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## Experimental study of the effect of salinity and surfactant on mass transfer characteristics of oxygen micro-nano bubbles

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### ABSTRACT

The application of micro-nano bubbles (MNBs) in water treatment technology has been gaining more and more attention recently. In order to investigate the effect of salinity and surfactant on mass transfer characteristics of oxygen MNBs, a series of laboratory experiments conducted on oxygen MNBs water with different salinities and surfactant concentrations. The test results showed that two ranges obtained for oxygen MNBs size and the main parts were 0.026-0.172  $\mu\text{m}$  and 1.635-6.540  $\mu\text{m}$ . With the salinity of 0 g/L, the peak value of dissolved oxygen (DO) in oxygen MNBs water was 44.13 mg/L and the saturation time of DO was 11400 min. But when the salinity was 3 g/L, the peak value of DO increased by 7.68% and the saturation time of DO was extended by 9.32%. When the salinity was between 0 g/L and 2 g/L, the mass transfer efficiency of oxygen MNBs was adversely affected by salinity. In addition, sodium dodecyl benzene sulfonate (SDBS) reduced the peak value of DO and extended the saturation time of DO by changing the interface potential of oxygen MNBs.

**Keywords:** Micro-nano bubbles, oxygen, mass transfer characteristics, surfactant, salinity

### 1 INTRODUCTION

Micro-nano bubbles (MNBs) are tiny bubbles with a diameter ranging from hundreds of nanometers to tens of micrometers (Attard et al., 2002; Chu et al., 2007). MNBs possess various unique properties that distinguish them from ordinary bubbles, such as large specific surface area, negatively charged surface, long residence time in water, high mass transfer efficiency and the generation of highly reactive free radicals (Takahashi et al., 2003; Ushikubo et al., 2010). Compared to chemicals such as disinfectants and oxidants, MNBs are more cost-effective and environment-friendly (Ahmed et al., 2017). Due to these special characteristics, more attention has been drawn to the promising applications of MNBs technology in various industrial applications including water treatment, agricultural and chemical engineering processes (Agarwal et al., 2011; Chu et al., 2008; Chu et al., 2007; Li et al., 2009a, b; Xu et al., 2008).

Many research studies have focused on the properties of MNBs. Bowley and Hammond (1978) studied the relationship between oxygen mass transfer and bubble diameter, and found that the MNBs generated by the micro-pore method can improve the oxygen mass transfer efficiency. Bredwell and Worden (1998) studied the effect of surfactants on dissolved oxygen (DO) and

mass transfer of MNBs. The bubble generation method was rotary cutting and the size of MNBs was 60  $\mu\text{m}$ . They found that MNBs greatly improve the oxygen mass transfer efficiency. The higher surfactant concentration was, the lower oxygen mass transfer efficiency would be. Wan et al. (2001) studied the residence time of MNBs with surfactants. The diameter of MNBs was 0.7-20  $\mu\text{m}$ . The residence time of MNBs was more than 6 weeks. The larger the bubbles were, the shorter the residence time would be. For MNBs, the mass transfer rate of gas from bubbles to surrounding liquid increases with a decrease in the bubble radius and an increase in bubble internal pressure. Oxygen MNBs stabilized by surfactants can provide higher mass transfer efficiency than macro-bubbles. However, it was demonstrated that an increase in liquid surfactant concentration decreased the mass transfer rate of MNBs by the increased mass transfer resistance in the gas-water interface (Bredwell and Worden, 1998).

As a key ecological factor of the environment, DO in groundwater influences biological activity and organic matter content of groundwater (Malard and Hervant, 1999). The DO content in groundwater plays a significant role in the aerobic biodegradation. Therefore, the mass transfer characteristic of MNBs influences its promising potential application in the field of water

treatment. Great DO enhancement is expected for MNBs, which will stimulate the microbial activity (Bowley and Hammond, 1978). Contaminated groundwater has different salinities, and surfactants may be used in the process of biodegradation of contaminated groundwater. Therefore, it is extremely important to study the mass transfer characteristics of MNBs with different salinities and surfactants. The main objective of this study is to examine the effect of salinity and surfactant on the properties of oxygen MNBs, including the peak value and the saturation time of DO in MNBs water.

