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Effect of bio-carrier filling rate on oxygen transfer coefficient of different diffusers in MBBR process

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ABSTRACT

This paper mainly discussed the effect of bio-carrier filling rate on the oxygen transfer coefficient of different diffusers in the MBBR process. The results show that bio-carriers could increase the oxygen transfer coefficients of the microporous diffusers both in clean water and in mixed liquor because of the shearing effect that created microbubbles and enhanced microscopic hydrodynamic flow regime of the reactor. Compared to the test without bio-carriers, dosing bio-carriers could increase the oxygen transfer coefficient of microporous membrane diffuser by 10.78% in clean water and 10.17% in mixed liquor. Dosing bio-carriers could increase the oxygen transfer coefficient of the campanulate corundum aerator and perforated pipe more than the microporous membrane diffuser. Compared to the control, dosing bio-carriers could increase the K_{La} of campanulate corundum aerator and perforated pipe diffuser by almost 13.40 and 17.74% in clean water, and 10.97 and 20.14% in mixed liquor, respectively.

Keywords: Filling rate; Diffuser; Oxygen transfer coefficient; MBBR process

1. Introduction

The literature has shown that oxygen transfer rate in biological wastewater treatment reactor is not only affected by the wastewater influent quality [1,2], but also related to the aeration diffusers, hydraulic conditions, and other parameters [3,4]. Moving Bed Biofilm Reactor (MBBR) process is one of the most commonly used processes for sewage treatment plant upgrading [5]. However, the effect of suspended bio-carriers (media) on oxygen transfer coefficient was seldom reported. When fluidized bio-carriers are moving in the reactor, hydraulic shearing might take place and influence the oxygen transfer efficiency significantly. Bio-carriers could shear air bubbles into smaller size, which increases the surface areas and induces higher oxygen transfer rates. Previous literature reported adding bio-carriers to wastewater treatment systems as a solution to modify hydraulic conditions [6,7]. However, the impact of bio-carriers filling rate has not been quantified. This paper mainly focuses on the effect of bio-carriers on oxygen transfer in MBBR

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process for domestic sewage treatment. Meanwhile, oxygen transfer coefficient (K_{La}) was measured under different bio-carriers filling rates. In addition, this study also determined the oxygen transfer coefficients of different types of diffusers. The shearing effects of bio-carriers on different sizes of bubbles, which were produced by different diffusers installed for the MBBR system, were measured and compared. The results of this paper provided useful information on diffuser selection and bio-carrier filling rates to increase the oxygen transfer coefficient in the MBBR process.

2. Materials and methods

2.1. Derivation of oxygen transfer coefficient

According to the Lewis and Whitman's double film theory, the oxygen transfer differential equation relevant to aeration in a reactor is shown in Eq. (1):

$$dC/dt = K_{La} \cdot (C_s - C) - R \quad (1)$$

where C_s is the saturation concentration of DO in water (mg/L), K_{La} is the oxygen transfer coefficient (h^{-1}), and R is the oxygen consumption rate of activated sludge micro-organisms ($kgO_2/(m^3\ h)$).

R is always equal to zero if the test is performed in clean water due to the absence of micro-organisms. In this case, Eq. (1) can be integrated and K_{La} can be expressed as Eq. (2):

$$K_{La} = \ln[(C_s - C_1)/(C_s - C_2)]/(t_2 - t_1) \quad (2)$$

where $t_2 - t_1$ is the length of the aeration time, C_1 (mg/L) is the DO concentration in the water at time t_1, and C_2 (mg/L) represents the DO concentration in the water at time t_2.

