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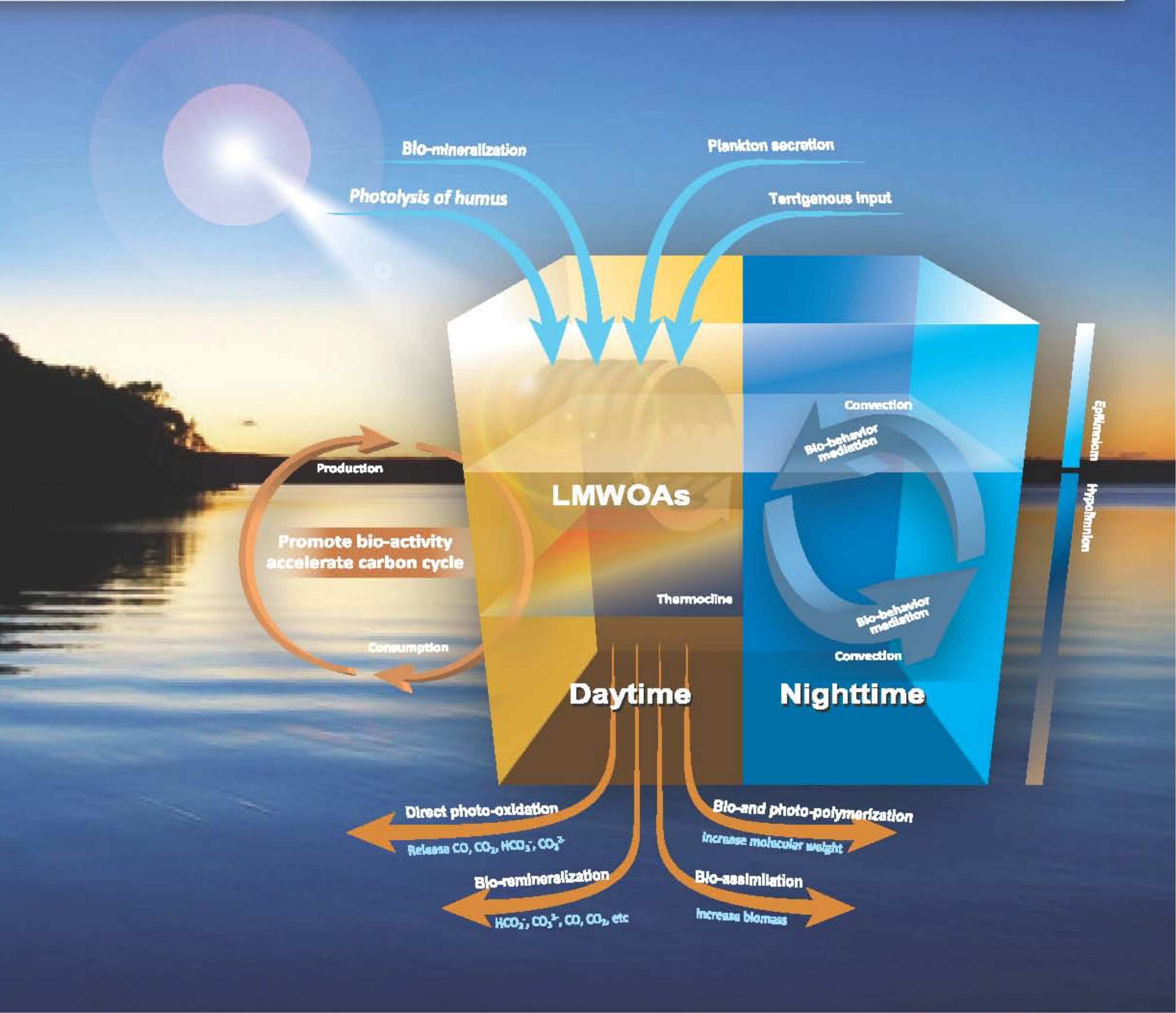

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Evaluation of oxygen transfer parameters of fine-bubble aeration system in plug flow aeration tank of wastewater treatment plant