## 2 EXPERIMENTS

### 2.1 Materials

Deionized water and oxygen were used in this study. The oxygen cylinder provided 99.9% concentrated oxygen. The anionic surfactant sodium dodecyl benzene sulfonate (SDBS) (Beijing Modern Eastern Fine Chemical Co., Ltd., Beijing, China) with the formula  $C_{18}H_{29}NaO_3S$ . In order to adjust solution salinity, sodium chloride (NaCl) was added to the water.

### 2.2 Experimental setup

An MNBs generator (Yunnan Xiazhichun Environmental Protection Technology Co., Ltd, China) was used to generate MNBs in this study. Water was pumped into the generator, and the liquid flow was rotated at high-speed. Oxygen was injected into the generator, and oxygen MNBs were then generated. A Microtrac S3500 particle-size analyzer with measuring range from 0.01 to 2800  $\mu m$  was employed to get the size distribution of MNBs. YSI ProSolo meter (Xylem, USA) was used to measure the DO in water. DO ranging from 0 to 50 mg/L with the accuracy of  $\pm 1\%$  could be recorded.

### 2.3 Experimental procedure

In this research, the flow rate of water was 20 L/min, and the injection rate of oxygen was 1.8 L/min. The MNBs generator started to generate MNBs in a water bucket and the generation process lasted 5 min. After the generation of oxygen MNBs, water samples were immediately collected into a 500 mL beaker for DO measurement. And the DO sensor recorded data until the DO value was less than 100%. MNBs were generated under different water conditions, as shown in Table 1 and Table 2.

Table 1. Water conditions for the MNBs generation (Without surfactant).

	NaCl			
Concentration (g/L)	0.0	0.2	0.4	0.6
	0.8	1.0	2.0	3.0

Table 2. Water conditions for the MNB generation (Salinity was 0 g/L).

Surfactant	SDBS			
Concentration (g/L)	0.50	1.00	3.00	5.00

The size distribution of MNBs in water was analyzed under the surfactant concentration of 0 g/L and a salinity of 0 g/L. After the MNBs generation, samples were immediately collected for particle size analysis. The analysis work was finished within 90 s.

## 3 RESULTS AND DISCUSSION

### 3.1 Size distribution of the oxygen MNBs and DO in oxygen MNBs water

The size distribution of the oxygen MNBs, which was generated in deionized water, was shown in Fig.1. The diameter of oxygen MNBs clustered around the ranges of 26-172 nm and 1.635-6.540  $\mu m$ . The quantity and size of the MNBs affect their mass transfer efficiency. A large number of MNBs result in larger total surface area and increase the mass transfer flux from bubbles to solution, and smaller bubble size results in higher internal pressure and larger specific area (Xia and Hu, 2019).

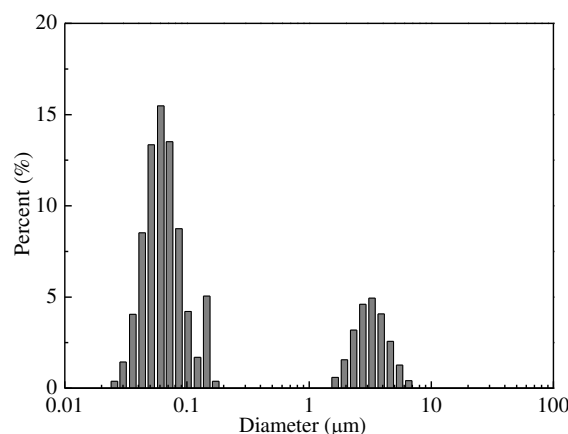


Fig.1. Size distribution of the oxygen MNBs.

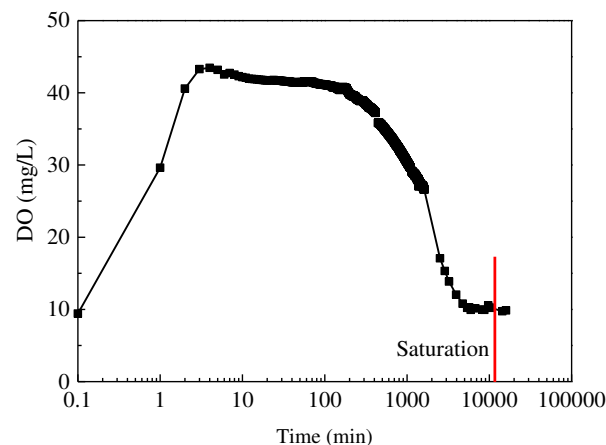


Fig.2. DO changes with time.

