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Study of the hydrodynamics and mass transfer in a rectangular air-lift bioreactor

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HIGHLIGHTS

- The hydrodynamics and oxygen mass transfer in a rectangular airlift bioreactor were studied.
- The ratio between the downcomer and the riser areas (A_d/A_r) was varied between 1:5 and 5:1 to study its effect on the oxygen mass transfer.
- An optimum value of A_d/A_r was determined in terms of the volumetric mass transfer coefficient of oxygen.
- An empirical correlation relating A_d/A_r and the volumetric mass transfer coefficient of oxygen was proposed.

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ABSTRACT

Despite the increasing importance of air-lift reactors, very little published information is available on how the ratio of aerated to non-aerated cross-sectional areas (A_d/A_r) of the reactor, and the aerating system affect the oxygen mass transfer and other performance characteristics. The influence of the ratio of cross-sectional areas of downcomer to riser (A_d/A_r), and the type of gas-distributor on volumetric oxygen mass-transfer coefficient, gas holdup, and liquid circulation velocity were investigated in a 114 L rectangular air-lift reactor with motile baffle, separating aerated from non-aerated compartments. The results indicated that the oxygen mass transfer characteristics of rectangular air-lift reactor are better at A_d/A_r of 2.0; the gas holdup and liquid circulation time showed maximum values at the same ratio. A new empirical model for the effects of the aeration rate and A_d/A_r ratio was proposed to account for the observed changes of volumetric oxygen mass transfer coefficient. The model took into account the different mixing patterns in the reactor for both cases: $A_d/A_r \leq 1$ and $A_d/A_r > 1$ using a wide range of these ratios.

1. Introduction

Air-lift reactors (ALRs) are widely used in industrial biotechnology and other multiphase processes, due to their improved hydrodynamics and mass transfer characteristics at comparable energy consumption, relative to the traditional stirred-tank vessels and bubble columns (Margaritis and Sheppard, 1981; Joshi et al., 1990; Schugerl, 1990; Chang et al., 1994; Fontana et al., 2009). The most important applications of airlifts are summarized by Chisti (1989). ALRs consist of four distinct compartments: (1) riser, (2) gas separator, (3) downcomer, and (4) base. Gas is injected at the base of the riser (aerated zone), where it flows mainly upwards, passes through the top of reactor, disengaging a part of the gas and entering the downcomer (non-aerated zone) where it descends to the base. The driving force for the liquid recirculation is the hydrostatic pressure difference between the riser and the downcomer; whereas, the resisting force is the frictional pressure drop around the flow circuit. Various configurations of ALRs have been reported (Trilleros et al., 2005; Kilonzo et al., 2007; Lu et al., 2000; Pi et al., 2014); however, one of the simplest and most common design is the split vessel. In split vessel ARLs, a partition board is placed within the reactor in order to create the compartments necessary for circulation (Merchuk, 1990). The advantages that ALRs offer include: simple construction, absence of moving parts, well defined fluid flow patterns, good mass transfer properties, high thermal stability, and low energy consumption, which together determine low construction and operation costs (Couvert et al., 2004; Majeed and Békásy-Molnár, 1995; Winterbottom, 2007). Crucial performance parameters, such as gas–liquid interfacial area, gas hold-up or gas–liquid mass transfer coefficient, depend on the reactor design, the architecture of the gas

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distributor, and on directly controlled parameters, such as the gas and liquid flow rates (Vial et al., 2001).

One of the most important parameters of ALRs for chemical and biochemical applications is the gas–liquid oxygen transfer rate (*OTR*), because the rate of oxygen consumption by microorganisms is usually high, compared to the rate of oxygen transfer from gas to the liquid media (Siegel and Merchuk, 1988; Merchuk et al., 1992; Kilonzo and Margaritis, 2004; Juraščík et al., 2006). That is why any variation in oxygen supply may affect significantly the process performance, thus requiring a fairly good estimation of oxygen mass transfer, especially when reactor design improvement and scale-up are considered (García-Ochoa and Gómez Castro, 1998; García-Ochoa et al., 2000, 2010; Badino et al., 2001; Çalik et al., 2004; Martin et al., 2004; Puthli et al., 2005; Kocabaş et al., 2006; Liu et al., 2006). The rate of oxygen concentration change across the gas–liquid interface per unit liquid is related to the volumetric mass-transfer coefficient (k_La):

$$\frac{dC}{dt} = k_La\cdot(C^* - C) - q_{O_2}\cdot C_X = OTR - OUR \tag{1}$$

where dC/dt is oxygen accumulation rate in the liquid phase, *OTR* represents the oxygen transfer rate from the gas to the liquid, and *OUR* is the oxygen uptake rate in the presence of microorganisms; the driving force for the oxygen mass transfer is the difference between C^* and C, which are the equilibrium and the available oxygen concentration in the solution; and, *OUR* can be expressed as the product between the specific oxygen uptake rate of the microorganisms (q_{O_2})and the biomass concentration (C_X). Several methods, based on chemical, physical or biological principles, have been developed for experimental determination of the oxygen transfer rate in bioreactors: (1) sodium sulfite oxidation method, (2) dynamic methods, (3) gas phase analysis, (Garcia-Ochoa and Gomez Castro, 2009; Moutafchieva et al., 2013).