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Abstract

Knowledge of the oxygen mass transfer of aerators under operational conditions in a full-scale wastewater treatment plant (WWTP) is meaningful for the optimization of WWTP, however, scarce to best of our knowledge. Through analyzing a plug flow aeration tank in the Lucun WWTP, in Wuxi, China, the oxygenation capacity of fine-bubble aerators under process conditions have been measured *in-situ* using the off-gas method and the non-steady-state method. The off-gas method demonstrated that the aerators in different corridors in the aeration tank of WWTP had significantly different oxygen transfer performance; furthermore, the aerators in the same corridor shared almost equal oxygen transfer performance over the course of a day. Results measured by the two methods showed that the oxygen transfer performance of fine-bubble aerators in the aeration tank decreased dramatically compared with that in the clean water. The loss of oxygen transfer coefficient was over 50% under low-aeration conditions (aeration amount < 0.67 Nm^3/hr). However, as the aeration amount reached 0.96 Nm^3/hr, the discrepancy of oxygen transfer between the process condition and clean water was negligible. The analysis also indicated that the non-steady-state and off-gas methods resulted in comparable estimates of oxygen transfer parameters for the aerators under process conditions.

Key words: fine-bubble aerator; off-gas method; non-steady-state method; oxygen transfer parameters

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Introduction

Oxygen transfer is an important part of wastewater treatment and accounts for as much as or even higher than 60% of energy consumption in the activated sludge process in full-scale wastewater treatment plants (WWTPs) (Jiang et al., 2012; Krause et al., 2003); therefore, the exact measurement of oxygen transfer parameters is essential and helpful in recognizing the influence of oxygen transfer on sewage quality and process operating conditions, as well as seeking the optimum operational parameters for an aeration system. Aeration systems transfer oxygen into liquid by either diffusing gas through a gas-liquid interface, or dissolving gas into the liquid solution using a semi-permeable membrane (Rosso et al., 2006). In the case of diffused aeration, aerator-related variables including the orifice diameter, bubble diameter, material of construction, depth of submergence, airflow rate per aerator, layout, aerator density, wetting property and fouling nature influence clean water oxygen transfer (Mahendraker et al., 2005a). Fine-bubble aeration is a subsurface form of diffusion in which air is introduced in the form of very small bubbles to aid or enhance the treatment of wastewater. It has become the most common aeration technology in wastewater treatment in the Organization for Economic Co-operation and Development countries, and usually exhibits higher efficiencies per unit energy consumed (Rosso et al., 2006).

Based on a large number of studies on oxygen transfer in clean water, the American Society of Civil Engineers (ASCE) standard was established to measure the oxygenation capacity of aeration devices in clean water (ASCE, 1992). The impacts of physical variables such as temperature, pressure, reactor geometry, mixing, surface tension and viscosity on oxygen transfer in clean water are well documented. Thus the mass transfer of oxygen is well understood in clean water; however, this is not the case under process conditions.

As pointed out by the ASCE guidelines for In-Process Oxygen Transfer Testing (ASCE, 1996), three methods of measuring the oxygen transfer parameters of oxygenation devices under process conditions can be taken into account: the steady-state oxygen uptake rate method, the non-steady-state method and the off-gas method. The

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major limitation of the steady-state oxygen uptake rate method is the requirement of a steady-state process condition, which is particularly difficult to achieve in full-scale WWTPs (Mahendraker et al., 2005a). For the non-steady-state method, the change in oxygen concentration can be achieved by changing power levels, adding hydrogen peroxide or aerating with pure oxygen. The non-steady-state method is commonly used in bench or pilot scale oxygen transfer testing under process conditions (Pratt et al., 2004; Mahendraker et al., 2005a, 2005b); however, its employment to evaluate the oxygenation capacity of aeration devices in full-scale operation has been scarce in previous literatures because the non-steady-state conditions are hard to achieve and maintain in WWTPs.

The off-gas method shows the most feasible characteristics for the determination of oxygen transfer rates in bioreactors operated at lab-scale or full-scale, such as the aeration tank in WWTPs (Redmon et al., 1983; Krause et al., 2003; Rosso et al., 2005; Schuchardi et al., 2007). This method offers the advantages of differentiation in location and time and the abandonment of respiration tests. It is performed at real in-process conditions without shutting off the inlet and effluent of the aeration tank (Krause et al., 2003). However, due to lack of comparison with other methods, the validity of the off-gas method in the determination of oxygen transfer parameters in a full-scale WWTP is still questionable. Moreover, the impacts of factors under operational conditions, which are different from those in clean water, on aeration performance need more experimental verification.

