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Hydrodynamics and mass transfer coefficient in three-phase air-lift reactors containing activated sludge

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Abstract

This study was to investigate the impacts of operating conditions and liquid properties on the hydrodynamics and volumetric mass transfer coefficient in activated sludge air-lift reactors. Experiments were conducted in internal and external air-lift reactors. The activated sludge liquid displayed a non-Newtonian rheological behavior. With an increase in the superficial gas velocity, the liquid circulation velocity, gas holdup and mass transfer coefficient increased, and the gas residence time decreased. The liquid circulation velocity, gas holdup and the mass transfer coefficient decreased as the sludge loading increased. The flow regime in the activated sludge air-lift reactors had significant effect on the liquid circulation velocity and the gas holdup, but appeared to have little impact on the mass transfer coefficient. The experimental results in this study were best described by the empirical models, in which the reactor geometry, superficial gas velocity and/or power consumption unit, and solid and fluid properties were employed.

Keywords: Activated sludge; Air-lift reactor; Gas holdup; Apparent viscosity; Liquid circulation velocity; Superficial gas velocity; Mass transfer coefficient

1. Introduction

Air-lift reactor (ALR) has been recognized as an economically and technically significant alternative with simple design and construction, high efficiency of homogenization and intense mixing for heat and mass transfer, low power consumption, and shear stresses [1–4]. The ALRs are particularly suitable for a process which demands rapid and uniform distribution of the reaction components, and for multiphase (gas–liquid–solids) systems in which high mass and heat transfer are necessary [5,6], and have been widely applied in biochemical industry, fermentation and biological wastewater treatment processes [2,7,8]. Compared with conventional activated sludge processes, oxygen transfer rates in air-lift devices are up to 10-fold greater [9]. In addition to supplying oxygen, sparged air provides a motive force for circulating wastewater and suspending flocs [10,11]. The rates of organic waste degradation are linked to several factors, including fast oxygen transfer, long gas–liquid contact times and intense turbulence in the circulating fluid [9–13].

Although many geometrical differences exist in the ALRs, all are characterized by two clearly differentiated sections: the riser and downcomer, which are interconnected near the top and bottom of the reactor. There are two broad categories of ALRs: the internal air-lift reactor (IALR) and external air-lift reactor (EALR) according to the reactor configuration and the liquid circulation. The circulation is induced by the net density differences between the riser and downcomer resulting from injecting and/or sparging air in the riser [7–9]. The IALR consists of a concentric tube or split vessel, in which a part of the gas is entrained into the downcomer. Typically, EALR consists of a riser and a downcomer column which are connected by side arms.

The major factors which affect the performance of ALRs are (1) the gas characteristics (superficial gas velocity, U_G, gas bubble size); (2) physical properties of the liquid and solids (density, concentration, viscosity); (3) operation variables (gas flow

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rate, R_G, dispersion height, h_D, volume of the gas–liquid separator, V_{GLS}, working volume of the liquid, V_L); (4) geometrical modifications (riser to downcomer cross-sectional area ratio, A_r/A_d, gas distributor–sparger) [1,2,14]. Hydrodynamics such as the gas holdup (ε), flow regimes, liquid circulation velocity (U_L), and volumetric mass transfer coefficient (k_La) are important parameters used in designing, operating and assessing the ALRs. Among these parameters, the ε and the k_La have been recognized as the most important parameters and have been the subject of much research interest. The ε can be an indicator for the mean residence time of the gas phase. It also affects the liquid circulation velocity and the mixing behavior [15]. The k_La is based on the concept that the liquid is the controlling resistance to mass transfer for comparing and evaluating different design intended for gas–liquid mass transfer applications [16]. A general form of a mathematical model which associates with the ε, k_La and U_L to the factors mentioned above may be given by Eq. (1) [1]:

$$y = \delta\left(\frac{\rho_L U_G h_D}{\mu_{ap}}\right)^{\gamma}\left(\frac{1}{1+(A_r/A_d)}\right)^{\psi}\left(\frac{V_{GLS}}{V_L}\right)^{\theta} \quad (1)$$

where y represents either ε and k_La or U_L, and δ, γ, ψ and θ are constant parameters.