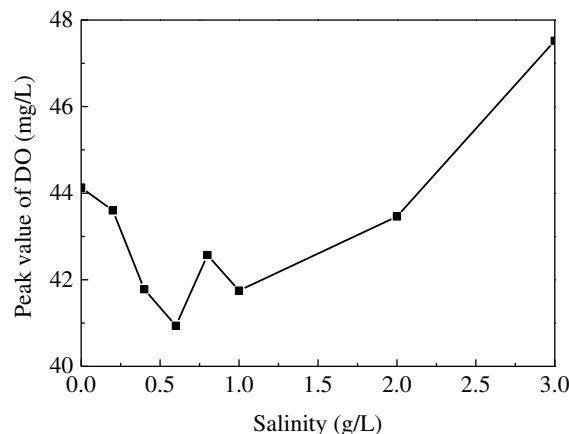
As can be seen in Fig.2, at the beginning of oxygen MNBs generation, the DO increased quickly with the formation and dissolution of a large number of oxygen MNBs. The concentration gradient of oxygen between water and atmospheric increased with the increase of DO in water. A relatively large concentration gradient led to an increase in the overflow rate of DO in water. Accordingly, the increase rate of DO in water slowed down gradually. Until the increase rate of DO and the overflow rate of oxygen in water reached equilibrium, the DO arrived at the peak value.

When the DO reached the peak value, the generation of oxygen MNBs was stopped. Because the number of MNBs no longer increased and the overflow rate of oxygen remained at a high level, the value of DO decreased rapidly. As the DO decreased, the concentration gradient of oxygen between water and atmosphere decreased. Smaller concentration gradient resulted lower overflow rate of oxygen and the variation rate of DO. When all MNBs were dissolved and the oxygen in water no longer overflowed, the DO reached a stable state. The saturation time of DO is the time that the DO decreases from the peak value (larger than 100%) to the stable state.

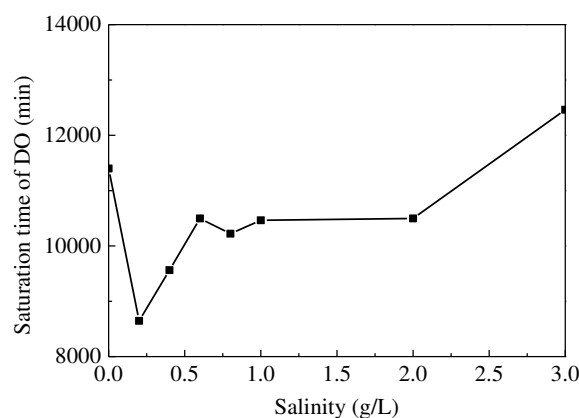
### 3.2 Size distribution of the oxygen MNBs and DO in oxygen MNBs water

As seen in Fig.3, the salinity had a significant impact on the mass transfer characteristics of oxygen MNBs. Fig.3(a) shows the peak values of DO with different salinity oxygen MNBs water. As a whole, the peak value of DO decreased with the increase of salinity of oxygen MNBs water. The peak value of DO in oxygen MNBs water with a salinity of 0 mg/L was 44.13 mg/L, and it was higher than that in the study of Li (2014). The reason for this phenomenon was possibly due to the difference of MNBs generator and generation conditions. In addition, the peak value of DO was 47.52 mg/L when the salinity was 3 g/L. It was 7.68% higher than that of oxygen MNBs water with the salinity of 0 g/L.

Fig.3(b) shows the effect of salinity on the saturation time of DO. An increase in the salinity of oxygen MNBs water led to a decrease in the saturation time of DO. When the salinity was 0 g/L, the saturation time of DO was 11400 min. The saturation time of DO in this study is consistent with the oxygen MNBs residence time of 10000 min (Li, 2014). When the salinity was 3.0 g/L, the saturation time of DO was 9.32% longer than that with the salinity of 0 g/L. Compared with the research results of Li (2014), the salinity of 3.0 g/L was beneficial to the mass transfer characteristics of MNBs, no matter what oxygen or air MNBs.