If there are oxygen-consuming substances or activated sludge in the water, the oxygen transfer coefficient calculation formula can be revised from Eq. (1) as Eq. (3) [8]:

$$C_s - C = [C_s \times K_{La} - ((dC/dt) + R)]/K_{La} \quad (3)$$

2.2. Experimental setup

The experimental setup for the oxygen transfer coefficient testing is shown in Fig. 1. The effective volume of the water tank was 70 L, and the diffuser was installed at the bottom of the tank. Airflow was measured by an airflow meter, which was installed along the intake tube. The water temperature was controlled at 20℃ and the airflow rate for the diffuser was controlled at 1.5 m^3/h. Two dissolved oxygen (DO) sensors (HACH and YSI-6920) were used simultaneously to monitor and record the DO in the water every 8 s, so as to avoid false measurements and minimize errors. Three types of diffusers, microporous membrane diffuser, corundum microporous diffuser, and perforated pipe diffuser, were assessed.

The bio-carriers used in this research were Type SPR-1 (Spring Co. Ltd, Qingdao, PRC), which are widely used for upgrading wastewater treatment plants in China. The shape of Type SPR-1 is flat cylinder with a diameter of 25 mm and a thickness of 10 mm, and has a symmetrical grid structure within the bio-carrier. The effective surface area of the bio-carriers is 500 m^2/m^3 and the specific gravity is 0.96 g/cm^3.

2.3. Determination of oxygen transfer coefficient

2.3.1. For clean water sample

To determine the oxygen transfer coefficient of clean water, the experimental setup shown in Fig. 1 was firstly filled with the test water sample and air was introduced into the water tank via the diffuser at an airflow rate of 1.5 m^3/h. As the water sample became saturated with oxygen, the measured DO concentration will stabilize.

Next, Na_2SO_3, as oxygen scavenger, was added into the water to consume the DO. As a result, the DO concentration in the aeration tank would reduce to zero rapidly. Subsequently, the DO concentration gradually recovered to saturation as the scavenger was consumed by the DO. Fig. 2 shows a typical DO profile with time for the experiment using clean water as the test sample. The oxygen transfer coefficient

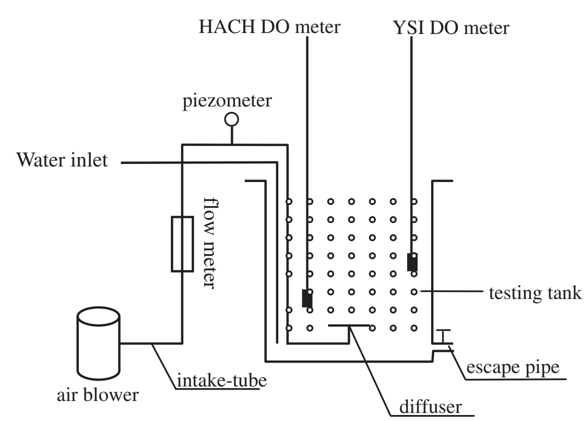

Fig. 1. Schematic diagram of the experimental setup.

based on each probe was then calculated individually. The average value would be applied as the test result if no significant difference was found. After each test, the oxygen transfer coefficient (K_{La}) of the clean water was calculated by substituting the DO concentrations (i.e. C_1 and C_2) and the corresponding time difference (i.e. $t_2 - t_1$) into Eq. (2).

2.3.2. For activated sludge sample

The testing procedure for the oxygen transfer coefficient in activated sludge sample was similar to the clean water sample except the calculation methods, which is summarized as follows:

The first step was to measure the oxygen consumption rate (R value) of the activated sludge mixed liquor according to the Standard Method [9]: (1) The mixed liquor was firstly aerated to achieve a high DO value of around 6–7 mg/L; (2) The aeration was then stopped; and (3) The DO decreasing rate within a certain time length was then measured.

The second step was to conduct the oxygen transfer coefficient test to measure the dC/dt. The oxygen transfer coefficient test was similar to the clean water testing except for mixed liquor, the aeration was stopped before the addition of Na_2SO_3 into the mixed liquor to perform deoxidization and the aeration was restarted when the DO concentration reached zero. Similarly, the DO concentration profile with time was obtained for the mixed liquor. With the experimental data, the DO concentration (y-axis) was plotted against $[(dC/dt) + R]$. The intercept of the y-axis is the C_s value, while the slope of the curve is $-1/K_{La}$ [10]. Therefore, the K_{La} value of the aeration equipment for the mixed liquor was determined.