This work evaluates a newly-established full-scale aeration tank in the Lucun WWTP in Wuxi, China, which provides us opportunities to obtain first-hand and valuable engineering data used in non-steady-state testing. The non-steady-state and off-gas methods were used to determine the oxygen transfer parameters of aerators under process conditions in the tank for comparison, including the volumetric mass transfer coefficient (K_{La}), oxygen transfer rates (OTR) and oxygen transfer efficiency (OTE). The α factor (ratio of process water to clean water transfer coefficients) of fine-bubble aerators located in different corridors of the aeration tank and at various sampling times was investigated. The results aim to offer basic statistics and guidance on the operation and optimization of WWTPs in terms of aeration system design and its energy-saving solution.

1 Materials and methods

1.1 Aeration system in wastewater treatment plant

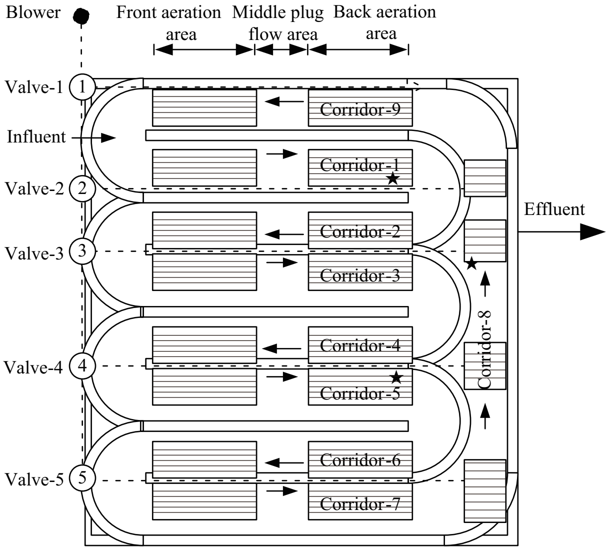

Fig. 1 Aeration system in Lucun WWTP, where the dashed lines stands for aeration pipes; arrows stand for wastewater flow direction; stripes stand for distribution positions of aerators and location indicated by the asterisk stands for the position of on-line oxygen meter.

The Lucun WWTP in Wuxi, China is operated in anaerobic-anoxic-oxic (A^2/O) process mode with treatment capacity of 100,000 tons per year. Two sets of identical A^2/O bioreactors are the main biological treatment processes supplied with separate influent. Taking one set of A^2/O processes as the target, the aeration tank was operated in plug flow and divided into nine corridors according to its physical structure as shown in **Fig. 1**. In each corridor, three zones designated the front aeration area, the middle plug flow area and the back aeration area were defined along the water flow direction. The aeration generated by the air blower was distributed into nine corridors through five ball valves and fine-bubble aerators were evenly installed. The aerators are GY·Q-type spherical fine-bubble ceramic aerators produced by Yixing Shihua Environmental Protection Company, China. The external diameter of an aerator is 240 mm with a height of 94 mm and a thickness of 12 mm. The service area is 0.4–0.6 m^2/unit for a water depth of 4–6 m and air flow rate of 2–6 m^3/hr for a single aerator.

1.2 Oxygen transfer testing methods under process conditions

1.2.1 Off-gas method

In the testing, the oxygen transfer capability of aerators was estimated by means of a gas phase mass balance over the aerated volume (Redmon et al., 1983). The oxygen transfer capacity, presented by the parameters of volumetric mass transfer coefficient (K_{La}, hr^{-1}), oxygen transfer rate (OTR, kg/hr) and oxygen transfer efficiency (OTE, %) of aerators under process conditions are determined from the molar ratios of the inlet and outlet gas fractions in the aerobic tank described by ASCE (1996) as follows:

$$K_{\mathrm{La}} = \frac{\rho \times Q(Y_{\mathrm{in}} - Y_{\mathrm{out}})}{V(C_{\mathrm{s}}^{*} - C)} \tag{1}$$

$$\mathrm{OTR} = \frac{K_{\mathrm{La}} \times C_{\mathrm{s}}^{*} \times V}{1000} \tag{2}$$

