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Production of high dissolved O_2/O_3 with rotating wheel entraining gas method for environmental application

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Abstract. There is a significant demand to make various dissolved gases in water. However, the conventional aeration method shows low gas mass transfer rate and gas utilization efficiency. In this study, a novel rotating wheel entraining gas method was developed for making high dissolved O_2 and O_3 in water. It produced higher concentration and higher transfer rate of dissolved O_2 and O_3 than conventional bubble aeration method, especially almost 100% of gas transfer efficiency was achieved for O_3 in enclosed reactor. For application of rotating wheel entraining gas method, aerobic bio-reactor and membrane bio-reactor (MBR) were successfully used for treatment of domestic and pharmaceutical wastewater, respectively; and vacuum ultraviolet (VUV)/UV+O_3/O_2 reactors were well used for sterilization in air/water, removal of dust particles and toxic gases in air, and degradation of pesticide residue and sterilization on fruits and vegetables.

Keywords: rotating whee; entraining gas; dissolved ozone; dissolved oxygen; air purification; water treatment

1. Introduction

There is a significant need to make various dissolved gases (such as O_2, O_3 and CO_2, etc.) in a liquid. For example, dissolved oxygen (DO) is a basic requirement for aerobic microbe growth and metabolism in wastewater treatment process (Scott and Ollis 1995, Melin *et al*. 2006, Liao *et al*. 2011) and cell culture process (Newby *et al*. 2005, Zhang *et al*. 2008). Dissolved ozone alone or with UV are widely used for sterilization and antisepsis in food industry (Guzel-Seydim *et al*. 2004, Pascual *et al*. 2007) as well as removing odors, colors and organics in drinking water/ wastewater treatment processes (Camel and Bermond 1998, Zhou and Smith 2000, Meunier *et al*. 2006, Ratpukdi *et al*. 2010, Treguer *et al*. 2010). In addition, dissolved carbon dioxide is widely employed as an important air fertilizer for photosynthesis of green plants and algas (Tate and Payne 1991, Taticek *et al*. 1994).

The gas-liquid transfer process is generally accomplished through aeration (Gillot and Duit 2000, Kies *et al*. 2004, Kumar *et al*. 2011), such as macro/micro-bubble aeration, gas jet aeration, and surface aeration, etc. However, macro-bubble aeration and surface aeration processes are both difficult to get high concentrations of dissolved gas in liquid in a relatively short period, which

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shows low overall gas transfer coefficient and gas utilization efficiency (Kumar *et al*. 2011). Gas jet aeration generally produces strong shear force to go against the growth of microorganism, animal and plant cells (Kies *et al*. 2004). Although micro-bubble aeration shows relatively high gas transfer efficiency and utilization efficiency, the micro pores are easily blocked, which lead to high operation cost (Gillot and Duit 2000). To sum up, the development of new aeration method with high efficiency and low shear force is a significant industrial and agricultural demand, which is also a major engineering problem to be resolved urgently.

In this study, a novel multi-layer net rotating wheel aerator (Hui 2010) is designed and tested for making high dissolved gases (oxygen, ozone) in water compared with conventional micro-bubble aerator. In addition, coupled with UV radiation and membrane bioreactor (MBR) (Konieczny *et al*. 2006), this novel reactor was used for wastewater treatment, water reuse and drinking water purification, air purification, and fruit and vegetable cleaning processes.

2. Materials and methods

2.1 Instruments and materials

The multi-parameters water quality tester and test kit were supplied by Lovibond (Germany). Dissolved oxygen meter was purchased from Hamilton (Switzerland). Ozone generator was purchased from Hangzhou Jinhai Electronic Co., LTD. (China). The pH meter was purchased from Hangzhou Aulilong Instrument Co., LTD (China). Ozone prober was purchased from Shenzhen Yiyuntian Electronic Technology Co., LTD (China). Rotating wheels are made in our laboratory. UV light tube was purchased from Jiangsu Taicang Youweitaike Electronics Co., LTD. (China).

Pharmaceutical wastewater and domestic sewage were collected from Hangzhou Longda Xinke Biological Pharmaceutical Co., LTD (China). Other reagents used were analytical reagents or guaranteed reagents supplied by Beijing Chemical Co., LTD (China).