3. Results and discussion

3.1. Effect of bio-carrier filling rate on oxygen transfer coefficient

Due to the function of hydraulic shearing force in the aerobic zone of the MBBR process, air bubble size was reduced and microscopic hydrodynamic flow regime was changed simultaneously by the bio-carriers. As the oxygen transfer coefficient is impacted by the bio-carrier filling rate, seven different commonly used bio-carrier filling rates (i.e. 20, 25, 30, 35, 40, 45, and 50%) of the MBBR process were investigated to quantify the effect of bio-carrier filling rate on the oxygen transfer coefficients of three commonly used diffusers.

The clean water experiment for the microporous membrane diffuser was conducted first. The pH value of the water was between 6.5 and 7.0. As shown in Fig. 3, the bio-carriers had a significant impact on the oxygen transfer coefficient of the microporous membrane diffuser. The oxygen transfer coefficients of the microporous membrane diffuser were increased by 1.13, 7.47, 10.78, 10.54, 9.49, 8.52, and 9.49% for the bio-carrier filling rates of 20, 25, 30, 35, 40, 45, and 50%, respectively, compared to the blank test with no bio-carriers added. The average percentage increase in the oxygen transfer coefficient was 8.09%. With increasing bio-carrier filling rate, the oxygen transfer coefficient increased until a bio-carrier filling rate of 30%, from which it declined gradually thereafter.

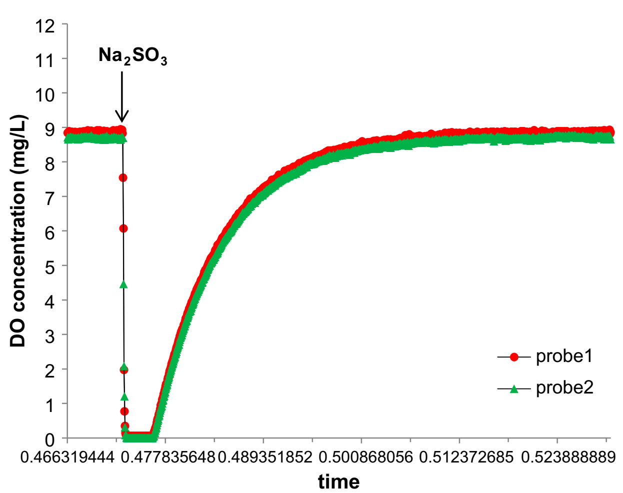

Fig. 2. Variation in DO concentration with time in clean water.

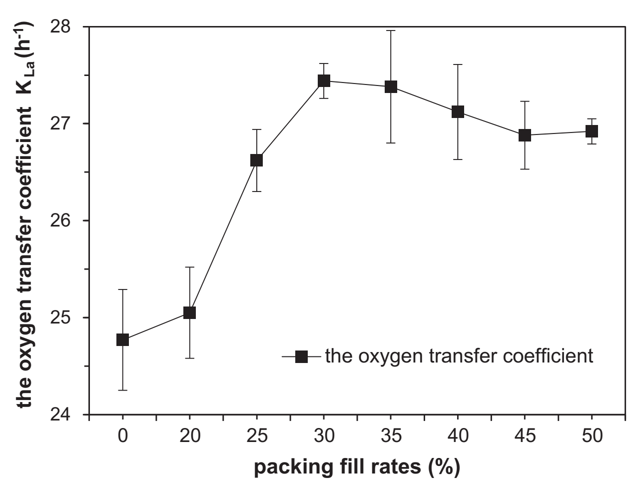

Fig. 3. Variation in K_{La} of microporous membrane diffuser with filling rate in clean water.

Therefore, the maximum oxygen transfer coefficient was attained at a bio-carrier filling rate of 30%.

From these results, it was observed that with increasing bio-carrier filling rate, the chances of bubbles being sheared by the bio-carriers to produce small microbubbles would increase, which was beneficial to improve the oxygen transfer coefficient of the diffusers. However, as the bio-carrier filling rate increased to a certain extent, the effect of fluidization of bio-carriers would deteriorate, which was not conducive to improve the oxygen transfer coefficients.