Although the ALRs have been studied extensively, most previous work was limited to use two-phase Newtonian gas–liquid systems. Carboxymethyl cellulose aqueous solutions were employed as a representative liquid phase in many literatures. Only a few of studies have considered a specific case employing a three-phase fluid. Most of them focused on the hydrodynamics and mass transfer of gas–liquid–solids phase in reactor using particles including activated carbon particles [17], plastic beads [18], Raney nickel particles [19], calcium–alginate beads [20] and polystyrene cylinders [21]. Three-phase fermentation ALR systems have recently been drawn attention [4,6,7,11,22]. The superficial gas velocity and power input unit (P_G/V_L) were studied in most literatures as functions employed in the mathematical models [9,15,23]. The solid properties and fluid characteristics, such as rheology, have largely been overlooked while studying the three-phase ALRs [11,15,18,20]. Like fermentation broths containing mycelial cells, activated sludge fluid exhibits a pseudoplastic non-Newtonian rheological behavior [4,24]. To date, there is little published information available on the hydrodynamics and the mass transfer coefficient in activated sludge process, which represents a typical gas–liquid–solid phase biological system. It is, therefore, important to understand how the presence of activated sludge particles affects hydrodynamics and oxygen transfer in the three-phase ALRs. This is the aim of this study.

This paper presents the hydrodynamics and mass transfer in laboratory scale activated sludge air-lift reactors. A bench scale internal air-lift reactor (IALR) and external air-lift reactor (EALR) were employed in this study. The three most important parameters, namely liquid circulation velocity, gas holdup and mass transfer coefficient were determined experimentally. The impacts of superficial gas velocity and sludge loading on these parameters were investigated. The experimental results were compared with data proposed by empirical models reported in the literature.

2. Experimental

2.1. Activated sludge

Activated sludges samples from the Wacol Sewage Treatment Plant, Brisbane, Australia were used for these experiments. The initial solid concentration of each sludge sample was adjusted by either diluting the sludge using the same sludge liquor or by thickening the sludge by gravity settling to achieve a number of samples with different solids loading concentrations. The effluent and the activated sludge were collected from the last sedimentation tank and were maintained at 4 °C before the experiments.

2.2. Air-lift reactor

Both IALR and EALR were geometrically different and dimensionally similar, as shown in Fig. 1. The reactors were constructed by a 200 mm ID and 800 mm high transparent Perspex column (wall thickness 4 mm). The reactor had a gas-free liquid height of 600 mm with a nominal working volume of 19 l for the IALR and 22 l for the EALR. The column (downcomer) was made by a conical bottom, which keeps the sludge flocs in suspension and minimizes the occurrence of dead spaces where sludge flocs may become trapped. The sparger was a 120 mm ID and 10 mm thick sinter glass plate with pore size of 50 μm and was located centrally in the conical bottom. For the IALR, a 100 mm ID and 400 mm high draft tube (riser), which made the ratio of the cross-sectional area of the riser to the downcomer (A_r/A_d) equal to 0.25, was located axially in the center of the column and fixed at 50 mm distance from the sparger. The EALR consisted of the riser and 100 mm ID and 400 mm high downcomer which was connected by two arm tubes jointed on the top and bottom of the riser. The distance between the riser and downcomer axes was 100 mm.

2.3. Experimental set-up

All experiments were performed as a batch-wise process at ambient conditions. The air was sparged into the riser at the bottom of the reactor by means of the sintered glass sparger. Each experiment was conducted in 15–45 min. To limit the microbial activities, the temperature of the sludge liquid in the reactor was controlled approximately 4 °C by an ice jacket around the reactor during the period of experiment. The effluent and the sludge were collected from the last sedimentation tank, the nutrients available in the sludge liquid were very low. Therefore, it can be assumed that the oxygen uptake by the bacterial activity was very low during the experiments, due to the limited nutrients and low temperature. The electronic probes and meters supplied by TPS (USA) for monitoring pH, temperature and dissolved oxygen were installed on line (Fig. 1). The input air flow rate (R_G) was measured by a calibrated gas rotameter. A pressure regulator was used to maintain the inlet air pressure at 1.0×10^5 Pa.