Despite numerous studies on hydrodynamic and mass transfer characteristics in different types of ALRs (Chisti, 1989; Chisti et al., 1988; Popovic and Robinson, 1989), very little published information is available on how these parameters are affected with the stepwise change of the downcomer to riser cross-sectional area ratio (A_d/A_r). For example, some authors report increasing of the overall gas holdup (ε) and k_La with decreasing A_d/A_r (Koide et al., 1983); whereas, others detect the opposite effect (Al-Azzi and Al-Kuffe, 2010; Sanjari et al., 2014). In all previous studies, experiments were performed in concentric draft tube air-lift reactors with limited number of A_d/A_r ratios (maximum of 5), originating from the innate hinders, associated with the cylindrical cross-sectional area. Due to the wide variability of reported ratios in the literature we chose to compare our results to more recent studies (Choi et al., 1996; Couvert et al., 2004; Gourich et al., 2005; Huang and Lu, 1997) at $A_d/A_r = 1$.

The concentric draft tube design differs significantly from the rectangular split design, which can be shown by comparing the ratios between the widths of the downcomer and riser for both configurations. Assuming that the annular section of the concentric tubes design is a riser, than the "width" of the concentric tube riser is the distance between the external wall and the draft tube, while the "width" of the downcomer is the diameter of the draft tube. For the rectangular airlift, the widths of the riser and the downcomer are equal to the distance between the partition board and the opposing external walls of the reactor. For example, for an $A_d/A_r = 5$, in the rectangular unit the ratio between the widths of the downcomer and riser is 5:1. However, for the same A_d/A_r ratio, the downcomer/riser widths ratio for a concentric tube airlift is 5:0.24. In general, ALRs with rectangular cross-section are more versatile, and give better performance characteristics for a given oxygen transfer rate (Merchuk and Gluz, 2002). Moreover big rectangular vessels are usually easier to build than cylindrical reactors (Couvert et al., 1999; Petersen and Margaritis, 2001).

In light of the above discussion, the aim of this work is to examine the changes of the volumetric liquid-phase mass-transfer coefficient of oxygen in a rectangular, split-vessel *ALR* with gradually changing of the downcomer to riser cross-sectional area ratio at different aeration flow rates using the dynamic ("gas on, gas off") method. The effects of different gas distributors on the volumetric mass transfer coefficient and hydrodynamic characteristics, such as the gas holdup and the liquid circulation time, were determined.

2. Materials and methods

2.1. Reactor

The reactor consisted of a poly(methyl methacrylate) (acrylic glass) column (17 mm wall thickness) with a rectangular cross-section, flat bottom and a total volume of 0.202 m^3 (0.300 × 0.273 × 2.470 m) (Fig. 1). Two flanges (0.14 m diameter) were situated on the two opposite walls at 0.110 m from the bottom to their central axes for

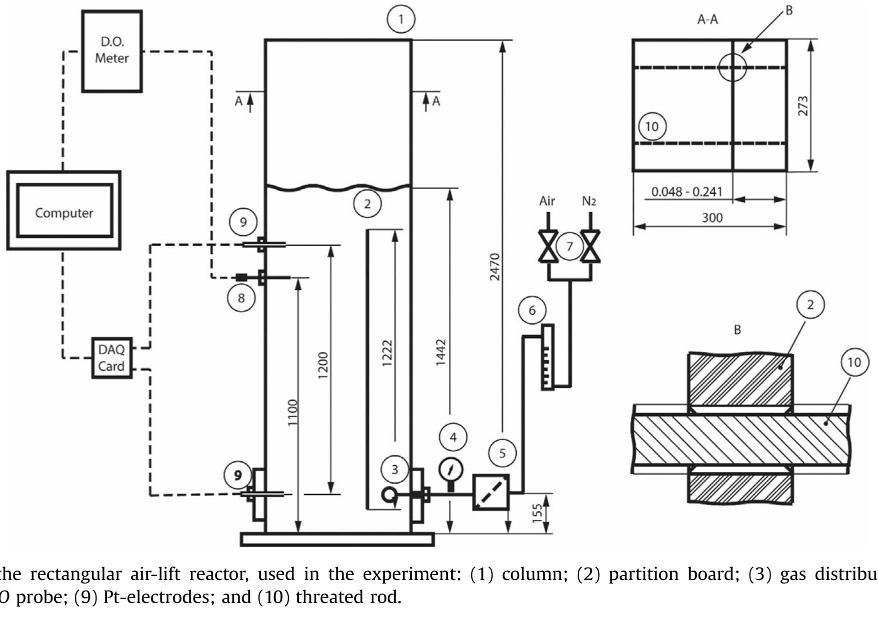

Fig. 1. Schematic diagram of the rectangular air-lift reactor, used in the experiment: (1) column; (2) partition board; (3) gas distributor; (4) manometer; (5) filter; (6) rotameter; (7) valves; (8) *DO* probe; (9) Pt-electrodes; and (10) threated rod.