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Aeration optimization through operation at low dissolved oxygen concentrations: Evaluation of oxygen mass transfer dynamics in different activated sludge systems

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A B S T R A C T

In wastewater treatment plants (WWTPs) using the activated sludge process, two methods are widely used to improve aeration efficiency — use of high-efficiency aeration devices and optimizing the aeration control strategy. Aeration efficiency is closely linked to sludge characteristics (such as concentrations of mixed liquor suspended solids (MLSS) and microbial communities) and operating conditions (such as air flow rate and operational dissolved oxygen (DO) concentrations). Moreover, operational DO is closely linked to effluent quality. This study, which is in reference to WWTP discharge class A Chinese standard effluent criteria, determined the growth kinetics parameters of nitrifiers at different DO levels in small-scale tests. Results showed that the activated sludge system could meet effluent criteria when DO was as low as 0.3 mg/L, and that nitrifier communities cultivated under low DO conditions had higher oxygen affinity than those cultivated under high DO conditions, as indicated by the oxygen half-saturation constant and nitrification ability. Based on nitrifier growth kinetics and on the oxygen mass transfer dynamic model (determined using different air flow rate (Q'_{air}) and mixed liquor volatile suspended solids (MLVSS) values), theoretical analysis indicated limited potential for energy saving by improving aeration diffuser performance when the activated sludge system had low oxygen consumption; however, operating at low DO and low MLVSS could significantly reduce energy consumption. Finally, a control strategy coupling sludge retention time and MLVSS to minimize the DO level was discussed, which is critical to appropriate setting of the oxygen point and to the operation of low DO treatment technology.

Introduction

Oxygen transfer from air to water is critical during the aerobic biological wastewater treatment process to ensure there is enough oxygen for microbial degradation and nutrient removal. Oxygen mass transport is achieved through the aeration system, which usually accounts for 45%–75% of total energy consumption in typical activated sludge process wastewater treatment plants (WWTPs) (Rosso et al., 2008). Reducing the energy consumption of aeration systems can therefore lead to significant reductions in total operating costs. In order to meet oxygen demand while ensuring low carbon operation, there needs to be a focus on improving aeration device efficiency and operating performance.

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The main parameters used to evaluate oxygen mass transfer performance are the global oxygen transfer coefficient K_La, oxygen transfer efficiency (OTE) ε, and the standard oxygen transfer rate (SOTR), with these based on the two-film theory proposed by Lewis and Whitman (1924). The theory assumes that the main resistance to oxygen mass transfer occurs on the liquid film between the gas- and liquid-phase interface. Oxygen is a poorly soluble gas, and the oxygen mass transfer rate is therefore determined by the gas–liquid film transfer process. According to other theories, the oxygen transfer rate (OTR) can be enhanced by enlarging the gas–liquid interface area turbulence intensity (Fan et al., 2014). During actual operation of WWTPs, a high K_La value can be obtained in the following two ways: (1) adopting fine bubble diffusers with high performance, and (2) operating with a long sludge retention time (SRT) in order to weaken the negative effects of surfactants on oxygen transfer (Rosso and Stenstrom, 2006). There are actually many factors that affect K_La, and the most effective way to reduce energy consumption may not be simply replacing diffusers to improve the K_La value. As K_La increases, the aeration energy requirements tend to increase linearly (Oprina et al., 2010). Longer SRTs can lead to better removal of surfactants because of the diversity of microorganisms; however, the accompanying higher mixed liquor suspended solids (MLSS) will lead to serious deterioration in K_La with increasing liquid viscosity (Krampe and Krauth, 2003; Germain et al., 2007; Henkel et al., 2009a, Q6 2009b; Fan et al., 2014). It is therefore crucial to comprehensively analyze the relationship between oxygen mass transfer dynamics and biomass properties during the aeration process.