$$\mathrm{OTE} = \frac{\mathrm{OTR}}{G_{\mathrm{s}}} \times 100\% \tag{3}$$

where, ρ is the oxygen density, equal to 1.33 kg/m^3 at 20°C with 50% relative humidity; Q (m^3/hr) is the air flow rate; V (m^3) is the aeration volume; Y_{in}, Y_{out} are the molar ratios of inlet and outlet gas fractions, respectively; $C_{\mathrm{s}}{}^{*}$ (mg/L) is the saturated oxygen concentration in the aerobic tank attained at infinite time and C (mg/L) is the average oxygen concentration in the aerobic tank; G_{s} (kg/hr) is the total oxygen mass supplied. If the test conditions are not at 20°C, K_{La} can be amended using Eq. (4):

$$K_{\mathrm{La}}(20^{\mathrm{o}}\mathrm{C}) = K_{\mathrm{La}}(T) \times 1.024^{(20-T)} \tag{4}$$

where, T (°C) is temperature.

A portable hood with the dimensions of 1 × 1 m^2 was immersed in the liquid with a depth of about 10 mm in the aeration tank and captured the gas bubbles that reached the surface. In the testing, the hood was moved in the aeration tank along the nine corridors. The measuring points of corridor-1, -2, -4, -6 and -9 were set in the middle plug flow area, while the measuring points of corridor-3, -5 and -7 were located in the front aeration area. Furthermore, the oxygen transfer testing in corridor-2 was performed at 9:00 a.m., 12:00 a.m. and 5:00 p.m. over the course of a day to observe the oxygenation change of aerators with time.

The gas flowed through an analyzer (Z1100, ESC Company) that measures the oxygen molar ratio, Y_{out}. Q was read through the flow meter mating with the ball valve. C was measured by a portable oxygen meter (LDO TM HQ, HACH Company). The oxygen molar ratios and C were measured for three minutes and the mean values were used for calculation. One liter mixed activated sludge liquid was taken from the aerated tank and aerated over 24 hr until the dissolved oxygen concentration remained constant. This saturated concentration for $C_{\mathrm{s}}{}^{*}$ was then recorded.

1.2.2 Non-steady-state method

The testing involved measuring the oxygen concentrations over time in the tank after elevating it by increasing aeration from the steady-state normal operating conditions and analyzing the data as follows (ASCE, 1996):

$$K_{\mathrm{La}} = \frac{1}{t - t_0} \ln\left(\frac{C_{\mathrm{s}}^{*} - C_0}{C_{\mathrm{s}}^{*} - C}\right) \tag{5}$$

where, t (hr) is the time and subscript zero means the starting time when the aeration power level was not changed. Expressions of OTR, OTE and the relationship of K_{La} with temperature are similar to Eqs. (2)–(4) in the off-gas method.

During the non-steady-state method, the objective aeration tank was cut off from its inlet and outlet, and continuously aerated for several hours until the oxygen concentration in the tank remained stably high, indicating that the activated sludge reached the endogenous respiration process. At this point, the aeration was stopped to make the oxygen concentration decrease to a low level. Then the non-steady state was achieved by increasing the changeable power levels in the tank. At four power levels, the increases in oxygen concentrations in corridor-1, -5 and -8 were recorded by the on-line oxygen meters (**Fig. 1**) and used for the calculation of oxygenation performance.

2 Result and discussion

2.1 Oxygenation performance of fine-bubble aerators in clean water

According to the non-steady-state oxygen transfer testing report of the GY·Q spherical fine bubble aerator in clean water presented by the National Quality Control and Inspection Center of Ministry of Construction for Water Supply and Discharge Equipment (China), under the conditions of the service area of 1 m^2/unit, effective depth of 6 m and the testing water temperature of 23.6–23.7°C, the relationship between oxygenation performance and aeration amount is shown in **Table 1**. Large studies have revealed that the oxygenation parameters of aerators under the same service area were a power function of the aeration amount (ASCE, 1992, 1996; Zamouche et al., 2007; Schuchardi et al., 2007). Therefore, a quantitative relationship between the oxygenation performance parameters of the GY·Q fine bubble aerator and aeration amount was derived and presented as follows:

$$K_{\mathrm{La}}(20^{\mathrm{o}}\mathrm{C}) = 1.787 \times Q^{0.877} \tag{6}$$

$$\mathrm{OTR} = 0.128 \times Q^{0.877} \tag{7}$$

$$\mathrm{OTE} = 0.459 \times Q^{-0.12} \tag{8}$$

2.2 Oxygenation performance of fine-bubble aerators under process conditions measured by off-gas method

The service area and aeration amount of a single aerator in the aeration tank of Lucun WWTP were 0.9 m^2 and 0.59–0.74 Nm^3/hr, respectively, with effective depth of aeration of 6 m. During the measurement, the testing temperature remained at (20 ± 2)°C. The oxygen saturation concentration C_{s}^{*} in the mixed liquid at 20°C was 8.25

Table 1 Oxygenation performance of fine bubble aerator in clean water

Aeration amount (Nm^3/hr)	OTR (kg/hr)	OTE (%)
2.55	0.293	41.1
3.82	0.415	38.8
5.11	0.541	37.8

OTR: oxygen transfer rate; OTE: oxygen transfer efficiency.

mg/L, lower than the 12 mg/L value for clean water. The oxygenation performance parameters of the fine-bubble aeration system in the WWTP are shown in **Table 2**, where K_{La} was converted to $K_{La}(20°C)$ according to Eq. (4).

According to the results shown in **Table 2** as well as the oxygenation parameters calculated at the average aeration amount of 0.65 m^3/hr in clean water, α factors for the ratio of process water to clean water in different corridors in the plug-flow aeration tank are shown in **Fig. 2**.

In **Fig. 2**, it can be easily seen that the oxygenation performance of fine bubble aerators in different corridors of aeration tank varied significantly. Since K_{La} is proportional to OTR, the trends of the two parameters as well as OTE in different corridors are similar. In the corridors which shared the same main aeration pipe, the front aeration area had better oxygen transfer performance than the middle plug flow area (α factors in corridor-2, -4 and -6 were smaller than those in the corridor-3, -5 and -7). Although a large number of studies have testified that α of fine-bubble aerators under process conditions can be influenced by water quality, organic load, aeration amount, operational type of aeration tank and fouling of the aerators (ASCE, 1992, 1996), we attributed the better oxygenation performance to the differences in aeration intensity caused by the uneven distribution of aerators in the tank. Among all the fine-bubble aerators, the oxygenation performance parameters of those located in the middle of the plug flow aeration tank in corridor-5 were the closest to the average values. Compared to the oxygenation performance in clean water ($K_{La}(20°C)$, OTR, and OTE were calculated to be 1.23 hr^{-1}, 0.088 kg/hr and 48.3%, respectively, at the aeration amount for a single aerator of 0.65 Nm^3/hr), $K_{La}(20°C)$. OTR and OTE of fine-bubble aerators under process conditions account for 31%–100%, 29%–96%, and 33%–86% of those in clean water. Moreover, the average values of $K_{La}(20°C)$, OTR and OTE for the fine-bubble aerators decrease by 41%, 43% and 42% in the actual sewage treatment plant.

Furthermore, α factors in corridor-2 over the course of a day are shown in **Fig. 3**. It can be concluded that the aerators at the same position in the tank almost shared the same oxygenation capacity in one day with a slight difference of morning > noon > evening. According to the water quality analysis at the testing point (**Table 3**), COD and NH_4^+-N concentrations at noon were the highest. Previous studies have revealed that higher organic load always led to weaker oxygen transfer capability (ASCE, 1992, 1996). However, possibly due to the influence of air and water temperatures, aeration performance at noon was not the worst during the whole day.

Table 2 Oxygenation performance of fine bubble aerator in aeration tank measured by off-gas method

Number	C (mg/L)	Y_{out} (%)	$K_{La}(20°C)$ (hr^{-1})	OTR (kg/hr)	OTE (%)
Oxygenation performance for different corridors					
Corridor-1	2.86	17.4	0.77	0.053	15.0
Corridor-2	2.14	18.7	0.38	0.026	8.1
Corridor-3	1.55	16.2	0.86	0.059	20.4
Corridor-4	1.22	17.5	0.62	0.043	14.2
Corridor-5	1.32	16.9	0.76	0.052	17.0
Corridor-6	1.95	17.8	0.72	0.049	12.7
Corridor-7	3.11	16.8	1.23	0.084	17.9
Corridor-9	2.61	18.6	0.48	0.033	8.7
Oxygenation performance at corridor-2 over a day					
9:00 a.m.	1.87	17.9	0.49	0.033	20.8
12:00 a.m.	0.27	17.5	0.45	0.031	19.4
5:00 p.m.	0.45	17.9	0.39	0.027	17.1