2.2 Experimental methods

2.2.1 Making dissolved O_2/O_3 by rotating wheel reactor

The different diameter towing wheels composed of multilayer reticulation were fixed in closed or open containers (as shown in Fig. 1). The wheel speed was adjusted by a motor and the liquid level was controlled around wheel center. A vacuum ultraviolet (VUV) tube (185~253.7 nm) and a drain pipe were installed at the bottom of the container. Furthermore, an additional UV tube (253.7 nm) was fixed on top of the closed container. Air or ozone above liquid level was transferred into water through the rotating action of the wheel to produce various high concentration and high stability of dissolved gases in water. In the same gas flow and environmental conditions, rotating wheel method was compared with aeration method in certain reaction time. Dissolved oxygen concentration in water was tested by DO electrode. The concentration of ozone in air was analyzed by ozone prober while the ozone concentration in water was tested by iodimetry titration method.

2.2.2 Application of rotating wheel reactor

Continuous operation of wheel reactor in closed or open spaces were selected, i) measuring the weight loss of the water every 4 hours in air purifier to study its humidification effect; ii) determination of the number of dust particles in air before and after 6 hours reaction, calculation of

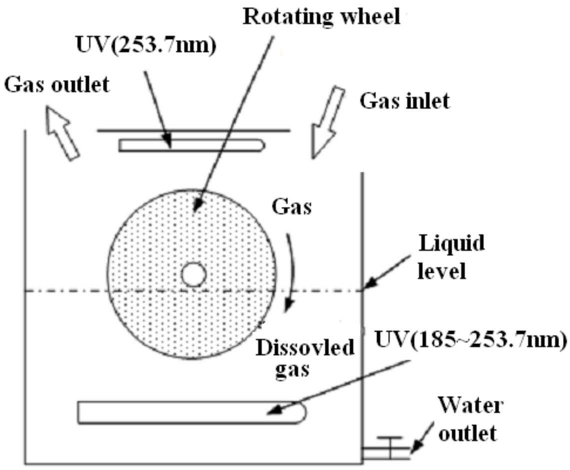


Fig. 1 Schematic diagram of rotating wheel reactor for manufacturing high concentration and high stability of dissolved gases in water

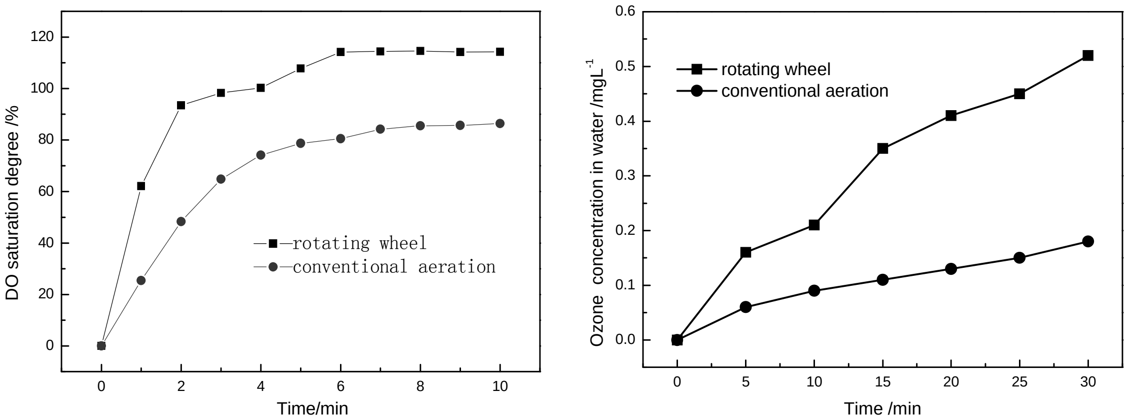
the removal rate of dust particles in air; iii) advanced oxidation processes (AOPs), in combination with different wavelengths of UV lamp and oxygen/ozone, can produce hydroxyl radicals and be used for the sterilization, degradation of formaldehyde, ammonia and pesticide, etc. in water and air; also evaluating the treatment effect of fruits and vegetables containing a certain concentration of pesticides; iv) using a wheel biological reactor for removal of COD, ammonia nitrogen, total phosphorus, total nitrogen in pharmaceutical wastewater or domestic sewage.