When the bio-carrier filling rate was lower (<20%), the shearing effect of the bio-carriers for generating microbubbles was not obvious. However, with increasing bio-carrier filling rate, the chance of air bubbles being sheared into microbubbles increased greatly. The mesh structure in the center and the outer extending fins of bio-carrier could effectively compress the thickness of the air film and liquid film, which enhanced the oxygen transfer coefficient of the diffuser. Meanwhile, when the bio-carrier was added to a certain extent (25–35%), it could change the microscopic hydrodynamic flow regime inside the reactor significantly, which strengthened the mutual interference and collision among bubbles. As a result, the corresponding oxygen transfer coefficient of the microporous membrane diffuser increased rapidly. When the bio-carrier dosing exceeded a critical value (i.e. 35%), hydraulic shearing effect on bubbles was limited because the fluidizing bio-carriers involved could not continue to increase. In other words, the oxygen transfer coefficient could only be increased to the maximum by increasing the bio-carrier filling rate up to 35%. This is because with the bio-carrier filling rate exceeding 35%, the bio-carriers fluidization degree would decline and the turbulent flow state of the water would weaken.

3.2. Effect of filling rate on oxygen transfer coefficient of microporous membrane diffuser in MBBR hybrid systems

In order to further understand the effect of bio-carrier filling rate on the oxygen transfer coefficient of microporous membrane diffuser in the mixed liquor of the MBBR process, activated sludge from a MBBR wastewater treatment plant in Qingdao was transferred to the tank as shown in Fig. 1. Bio-carriers were added with different filling rates to the tank and the oxygen transfer coefficient tests were carried out at each bio-carrier filling rate. In order to assess the impact of biofilm presence on the oxygen transfer coefficient, control tests using bio-carriers with and without biofilm were comparatively carried out during the experiment. The concentration of the mixed liquor was controlled at around 8,000 mg/L for each test. The bio-carriers with biofilm were taken from the same MBBR wastewater treatment plant. Biomass concentration of the suspended bio-carrier was about 11,000 mg/L.

Fig. 4 shows that the water quality of the mixed liquor had a greater impact on the flow state compared with that in clean water. The oxygen transfer coefficient of the mixed liquor was slightly lower than that in the clean water regardless of the bio-carrier filling rate. The trends in the variation of the oxygen transfer coefficient of the bio-carriers with or without biofilm were consistent. Due to the biofilm on bio-carriers, oxygen consumption by the biofilm caused the oxygen transfer coefficient of the biofilm bio-carriers to be higher than bio-carriers without biofilm under the same bio-carrier filling rate. The oxygen transfer coefficient reached the maximum when the filling rate of the bio-carriers with biofilm was 40%, and was about 10.17% higher than the case of no bio-carriers under the same conditions. For bio-carriers without biofilm, oxygen transfer coefficient of the microporous membrane diffuser reached the maximum when the bio-carrier filling rate was 35%, an improvement of about 6.89% compared to the case of no bio-carriers dosing in the mixed liquor.

3.3. Effect of bio-carrier filling rate on oxygen transfer coefficient of different diffuser

In order to investigate the effect of bio-carrier filling rate on the oxygen transfer coefficient of different diffusers, three different types of diffusers as

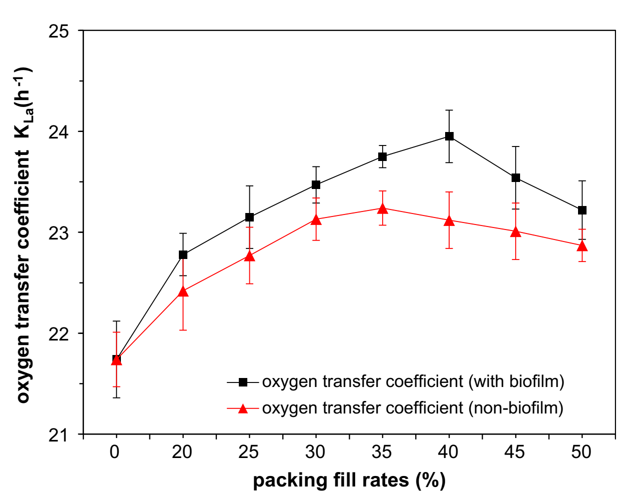

Fig. 4. Variation in K_{La} of microporous membrane diffuser with different bio-carrier filling rate with and without biofilm in mixed liquor tests.