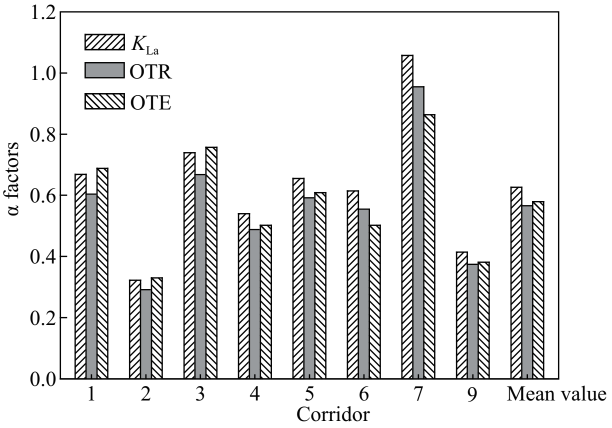

Fig. 2 α factors of fine bubble aerator in the different corridors of the plug-flow aeration tank measured by the off-gas method.

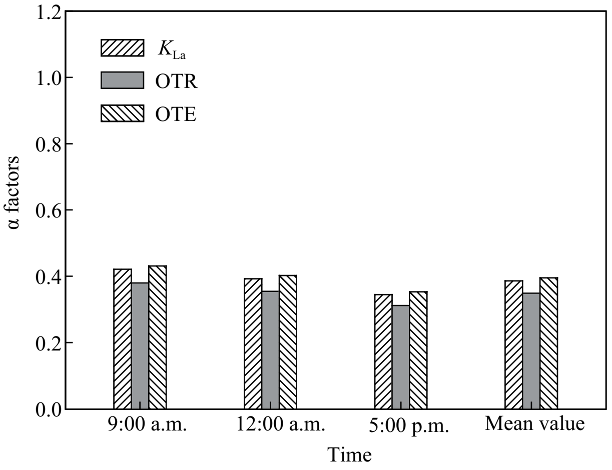

Fig. 3 α factors of fine-bubble aerator in corridor-2 over one day.

Table 3 Water quality in the corridor-2 of aeration tank

Time	COD (mg/L)	NH_4^+-N (mg/L)
9:00 a.m.	190	1.7
12:00 a.m.	282	2.7
5:00 p.m.	233	1.4

2.3 Oxygenation performance of fine-bubble aerators under process conditions measured by the non-steady-state method

After three hours' aeration with inlet and outlet shut off in the tank, the dissolved oxygen concentration reached about 9–10 mg/L. After the aeration stopped, the reductions measured by the on-line oxygen meters in corridor-1, -5 and -8 are presented in **Fig. 4**. The temperature in the tank was (13 ± 2)°C. The respiration rates of microorganisms in corridor-1, -5 and -8 were calculated to be 3.66, 3.78 and 3.48 mg/(L·hr), respectively, with the specific respiration rates of 1.09–1.43 mg/(g MLSS·hr) at the activated sludge concentration of 3 g MLSS/L in the tank. Zhang et al. (2003) have concluded that the microorganisms reached the endogenous respiration process when the specific respiration rate decreased to 3.33 mg/(g MLSS·hr). Therefore, the values measured in this study demonstrated that the endogenous respiration process was reached in the tank after three hours' aeration. Furthermore, low temperature and lack of metabolic storage substances contained in the cells are both likely to lead to a low endogenous respiration rate. **Figure 4** also indicates that the dissolved oxygen was distributed relatively uniformly in the tank during the endogenous respiration process, especially in corridor-1 and -5.

In the non-steady-state testing, the oxygenation performance parameters of the fine-bubble aeration system in WWTP were calculated at variable aeration intensities (**Table 4**). The aerator service area of the aerators was 0.9 m^2/unit and the effective depth was approximately 6 m. The K_{La} was converted to $K_{La}(20°C)$ using Eq. (4). Furthermore, the values of K_{La}, OTR and OTE in clean water at different aeration intensities (0.29–1.03 m^3/hr) were calculated according to Eqs. (6)–(8). The α factors in different corridors in the plug-flow aeration tank are shown in **Fig. 5**.