In the case of biological nutrient removal (BNR), growth kinetic parameters are very important for designing aeration processes; these include the half-saturation constant, the decay rate of autotrophs, and the specific oxygen uptake rate (SOUR). If SOUR and nitrifier biomass concentrations are obtained, the oxygen uptake rate (OUR) can be calculated. OUR is closely related to influent quality and microbial respiration. Theoretically, 4.57 g of oxygen is needed to completely oxidize 1 g of NH_4^+-N into nitrate, with 3.43 g-O_2/g-N for first-step nitrification (ammonia oxidation) and 1.14 g-O_2/g-N for second-step nitrification (nitrite oxidation) (Metcalf and Eddy Inc., 2003). As biomass synthesis requires a small amount of ammonia as a nitrogen source, the specific oxygen demand for ammonia oxidation and nitrite oxidation reactions is lower than the aforementioned theoretical values (Rittmann and McCarty, 2001). It would be useful to more accurately determine the ammonia consumption and oxygen uptake of the nitrification process to construct oxygen demand and supply balances that enable better control of the air flow rate.

The oxygen demand and supply balance can be represented by operational dissolved oxygen (DO) concentrations, since these affect the oxygen mass transfer driving force and microbial respiration. A commonly used expression relating SOUR to the DO concentration is the Monod function, used to describe bacterial growth dynamics in wastewater treatment modeling and analysis (Monod, 1942). In the Monod function the growth rate is, with respect to a certain substrate (DO, chemical oxygen demand (COD), or ammonium) limiting for growth, being a monotonically increasing non-linear function that eventually approaches its maximum specific value at high substrate concentrations (Blackburne et al., 2007). Because of its non-linearity, in nitrification processes with low substrate concentrations, a small change in DO or ammonium concentration will have a larger effect on the nitrification rate. Low DO adversely affects the growth rates of ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB), and the kinetics among different nitrifiers are significantly different from each other (Schramm et al., 1999; Kim and Kim, 2006; Dytczak et al., 2008). However, according to the results of Liu and Wang (2013), in activated sludge systems with 10 and 40 day SRTs, complete nitrification was accomplished after long-term operation with DO values of 0.37 mg/L and 0.16 mg/L, respectively. From the above information, it is evident that there is significant energy saving potential when operating in low DO conditions.

Unnecessarily high airflow rates and DO concentrations should be avoided due to the decreased aeration efficiency and oxygen transfer this will cause (Olsson et al., 2005; Thunberg et al., 2009). In this study, diffuser performance was determined in a pilot scale test with different Q'_{air} and MLVSS values, and activated sludge dynamic properties were determined in small-scale tests using low (0.5 mg/L) and high (1 mg/L) DO conditions. Based on the results, we identify optimal DO points for different activated sludge systems, also developing a new control strategy coupling SRT and MLSS through the establishment of an oxygen supply and demand balance. Long-term and short-term aeration control paths are explained, to provide insights into how to set the DO control point to achieve minimum energy consumption while still complying with effluent criteria.

1. Materials and methods

1.1. Description of reactors and operating conditions

The experiment had two parts: tests of oxygen mass transfer dynamics and nitrifier growth kinetics tests.

Fig. 1a shows the reactor used for tests of oxygen mass transfer dynamics; this had a working volume of 10.6 m^3 (high = 7 m, ø = 1.5 m, effective water depth = 6 m). Oxygen mass transfer dynamic parameters (such as K_La values, OTE, and OTR) were determined using the process described in the standard methods for measurement of oxygen transfer in clean water (ASCE, 2000). Ceramic disc fine bubble diffusers (ø = 178 mm, pore size = 100 μm) were used for aeration. The airflow rate was adjusted to a target value with a calibrated rotameter. Anhydrous sodium sulfite was used to reduce DO concentrations to zero in test water. DO was measured with two LDO fluorescent DO electrodes (Tengue Instrument Co., Ltd., Beijing), which were placed in the column at depths of 1 m and 3 m below the water surface, respectively. DO data was stored online using a recorder and computer.

After the clean water test, a process test was performed following standard guidelines for in-process oxygen transfer testing (ASCE, 1997). Seed sludge was taken from the aeration tank of the Gao Beidian WWTP in Beijing; this WWTP uses a typical anaerobic–anoxic–aerobic (A^2O) process to treat municipal wastewater, with good performance through complete nitrification and denitrification. The initial concentration of MLSS was about 3500 mg/L, and different MLSS levels were

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