discussed in section 2.2 were evaluated at a similar airflow rate of 1.5 m^3/h. The bio-carriers without biofilm were adopted for this group of tests, and the test was conducted under the same condition. The oxygen transfer coefficient tests were conducted in both clean water and mixed liquor. The experimental conditions used were similar to those used in section 3.2.

Fig. 5 shows the variations in the oxygen transfer coefficient of the three diffusers at different bio-carrier filling rates. When the bio-carrier filling rate was below 30%, the oxygen transfer coefficients of all the three diffusers increased with increasing bio-carrier filling rate in clean water, and all the three diffusers attained maximum values at a bio-carrier filling rate of 30%. Fig. 6 shows the variations in the oxygen transfer coefficient of the three diffusers in the mixed liquor, which showed similar trends as those in the clean water. The only difference between the clean water and mixed liquor is that the oxygen transfer coefficient of the three diffusers in mixed liquor attained the maximum oxygen transfer coefficients when the bio-carrier filling rate was 35%, compared to 30% for the case of the clean water.

When the bio-carrier filling rate was 30%, the oxygen transfer coefficient of the microporous membrane diffuser increased by 10.78% compared to the control test without bio-carriers dosing in clean water. As for the corundum diffuser and perforated pipe diffuser, the oxygen transfer coefficients increased by 13.40 and 17.74%, respectively. For the tests in mixed liquor, when the bio-carrier filling rate was at 35%, the oxygen transfer coefficient of the microporous membrane diffuser increased by 6.89% compared to the control test without bio-carriers dosing. On the other hand, the oxygen transfer coefficient of the corundum

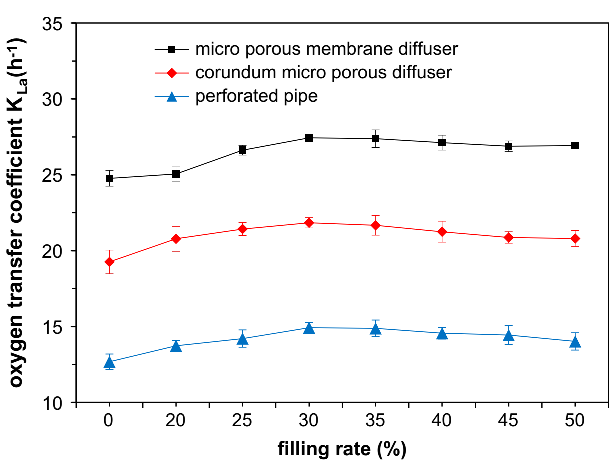

Fig. 5. Variation in K_{La} of different diffusers with bio-carrier filling rate in clean water.

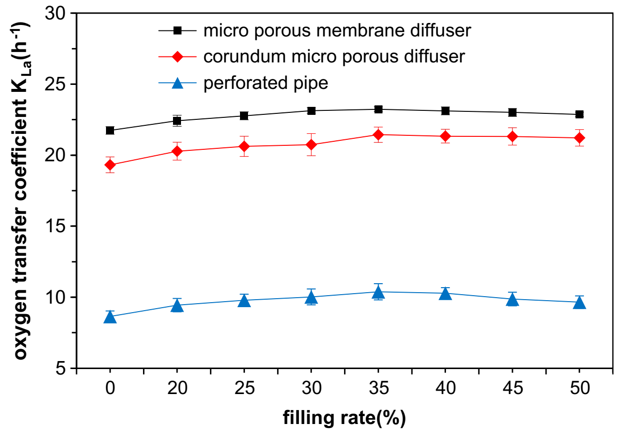

Fig. 6. Variation in K_{La} of different diffusers with bio-carrier filling rate in mixed liquor.

diffuser and perforated pipe diffuser increased by 10.97 and 20.14%, respectively.