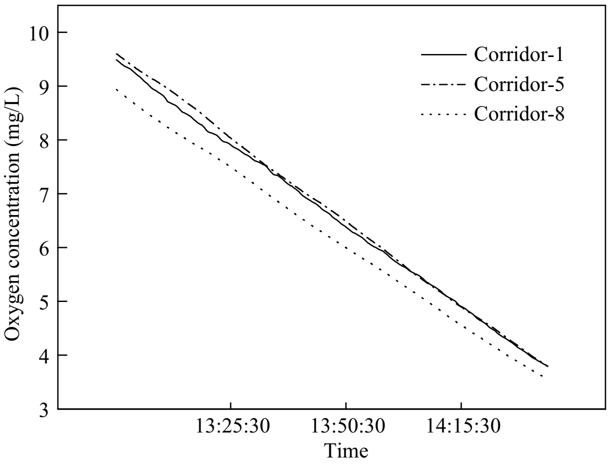

Fig. 4 Oxygen depletion measured by the on-line oxygen meters at corridor-1, -5 and -8 of aeration tank.

Table 4 Oxygenation capability of fine bubble aerator in the activated sludge tank measured by non-steady-state testing

Number	Q (Nm^3/hr)	$K_{La}(20°C)$ (hr^{-1})	OTR (kg/hr)	OTE (%)
Corridor-1	0.29	0.006	0.00036	0.3
Corridor-5		0.140	0.00904	11.6
Corridor-8		0.004	0.00027	0.4
Mean		0.055	0.00355	4.5
Corridor-1	0.64	0.629	0.04066	20.5
Corridor-5		0.908	0.05873	31.9
Corridor-8		0.838	0.05421	28.9
Mean		0.751	0.04857	25.8
Corridor-1	0.79	1.257	0.08132	33.7
Corridor-5		1.187	0.07680	34.7
Corridor-8		1.048	0.06777	29.5
Mean		1.082	0.07003	30.6
Corridor-1	1.03	1.746	0.11295	36.9
Corridor-5		1.955	0.12650	42.1
Corridor-8		1.257	0.08132	27.1
Mean		1.641	0.10617	35.2

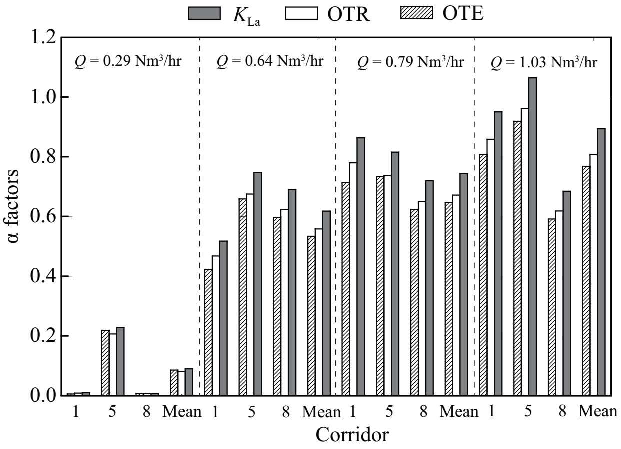

Fig. 5 α factors of fine-bubble aerator in corridor-1, -5, -8 of activated sludge tank measured by non-steady-state method.

As shown in **Fig. 5**, the oxygenation performance of different corridors was different, similar to the results measured by the off-gas method. Under the four aeration conditions, corridor-5 possessed the best performance. Since the inlet of the aeration tank was closed during the non-steady-state measurement, the aeration tank was almost fully mixed. Therefore, the difference of the oxygenation performance is likely due to the variable gas pressure allocation and blocking levels of aerators in different corridors.

The oxygen transfer performance of the fine-bubble aerators under process conditions decreased compared with the oxygenation in clean water. The α factors in K_{La}, OTR and OTE values increased with the increased aeration intensity. At the low aeration amount of 0.29 Nm^3/hr, the average value of K_{La}, OTR and OTE along the whole tank dropped by 91%, 92% and 91% compared to clean water conditions. However, the discrepancies decreased to 11%, 19% and 23% when the aeration amount increased to 1.03 Nm^3/hr.

