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Distribution and mass transfer of dissolved oxygen in a multi-habitat membrane bioreactor

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HIGHLIGHTS

- Detailed distribution of DO in a multi-habitat membrane bioreactor was revealed.
- Growth of biomass was an important factor influencing the distribution of oxygen.
- Adjusting the viscosity was a feasible method to improve the mass transfer of DO.

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ABSTRACT

This work investigated the DO distribution and the factors influencing the mass transfer of DO in a multi-habitat membrane bioreactor. Through the continuous measurements of an *on-line* automatic system, the timely DO values at different zones in the bioreactor were obtained, which gave a detailed description to the distribution of oxygen within the bioreactor. The results indicated that the growth of biomass had an important influence on the distribution of oxygen. As the extension of operational time, the volumetric oxygen mass transfer coefficient (k_La) was generally decreased. With the difference in DO values, a complex environment combining anoxic and oxic state was produced within a single bioreactor, which provided a fundamental guarantee for the total removal of TN. Aeration rate, the concentration and apparent viscosity of MLSS have different influences on k_La, but adjusting the viscosity is a feasible method to improve the mass transfer of oxygen in the bioreactor.

1. Introduction

In a biological process to treat municipal or industrial wastewater, dissolved oxygen (DO) is an essential factor, whose value totally determines the state of an aqueous environment and the composition of a microbial community. In an artificial bio-process, the concentration of DO is generally adjusted to various values for achieving an oxic (O) or an anaerobic (A) status. Only with the alternative aerobic–anaerobic condition in a bio-process, it could be successfully realized the purpose of degrading complex organic pollutants and converting nutrients, including nitrogen (N) (Hocaoglu et al., 2011) and phosphorus (P). Such a strategy was extensively used in engineering fields and has created series practical processes such as A/O and A^2/O techniques, which have so far played very important roles in modern environmental engineering.

For optimizing the performance of a traditional bio-process, combining membrane modules with a conventional activated sludge (CAS) process has created a new technique, which was called a membrane bioreactor and has attracted lots of interests in scientific researches and industrial applications (Le-Clech, 2010; Mutamim et al., 2013). With the total retention by a membrane module, activated sludge can be retained in a bioreactor for a long time, and enables the separation of sludge retention time (SRT) from hydraulic retention time (HRT). This is a dominant merit, which not only makes it possible to operate a bioreactor at very high biomasses, but also markedly reduces the investments for constructing a secondary sedimentation tank. A crucial obstacle that limits the large-scale applications of MBRs so far is the fouling of membrane modules, which has still exhibited a great challenge in academic researches (Drews, 2010; Meng et al., 2009). For fully utilizing the advantages of an MBR and avoiding its disadvantages, numerous attempts have been tried in recent decade (Kraume and Drews, 2010), one of the focuses was to arrange a sequential or an alternating anoxic–oxic (A/O) bioreactor to compose a combined A/O system, in which nutrients and some complex organic pollutants could be effectively decomposed and then removed

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from the effluents (Fu et al., 2009; Hu et al., 2013; Li et al., 2010). In a combined A/O system, the adjustment of DO was also a very important factor (Holakoo et al., 2007), which totally determined the success of removing nutrients and organic pollutants. In the previous investigation (Tang et al., 2014), an interesting phenomenon was also found, namely, the DO value was strongly affected by the growth of biomass in the used bioreactor, and the consumption of DO in turn affected the biodiversity and succession of the microbial community in the bioreactor. Based on this new finding, a novel bioreactor, named as a multi-habitat membrane bioreactor (MHMBR), was designed and operated.

In each bioreactor, mixed liquid suspended sludge (MLSS) is an essential factor and a complex mixture, which includes dead or live microorganisms, colloids, organic polymer and dissolved nutrients (Germain et al., 2007). Live microorganisms are generally the aggregates of various microbial species; they compose a microbial community with clear functions, and play an important role in transferring the mass and energy within the whole system, which also determine the performance of a bioreactor to remove pollutants. Undoubtedly, sufficient supply of oxygen is an essential factor to any bioreactor (Garcia-Ochoa et al., 2010; Krampe and Krauth, 2003). However, variations of the DO value in a bioreactor can also realize the novel functions of removing N and P, which suggests the possibility to construct multi-environments to improve the biodiversity in a microbial ecosystem. While, some recent reports (Andersen et al., 2013; Colares and Melo, 2013; Duan et al., 2013) have verified the importance of multi-environments in supporting diversified microbial communities. According to the above analyses, exploring the distribution and mass transfer of DO is especially necessary in designing and operating an MHMBR. Therefore, the present investigation mainly focused on the following two aspects: (1) elucidating the distribution of DO as the growth of biomass within an MHMBR; (2) determining the factors influencing the volumetric oxygen mass transfer coefficient.