Differences observed in the oxygen transfer coefficients for the three different diffusers being tested under similar condition were probably due to the impact of the bio-carriers on the microscopic hydrodynamic flow regime. Due to the different sizes of bubbles produced by different type of diffusers, the bio-carriers had different impact on the oxygen transfer coefficient of each diffuser. The shearing action of bio-carriers for the perforated pipe diffuser was more obvious because it produced larger sized bubbles, and the increase in oxygen transfer coefficient with bio-carriers addition was more apparent too. In contrast, because of the smaller sized bubbles produced by the microporous membrane diffuser, the shearing action of the bio-carriers for this kind of bubbles was relatively small, resulting in relatively small increase in the oxygen transfer coefficient.

4. Conclusions

This paper studied the effect of bio-carrier filling rate on the oxygen transfer coefficient of different diffusers in the MBBR process through lab-scale experiments. The main conclusions are as follows:

(1) Suspended bio-carrier dosing could increase the oxygen transfer coefficient significantly, due to hydraulic shearing effect produced by the bio-carriers in the aeration tank. The oxygen transfer coefficient of microporous membrane diffusers could be increased by 10.78% in clean water and 10.17% in activated sludge mixed liquor.

(2) The effect of bio-carriers on oxygen transfer coefficient would reach a maximum value and then decreased slightly with increasing bio-carrier filling rate.
(3) The impact of bio-carriers on the oxygen transfer coefficient of different diffusers differed significantly. Greatest impact of bio-carriers with perforated pipe diffuser was found, with the oxygen transfer coefficients increased by 17.74 and 20.14% in the clean water and mixed liquor, respectively.

Acknowledgments

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References

[1] L. Tyroller, D.P.L. Rousseau, S. Santa, J. García, Application of the gas tracer method for measuring oxygen transfer rates in subsurface flow constructed wetlands, Water Res. 44 (2010) 4217–4225.
[2] R. Gori, A. Balducci, C. Caretti, C. Lubello, Monitoring the oxygen transfer efficiency of full-scale aeration systems: Investigation method and experimental results, Water Sci. Technol. 70 (2014) 8–14.
[3] J. Huang, L.G. Shao, A Comparative Study of SBBR and SBR oxygen mass transfer characteristics, Ind. Water Wastewater 34 (2003) 4–6.
[4] L.J. Zhao, F. Ma, Q.H. Lu, Experimental study on the oxygenation performance of the four bio-carrier, Environ. Sci. Manage. 31 (2006) 106–109.
[5] K. Calderón, J. Martín-Pascual, J.M. Poyatos, B. Rodelas, A. González-Martínez, J. González-López, Comparative analysis of the bacterial diversity in a lab-scale moving bed biofilm reactor (MBBR) applied to treat urban wastewater under different operational conditions, Bioresour. Technol. 121 (2012) 119–126.
[6] X.H. Zhou, H.C. Shi, Y.Q. Qiu, Determination of the impact of micro-electrode structure spherical packing on the mass transfer process, J. Tsinghua University (Natural Sci.) 47 (2007) 834–837.
[7] A. Malovanyy, J.J. Yang, J. Trela, E. Plaza, Combination of upflow anaerobic sludge blanket (UASB) reactor and partial nitritation/anammox moving bed biofilm reactor (MBBR) for municipal wastewater treatment, Bioresour. Technol. 180 (2015) 144–153.
[8] S.S. Yang, Theory and Practice of Aeration, China Building Industry Press, Beijing, 1982.
[9] People's Republic of China Urban Construction Industry Standards, (CJ/T3015.2-1993) Oxygen Transfer Measurement of Aerators in Clean Water, Beijing, 1993.
[10] M. Wu, N.M. Yao, Discussion on the comparison and selection of micro porous aerator, Eng. Technol. 5 (2002) 16–18.