(a) Peak value of DO.



(b) Saturation time of DO

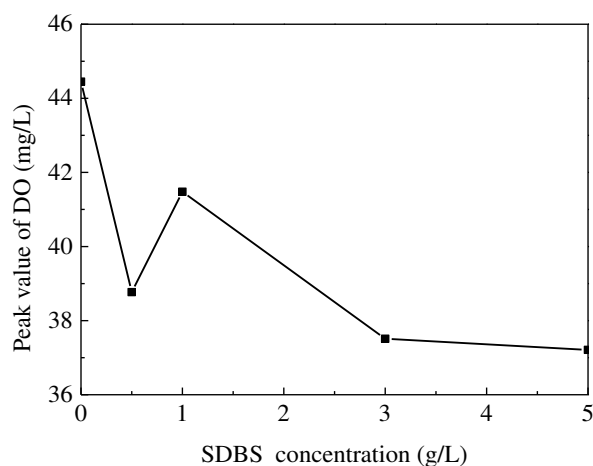
Fig.3 The effect of salinity on mass transfer characteristics of oxygen MNBs

### 3.3 The effect of surfactant on mass transfer characteristics of oxygen MNBs

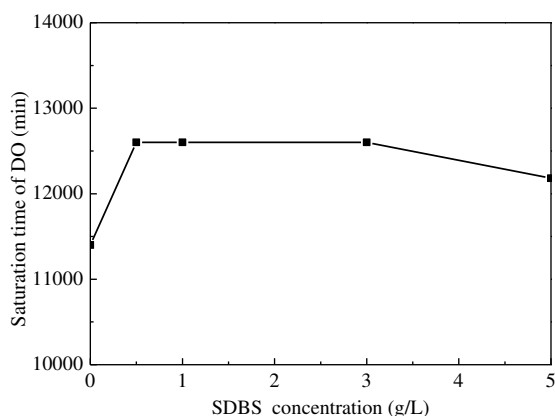
Fig.4 shows the effect of SDBS on the mass transfer characteristic of oxygen MNBs. As can be seen in Fig.4(a), the SDBS was harmful to the peak value of DO. SDBS is an anionic surfactant, which can increase the zeta potential of oxygen MNBs (Li, et al., 2014). With the increase of anionic surfactant concentration, the absolute value of zeta potential increased. Relatively high zeta potential reduced the peak value of DO of oxygen MNBs.

As shown in Fig.4(b), with the addition of SDBS, the saturation time of DO has been extended by approximately 10%. The reason was that the interface charge concentration increased with the increase of zeta potential on the surface of oxygen MNBs. Relatively large interface charge concentration resulted in an increase of gas dissolution resistance in oxygen MNBs. Thus, the mass transfer efficiency of oxygen MNBs reduced and oxygen MNBs residence time had been extended. Besides, the interface charge caused electrostatic repulsion between the MNBs, which reduced the coalescence of MNBs and extended the

residence time of MNBs (Jávor, et al. 2016).



(a) Peak value of DO.



(b) Saturation time of DO

Fig.4 The effect of SDBS on mass transfer characteristics of oxygen MNBs

## 4 CONCLUSIONS

In this paper, the oxygen mass transfer characteristics in oxygen MNBs water were analyzed. The effect of surfactant and salinity on the mass transfer characteristics of oxygen MNBs was examined through batch test. The main conclusions of this research are summarized as follows:

In deionized water, the oxygen MNBs size distributed around the ranges of 0.026-0.172  $\mu\text{m}$  and 1.635-6.540  $\mu\text{m}$ . The change of DO in oxygen MNBs water was the simultaneous effect of the dissolution of oxygen MNBs and the overflow of oxygen in the water.

When the salinity was between 0 g/L and 2 g/L, the mass transfer efficiency of oxygen MNBs was adversely affected by salinity. When the salinity was 3 g/L, the peak value of DO increased by 7.68% and the saturation time of DO was extended by 9.32%.

The addition of SDBS reduced the peak value of DO and extended the saturation time of DO by changing the interface potential of oxygen MNBs.

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