2. Methods

2.1. Experimental process and operational conditions

Details of the experimental process and the bioreactor configuration were nearly the same as those described in the previous report (Tang et al., 2014). For accurately reflecting the DO distribution within the MHMBR, one more DO probe was installed between the oxic (O) and the anoxic-anaerobic (A) zone, whose value reflected the DO concentration in the transition (T) zone. All the three DO probes were connected to a computer to record the DO value of the corresponding zones simultaneously. The schematic diagram is shown in Fig. 1.

The inoculated sludge was the activated sludge obtained from the aeration tank of a local WWTP (Lijiao municipal wastewater treatment plant, located in Haizhu district, Guangzhou, China), whose inoculation concentration was controlled at about 3200 mg/L MLSS. The influent was the synthetic wastewater obtained by mixing tap water with concentrated nutrient solutions. The concentrated nutrient solution, with the ratio of COD:N:P at 100:5:1, was prepared by dissolving chemically pure glucose (206.80–537.78 mg/L), NH_4Cl (38.42–99.86 mg/L), KH_2PO_4 (8.82–22.94 mg/L) and other nutritive salts ($NaHCO_3$: 160 mg/L, $MgSO_4$: 40 mg/L, $MgSO_4$:12 mg/L, $CaCl_2$: 8 mg/L, $FeSO_4$: 0.6 mg/L) into the tap water. Water quality conditions in the influent in every operational stage are shown in Table 1.

Controlling and pumping of the influent and the effluent were totally the same as the mentioned previous report. For comparison, the operational parameters were adjusted to adapt the present water qualities and are shown in Table 2.

2.2. Determination of oxygen transfer coefficient

In a bioreactor, DO is a pivotal factor to sustain the growth of biomass, thus, the reasonable distribution of DO determines the successful operation of a bioreactor to a large extent. The index of quantitatively describing the mass transfer of DO is mainly the volumetric mass transfer coefficient (k_La), whose measurement and calculation methods have been extensively discussed, and a standard method to evaluate the transferring rate of DO has been proposed (Garcia-Ochoa and Gomez, 2009).

In the presented experiments, an MHMBR was built and operated for a long time (125 days), in which a stable internal circulation was formed by the comprehensive action of the stirring paddle and the aeration. As the growth of biomass, the DO gradually exhibited a concentration gradient within the bioreactor, and formed "A", "O" and "T" zones. Mass transfer of oxygen in a process or a bioreactor is of primary importance. However, because of the heterogeneous composition of MLSS, the mass transfer of oxygen from the gas to the liquid, and then to the sludge particles (the biomass) generally includes several steps, which makes it difficult to accurately measure the mass transfer rate of oxygen of each step. For quantitatively describing the mass transfer of oxygen in a process or a bioreactor involving solid flocs and non-Newtonian fluids, the following differential equation was usually adopted in theoretic analyses or experimental measurements (Zerari et al., 2013):

$$\frac{dC_L}{dt} = k_La_{(T)} \cdot (C_S^* - C_L) \tag{1}$$

where $k_La_{(T)}$ is the overall volumetric mass transfer coefficient at T temperature from the gas phase to the liquid phase, $\frac{dC_L}{dt}$ is the variation rate of oxygen in the liquid phase. C_S^* is the saturated concentration of oxygen at that temperature, and C_L is the instantaneous concentration of oxygen in the liquid phase at t time. Integrating Eq. (1), the following equation can be obtained (Rodriguez et al., 2011):

$$k_La_{(T)} = \ln\frac{C_S^* - C_0}{C_S^* - C_L} \tag{2}$$

where C_0 is the oxygen concentration in the liquid phase at $t = 0$. On the basis of Eq. (2) and the measured concentration of oxygen at different points, the value of $k_La_{(T)}$ can be determined. In the presented experiments, the DO values at different zones were measured automatically and simultaneously by three independent probes, which made it possible to determine the values of k_La very conveniently. The experimental period lasted for 125 days, which covered spring and summer days and led to the temperature in the bioreactor fluctuating every day. For the convenience of comparison, k_La at diffident temperature was all transferred into the volumetric mass transfer coefficient at the same temperature by the following empirical equation (Stenstrom and Gilbert, 1981).

$$k_La = k_La_{(T)} \cdot 1.024^{(20-T)} \tag{3}$$

where k_La is the oxygen mass transfer coefficient at 20 °C, and $k_La_{(T)}$ is the oxygen mass transfer coefficient at temperature T °C.

With the above equations, a complex mass transfer process could be described by a relatively simple way. In here, k_La is used to describe the intrinsic factors of the involving system, and the mass transfer rate of oxygen has a linear relation with the values of k_La under the same concentration gradient of oxygen. Obviously, larger value of k_La implies a faster mass transfer rate of oxygen, thus, the status of the mass transfer of oxygen in the bioreactor could be quantitatively expressed.