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Gas–liquid mass transfer in a circulating jet-loop nitrifying MBR

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Abstract

Based on airlift configuration, a novel circulating jet-loop submerged membrane bioreactor (JLMBR) adapted to ammonium partial oxidation has been developed. Membrane technology and combined air and water forced circulation are adopted to obtain a high biomass retention time and to achieve a separate control of mixing and aeration. This study is intended to determine how gas–liquid mass transfer is affected by operating conditions. In a first approximation, liquid was assumed to be perfectly mixed. A classical non-steady state clean water test, known as the "gas out–gas in" method, was used to determine the gas–liquid mass transfer coefficient $k_L a$. Air and recirculated liquid superficial velocities were gradually increased from 0.013 to 0.019 $\mathrm{m\,s^{-1}}$ and 0.0056 to 0.011 $\mathrm{m\,s^{-1}}$, respectively. Subsequently, the gas–liquid mass transfer coefficient $k_L a$ varied from 0.01 to 0.02 $\mathrm{s^{-1}}$. It appears to be influenced by the combined action of air and recirculated liquid flowrates in the range 0.72–1.03 $\mathrm{N\,m^3\,h^{-1}}$ and 0.30–0.58 $\mathrm{m^3\,h^{-1}}$, respectively, for air and liquid. Correlations are proposed to describe this double influence. Experiments were performed on tap water and a culture medium used for the autotrophic growth of nitrifying bacteria, respectively. Oxygen transfer appeared to be not significantly affected by the mineral salt (0.48 $\mathrm{g\,l^{-1}}$) encountered in this medium.

Keywords: Aeration; Bioreactors; Bootstrap; Mass transfer; Membrane; Recirculation reactor

1. Introduction

Recent researches on biological nitrogen removal in wastewaters have been mainly dedicated either to improving process performances (e.g. fixed biomass, membrane reactor, etc.) or to the identification of new pathways such as nitrite route or Anamox process (see e.g. Garrido et al., 1997; Strous et al., 1997; Jetten et al., 1999). This paper presents the first stages of development of a novel membrane bioreactor (MBR) adapted to the partial oxidation of ammonium into nitrite. The main advantages of partial versus complete oxidation are energy savings up to 25% in terms of aeration and reduced organic substrate consumption during the following heterotrophic denitrification step. The main problem associated with MBR is the rather large sludge retention time that could jeopardize the stability of the nitrite forming biomass. The limitation of dissolved oxygen (DO) concentration has been shown to be the most efficient way to stabilize this flora (Pollice et al., 2002). However, a low aeration rate—either under alternated flowrate or under continuous low flowrate—can cause sludge settling in bubble column or airlift configurations. In this paper, we propose to combine air and water flowrates in a novel type of jet-loop membrane bioreactor (JLMBR) ensuring good mixing whatever the air flowrate level. The dependency of the overall mass transfer coefficient $k_L a$ versus air and water flowrates was investigated in order to develop a control strategy of such a three-phase nitrifying bioreactor, which has to be operated at low dissolved oxygen level.

2. Literature survey

Several types of new gas–liquid reactors configurations have been developed in order to improve the quality of contact between the two phases and hence to improve the

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volumetric oxygen mass transfer coefficient k_La. The novel circulating bed (CB) reactor (Lazarova et al., 1997), the down flow jet-loop (DJB) reactor (Masoud et al., 2001) and the forced recirculation tank (FRT) reactor (Nordkvist et al., 2003), for example, correspond well to this new trend in the design of aeration systems in bioreactors. Their configurations are inspired of that of airlift reactors where a downcomer and a riser compartment are interconnected and fluids flow together. The contact of liquid and gas offers to these technologies certain specific properties such as high mass transfer performance, good dispersing and relatively low power requirements. In other words, the increase of gas residence time into liquid phase favors high mass transfer, which makes such technologies suitable for conducting aerobic reaction (e.g. ammonium oxidation). As oxygen transfer is the most important hydrodynamic parameter that influences metabolic activity, the efficiency of such reactors will be defined by their capacity to make dissolved oxygen available to microorganisms. Improved hydrodynamics and mass transfer of the circulating bed reactor guarantee high nitrification rates (Lazarova et al., 1997). In practice, the mass transfer kinetics is quantified by the volumetric oxygen mass transfer coefficient k_La.

