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Suspended particle effects on ClO_2/ultraviolet light combined disinfection of effluent

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Abstract: The concentration of suspended solids of effluent often varies in a wide range, therefore the dose of ultraviolet light (UV) in disinfection process needs to be adjusted to meet the disinfection criterion at a high frequency, and the desired disinfection effect is difficult to be ensured. The particles size and particle-associated fecal coliform (F.C.) contribution, and their influence on UV disinfection were investigated when ClO_2 and UV combined disinfection process was used. The results showed that suspended solids content had a major impact on UV disinfection efficiency, especially the large particle size fraction. Particles (D>10 μm) associated F. C. were difficult to be disinfected and were the main part of the tailings of F.C. inactivation curve. Pre-ClO_2 oxidation could reduce the number of particles in effluent, and make large particles decrease to small ones. Therefore, the influence of particles on UV disinfection could be reduced after pre-ClO_2 oxidation, and the resistance ability to particle loadings of combined process was enhanced. Moreover, the combined process has a lot of advantages, such as low toxicity, low operational/maintenance costs; it is also convenient to be established in the existing wastewater plant or the new planned one.

Keywords: effluent disinfection; bio-toxicity; UV disinfection; ClO_2/UV combined disinfection

Introduction

The secondary effluent of wastewater treatment plant should be disinfected to eliminate pathogenic protozoan cysts, bacteria species, and virus, before treated effluent discharge or reuse. UV disinfection has gained considerable popularity due to the fact that it imparts only energy to the water or wastewater without producing quantifiable amounts of known disinfectant by-products, as do chemical disinfectants (Ronald *et al.*, 2003; White, 1999).

Some studies (Emerick *et al.*, 1999; Frank *et al.*, 2002) show that the suspended solids content of wastewater has a major impact on UV disinfection efficiency. Because the activated sludge floc flows with the influent, and is in suspension in secondary clarifiers, suspended solids concentration in effluent often varies in a wide range. To satisfy disinfection criteria, UV disinfection doses should be adjusted, and as a result UV process is highly operational and maintenance-sensitive. Prior particles removal by coagulation or filtration is often used in wastewater treatment plants in west countries, if disinfected with UV process (Chiu *et al.*, 1999; Andreadakis *et al.*, 1999). In this case, more space and investment are required. Now, the disinfection by UV light radiation has not been widely used in China. Almost all of the constructed wastewater treatment plants in operation have used Cl_2 or ClO_2 disinfection process, and the Cl_2 or ClO_2 facilities have been installed. However, because of operation costs, many wastewater disinfection processes have not be run normally (Cheng *et al.*, 2003). Furthermore, awareness of the adverse health and environmental effects associated with Cl_2 or ClO_2 has led to serious consideration of doses control, which is negative to ensure the disinfection effect. All the above shows that it is in urgent need to find a high efficiency, relatively inexpensive and safe disinfection process for effluent.

In this paper, the ClO_2/UV disinfection process was brought forward. Pre-ClO_2 addition was used to oxidize the organic constituents within particles, and transform the large particle size fraction of wastewater to small fraction. Particles counting and size distribution measurements were conducted to investigate the relationship between particle size and UV disinfection effects. Furthermore, particle size contribution, particle-associated fecal coliform (F.C.) contribution of wastewater and disinfection efficiency of ClO_2 disinfection, UV and ClO_2/UV were studied respectively.

1 Materials and methods

1.1 Effluent characterization

The test water was taken from the effluent of Shenzhen Binhe WWTP using A/O process (300000 m^3/d). Table 1 shows the main wastewater characteristics. The experiment was conducted from February to August in 2005.

Table 1 Characteristics of the effluent from Binhe WWTP using A/O process

Parameter	COD, mg/L	NH_3-N, mg/L	SS, mg/L	F.C., MPN/L	pH	Water temperature, ℃
Aver.	28	18	13	2.4×10^6	7.1	26
Min.	20	14	7	7.2×10^5	6.8	24
Max.	38	22	18	5.4×10^6	7.5	28

Notes: SS. Suspended solid; F.C. fecal coliform; MPN. most probable number

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1.2 Experimental procedure

A collimated beam apparatus was specially constructed. A diagram of the collimated beam apparatus is shown in Fig.1. The UV dose and depth-averaged UV intensity within the Petri dish sample can be computed based on Beer's law (George and Franklin, 2003).

$$D = I_{ave} \times t \tag{1}$$

$$I_{ave} = I_0 \times \frac{(1 - e^{-2.303Ad})}{2.303Ad} \tag{2}$$

where D is the UV dose, mJ/cm^2; I_{ave} is the average UV intensity, mW/cm^2; t is the exposure time, s; I_0 is the average incident UV intensity at the water surface of the sample, mW/cm^2 (detected before test every time by UV intensity detection instrument); A is the absorbance, cm^{-1}; d is the depth of sample, cm.