3. Results and discussion

3.1 Comparison of different gas transfer methods

In this work rotating wheel and aeration methods were used to deliver air/ozone into water, respectively. The results are shown in Fig. 2. Compared with aeration, the rotating wheel can make the dissolved oxygen saturation degree (DO%) increased rapidly to over 80% in 2 min (Fig. 2(a)), and can get super-saturated oxygen (DO% > 110%) in 5 min. For ozone transfer, ozone concentration in water using rotating wheel reached 0.52 mg/L, while ozone concentration in water using aeration only reached 0.18 mg/L in same energy consumption (Fig. 2(b)). In confined space, the ozone utilization efficiency of rotating wheel can reach close to 100%.

Márquez *et al*. (1994) and Kies *et al*. (2004) generally recognized that the transfer efficiency of gas into the water is relative to the contact area between the gas and the water. Bubbles generated by aeration show larger diameter and relatively small number. The large bubbles quickly rise to the water surface with short retention time, so the gas transfer efficiency and utilization efficiency are both low. While Hui (2010) invented arotating wheel aeration method, wherein the high shear force of network-structure rotating wheel can entrain ambient gas into water to produce large amounts of tiny bubbles, which can quickly dissolve in water before bursting on the water surface, resulting in production of stable high concentration of dissolved gases. In addition, the efficiency



(a) (b)

Fig. 2 Comparison of two gas transfer methods for manufacturing high stability of (a) dissolved oxygen; and (b) ozone in water

(a) (b)

Fig. 3 Pictures of (a) single rotating wheel lifting bioreactor; and (b) rotating wheel bioreactor combined with hollow fiber filtration system

of rotating wheel oxygen transfer is related to the material of the wheels, the pore diameter of the mesh structure, the surface physicochemical properties, the wheel rotating speed and other factors. The rotating wheel towing gas transfer technology suggests that there may present a new gas transfer mechanism.

3.2 Wastewater treatment with rotating wheel bio-reactor

A single rotating wheel lifting bioreactor (WBR) was carried out for domestic sewage treatment. The picture of the bioreactor was shown in Fig. 3(a). When the influent COD and ammonia were 200-400 mg/L and 20-40 mg/L, respectively, under the condition of temperature 20-30°C, HRT 4-6 h, DO 2-4 mg/L and initial pH 7-8, the effluent COD reached 30-60 mg/L and the ammonia 10 mg/L or less. This biological water treatment system can continuously and stably operate for 3 weeks, the effluent water qulity can consecutively reach the domestic sewage discharge standard of China (GB 18918-2002, shown in Table 1).

The rotating wheel bioreactor combined with hollow fiber filtration system (WMBR) was used for the pharmaceutical wastewater treatment. The picture of the bioreactor was shown in Fig. 3(b). When the influent COD was 200-300 mg/L, ammonia nitrogen 10-20 mg/L, temperature 20-30°C, DO 2-4 mg/L and HRT 4-6 h, the effluent water quality reached the standards of "fermented pharmaceutical industrial water pollutant discharge standards" (GB21903-2008, shown in Table 1). This system can continuously and stably run for 4-6 weeks.

3.3 Different disinfection processes with rotating wheel for water recovery

The pharmaceutical wastewater and domestic sewage after treatment can meet the discharge standard. To investigate water recovery for such as the irrigation systems and cleaning systems, high dissolved ozone or air through rotating wheel was combined with VUV, UV and other advanced oxidation processes for disinfection of the treated water. The results are shown in Table 2, the ozone combined with the vacuum ultraviolet process performed best with bacteria inactivation rate over 99.9%.

3.4 VUV/air process with rotating wheel for drinking water and air purification

Rotating wheel technology can manufacture high dissolved oxygen in water. Combined with VUV (185~253.7 nm) and dissolved oxygen, dissolved O_3, hydroxyl radicals (·OH) and other active oxygen radicals are produced in water for drinking water disinfection. The results are shown in Table 3. The bacteria removal rate was 100%. The nitrite and residual ozone concentration in water are less than 0.03 mg/L and 0.02 mg/L. Resudual chlorine, ferric and manganese were not detected. Therefore, this system may perform well on drinking water purification.