For all types of airlift reactors, k_La increases with gas velocity (Lazarova et al., 1997; Masoud et al., 2001).

Several correlations have been reported in the literature to link the volumetric oxygen mass transfer coefficient to the gas flowrate. Usually, a power function law of gas superficial velocity is used:

$$k_La = bU_g^{\beta}. \tag{1}$$

For circulating reactors, Bello et al. (1985) observed that the downcomer liquid flow is free of gas so that transfer occurs mainly in the riser compartment. They proposed accordingly to use a correlation including the ratio between the downcomer and riser area, A_d and A_r:

$$k_La = 0.76U_g^{0.8}\left(1 + \frac{A_d}{A_r}\right)^{-2}. \tag{2}$$

Popovic and Robinson (1984) proposed the following expression to take the liquid apparent viscosity into account:

$$k_La = 1.19 \times 10^{-4}U_g^{0.525}\left(1 + \frac{A_d}{A_r}\right)^{-0.853}\mu_{\text{app}}^{-0.89}. \tag{3}$$

Although Eq. (1) is confirmed by both Eqs. (2) and (3), it is interesting to note that the exponential constant β ranged between 0.5 and 0.8, depending on authors and experimental conditions.

Nordkvist et al. (2003) observed that in aerated reactors, the dispersion of gas also contributes to the liquid mixing process, which can also have an effect on k_La values. Onken and Weiland (1983) reported that the characteristic k_La values measured in reactors with internal recirculation (0.003–$0.15\,\text{s}^{-1}$) are up to 2.5-fold higher than in airlifts with external recirculation. Nordkvist et al. (2003) studied the effect of liquid mixing on k_La in a forced recirculation tank reactor, by recirculating liquid through either an internal or an external loop. The authors proposed a correlation based on power law functions of the liquid and gas superficial velocities.

$$k_La = 345U_g^{0.764}U_l^{0.700}. \tag{4}$$

Velan and Ramanujam (1992), who worked with Newtonian and non-Newtonian fluids in a down flow jet-loop reactor, confirmed that the volumetric mass transfer coefficient increases with gas and liquid flow rates.

3. Materials and methods

3.1. Experimental setup

The MBR used in this study is presented in Fig. 1. It consists of a 60 l ($1.5\,\text{m} \times 0.5\,\text{m} \times 0.08\,\text{m}$) rectangular circulating jet-loop submerged membrane bioreactor (JLMBR) inspired by an airlift design. It mainly differs from an airlift by a forced external liquid recirculation allowing liquid circulation time (and thus mixing) to be controlled independently from the bubbled gas flowrate. The reactor consists of two equal volume interconnected compartments: the downcomer and the riser. The cross-section area of each these two compartments equals $0.04\,\text{m}^2$. Two perforated tubes (46 holes per tube, hole diameter $10^{-3}\,\text{m}$) are situated at 50 and 100 mm from the bottom of the riser. The upper tube allows gas sparging while the lower one allows liquid recirculation. The separation wall has a total height of 1.42 m. It is situated 0.08 m from the bottom of the reactor. An opening in its upper part ($\pm 64\,\text{cm}^2$) facilitates liquid circulation from the riser to the downcomer, avoiding gas entrainment in the external recirculation loop. A submerged membrane (Sterapore-L, Mitsubishi; $S = 1.5\,\text{m}^2$) is located in the riser at the bottom of which air (0.72–$1.03\,\text{N}\,\text{m}^3\,\text{h}^{-1}$) and recirculated water (0.30–$0.58\,\text{m}^3\,\text{h}^{-1}$) are supplied. Air and recirculated water flowrates are controlled by means of two flowmeters: Brooks Instruments, R6-15B and Krohne, 164010, respectively.

The dissolved oxygen (DO) level is monitored by a potentiometric oxygen probe (Oxypol, SON-10-17) plunged into the reactor. A data acquisition software (Labview 5.0) installed on a PC allows monitoring and control of the experimental setup.

3.2. Measurement methods

3.2.1. Determination of the oxygen probe time constant

The oxygen probe initially kept in an oxygen-saturated medium was transferred immediately into an oxygen-free system obtained by adding sodium sulfite in the presence of Co^{2+} ions. In that case, the dynamic response of the