The relationships of aeration intensity and oxygenation performance under process conditions, which were also proved to be in accord with the power curves similar to those in clean water in previous studies (ASCE, 1992, 1996; Zamouche et al., 2007; Schuchardi et al., 2007):

$$K_{\mathrm{La}}(20°\mathrm{C}) = 1.925 \times Q^{2.775} \tag{9}$$

$$\mathrm{OTR} = 0.422 \times Q^{1.708} \tag{10}$$

$$\mathrm{OTE} = 0.125 \times Q^{-2.774} \tag{11}$$

From the simulation results, it can be easily seen that the loss of oxygen transfer coefficient was over 50% under the low-aeration conditions ($Q < 0.67$ Nm^3/hr). However, the increase rates in oxygenation parameters under process conditions were faster than those in clean water. As the aeration amount reached 0.96 Nm^3/hr, the discrepancy of K_{La}(20°C) between the process condition and clean water was negligible.

2.4 Comparison of oxygenation performance of fine bubble aerator in WWTP measured by non-steady-state method and off-gas method

We have noticed the fact that a common feature in the evaluation of oxygen transfer testing methods in the previous studies is that each one yields different results. Mahendraker et al. (2005a) indicated that steady-state oxygen uptake rate and off-gas methods resulted in comparable estimates of oxygen transfer parameters; however, the validity of the non-steady-state method to measure the oxygen transfer under process conditions was questionable. Pratt et al. (2004) found that the off-gas method resulted in the highest K_{La} of oxygen for a given reactor, while the non-steady state method resulted in the lowest K_{La}. However, in the study of oxygen transfer testing procedures in full-scale membrane bioreactors (Krause et al., 2003), using non-steady state methods and the off-gas method resulted in the same average value of OTR. Consequently, this inconsistency also increases the demand for more experimental comparison between these methods. In our study of the off-gas testing, the average aeration amount was 0.65 Nm^3/hr, approximately equal to the average aeration amount of 0.64 Nm^3/hr of the second stage in the non-steady-state method. Under the same aeration amount, the oxygenation performance parameters of the two methods, shown in **Fig. 6**, indicate that the results obtained by the two methods were relatively comparable. There is no doubt that the off-gas method is superior for the oxygen transfer testing of aerators under full-scale process conditions, as it does not require changing the power level of the aeration tank, which makes it a good and economical testing option for WWTPs in operation.

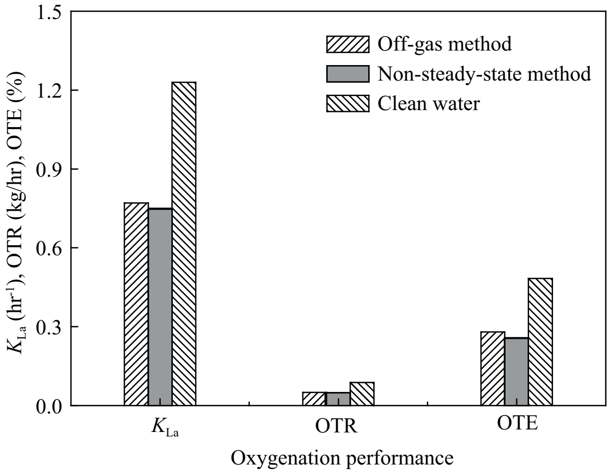

Fig. 6 Oxygenation performance parameters measured by the off-gas method and non-steady-state method.

3 Conclusions

(1) The oxygenation performance parameters of fine-bubble aerators in different corridors of an aeration tank varied significantly as measured by the off-gas method, however, the oxygen transfer capacity varied only slightly over the course of a day. (2) Results measured by the off-gas method and non-steady-state method of the oxygen transfer performance of the fine-bubble aerators in the aeration tank are almost corresponding and comparable. (3) At the measured aeration intensities, the loss of oxygen transfer coefficient was over 50% under low-aeration conditions ($Q < 0.67$ Nm^3/hr); however, the discrepancy of K_{La}(20°C) between the process condition and clean water was negligible as the aeration amount reached 0.96 Nm^3/hr.

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