Rotating wheel reactor coupled with VUV light radiation was also used for purification of

Table 1 Performance of rotating wheel bioreactor for domestic sewage and pharmaceutical wastewater treatment

Parameters	Unit	WMBR			WBR		
		Influent	Effluent	Standard	Influent	Effluent	Standard
pH	-	7 - 8	6 - 8	6 - 9	7 - 8	6 - 9	6 - 9
COD	mg/L	200 - 300	< 40	< 100	200 - 400	30 - 60	< 60
SS	mg/L	50 - 100	< 4	< 60	-	-	< 20
NH_4-N	mg/L	10 - 20	< 5	< 25	20 - 40	< 10	< 15

Table 2 Comparison of various advanced oxidation processes for disinfection efficiency

Disinfection methods	Bacteria inactivation rate (%)
O_3 +VUV	> 99.9
O_3 +UV	98.8
O_3	98.6
VUV	98.9
UV	97.5

Table 3 Performance of rotating wheel reactor coupled with VUV radiation for drinking water purification

Effluent parameters	Values
Bacteria removal rate (%)	100
Nitrite content (mg/L)	< 0.03
Ozone content (mg/L)	< 0.02
increased pH value	< 0.2
Resudual chlorine, ferric and manganese (mg/L)	not detected

Table 4 Performance of rotating wheel reactor coupled with VUV radiation for air purification

Performance	Efficiency
Humidifying volume/mlh^{-1}	95
Removal of ammonia in air/%	85.3
Removal of bacteria in air/%	97.5
Removal of bacteria in water/%	100
Removal of formaldehyde in air/%	97.5
Removal of dust particles in air/%	71.3

Table 5 Performance of rotating wheel reactor with UV/O_3 for fruit and vegetable cleaning process

Performance	Results	
Bacterial removal rate/%	In water	98.7
	Leafy vegetables	99.3
	Stem vegetables	98.2
	Fruits	99.1
Nitrite output / mg L^{-1}	< 0.03	

polluted air, the performance of this reactor was shown in Table 4. This device can not only greatly kill the bacteria in water and air, but also can effectively remove ammonia, formaldehyde and dust particles in air. Furthermore, harmful ozone is undetectable in air. In addition, this device also has a function of humidification for air, which is more practical for air drying area.

3.5 Rotating wheel reactor with UV/O_3 for fruit and vegetable cleaning process

The rotating wheel reactor was used for ozone transfer into water. Combined with UV, it was used for fruit and vegetable cleaning process. The results are shown in Table 5. After 15 min purification, the bacteria removal rate in water and the fruits and vegetables surface was higher than 98%, no ozone was residual in air, and nitrite production was less than 0.03 mg/L (much less than the standard of GB8537-2008 which is less than 0.1 mg/L). Furthermore, the reactor can remove the residual pesticide on fruits and vegetables. According to national standards of technical design requirements “GB/T5009.199-2003”, TMYQ-108 pesticide residue detector was used to determine the organophosphorus or carbamate pesticide content level of in the sample by testing the acetylcholinesterase inhibition rate. The higher the enzyme inhibition rate, the lower the pesticide removal efficiency. The results are shown in Fig. 4. The enzyme inhibition rates of

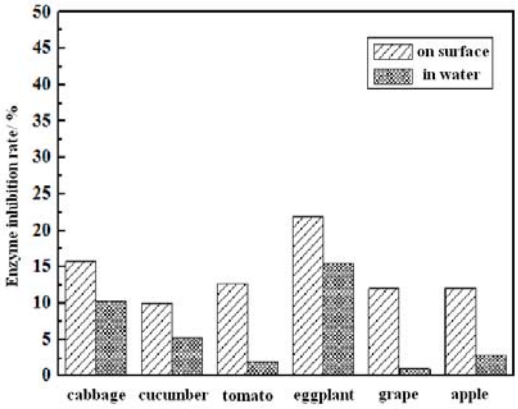


Fig. 4 Pesticide removal conditions of fruit and vegetable by rotating wheel reactor with UV/O_3

different fruits and vegetables both in water and on surface were less than 25%, which was lower than the specified standard (enzymatic inhibition rate < 50%).

4. Conclusions

In this study, a novel rotating wheel reactor is designed for making high dissolved gases (O_2 and O_3) in water. The oxygen and ozone were efficiently dissolved in water by the rotating wheel reactor. Further combined with the novel gas transfer process with biological process or UV radiation, this reactor has successfully been used for wastewater treatment, water recovery, drinking water disinfection, air purification, fruit and vegetable cleaning process. The new reactor has advantage of simple structure, low cost, high efficiency and promising application.

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