area between gas and liquid phases. Due to their high maintenance cost and energy requirements, use of traditional methods (e.g. stirred tanks) to achieve certain preset goals is not economically convincing. However, this scenario could be changed if microbubbles systems are used in chemical and biochemical processes. These systems would make dramatic improvements to mass flux by increasing surface-area-to volume ratios of a bubble.