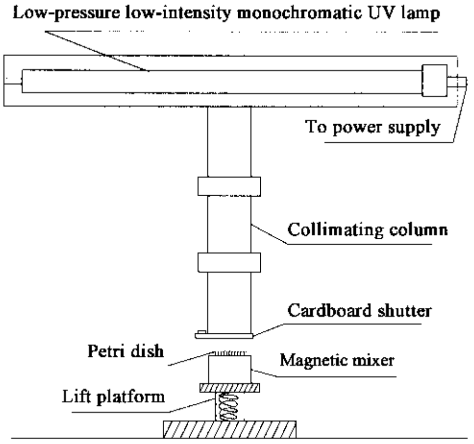

Fig.1 Diagram of collimated bream apparatus

Different doses of ClO_2 (0—15 mg/L) were added to effluent of A/O process, and mixed by magnetic mixer. At the end of contact time (30 min in this study), residual ClO_2 was detected, and a little excessive $NaSO_3$ was used to end up the disinfection reaction. Then, the samples by ClO_2 disinfected continued to be disinfected by UV apparatus (0—20 mJ/cm^2). Bio-toxicity and F.C. number of all samples were analyzed. The filtration/re-suspension technique was used to separate the particles into different size classes (Berman *et al.*, 1988). Different size filters (0.45—50 μm) were chosen for sequential filtration. Washing and rinsing solution, used to re-suspend particles, was generated by 0.45 μm filter, and disinfected at high temperature. The particles and their associated bacteria captured on each filter were re-suspended and mixed uniformly by the magnetic mixer.

1.3 Materials and analytical procedures

The stock ClO_2 solution was produced by mixing a hydrochloric acid solution and a sodium chlorite solution. The stock solution of ClO_2 was stored in dark at 4℃ and was standardized daily. Sodium thiosulfate (Na_2SO_3) solution of analytical grade, prepared every day, was used to dechlorinate ClO_2 residuals. Other chemical solutions were all prepared by analytical grade products and double deionized water.

The toxicity of samples was analyzed by reading light produced by luminescent bacteria (SDI, U.S.) after exposure to a test sample and the result was compared with the light output of a reagent blank. The degree of light loss percentage(an indication of metabolic inhibition in the test organisms) indicated the relative toxicity of the sample, classified into four grades as shown in Fig.2 (John and Ernest, 1999; Kaiser and Palabrica, 1991). Particle counting and size distribution were detected by particle counting apparatus (measuring capacity: 2 μm, IBR, U.S.). Residual ClO_2 was determined by ClO_2 residuals analyzer (measuring capacity: 0.05 mg/L). Facal coliform (F.C.) number and the chemical oxygen demand (COD) were measured according to the standard methods (U.S. APHA, 1998). All the analyses were started to make within 30 min after sample collection.

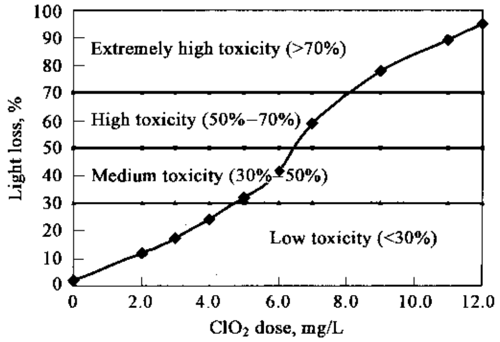

Fig.2 Effect of ClO_2 dosage on bio-toxicity of wastewater
F.C.=3.2×10^6 MPN (most probable number)/L; SS=16 mg/L; T=26.5℃

2 Results and discussion

2.1 Particles and associated F.C. distribution

Particle counting and size distribution, and F.C. distribution are shown in Table 2, from which it was found that 95% of all the particles have the size smaller than 10 μm. Of all the particles, 3—5 μm particles account for the most, and 2—3 μm particles take the second place. F.C. associated with particles smaller than 10 μm (free F.C. included) was 3.2×10^6, about 98% of all F.C.

2.2 Particle size effect on performance of UV disinfection

The influence of different size particles is listed in Fig.3 (UV dose was 20 mJ/cm^2). F.C. in samples filtered by particle size D=0.45 μm filters was considered to be free ones. The disinfection efficiency was calculated as the negative logarithm of the ratio of F.C. after disinfection (N_t) to that before disinfection (N_0).

Fig.3 shows that the larger particle size fraction

Table 2 Distribution of particles and facal coliform (F.C.) of secondary effluent

Particles size, μm	<2[a]	2—3	3—5	5—10	10—20	20—30	30—50	>50	Total
SS distribution, mg/L	5	3	4	5	1	-[b]	-[b]	-[b]	18
Particle counting, particle/L	-[b]	6910	16450	5410	980	200	120	30	30100[c]
Particle counting ratio[b], %	-[b]	22.9	54.7	17.9	3.2	0.7	0.4	0.1	100[c]
F.C. contribution[c], MPN/L	1.9×10^6	4.5×10^5	6.9×10^5	2.4×10^5	1.2×10^4	4.2×10^3	6.4×10^2	1.6×10^2	3.3×10^6
F.C. contribution, %	57.6	13.6	20.9	7.3	0.3	0.1	0.01	0.004	100

Notes: F.C.=3.3×10^6 MPN/L, SS=18 mg/L, T = 25.5℃; a. Free F.C. included; b. the weight and number of particles could not be detected; c. the particles counting ratio is justly aim at particles with the size D>2 μm

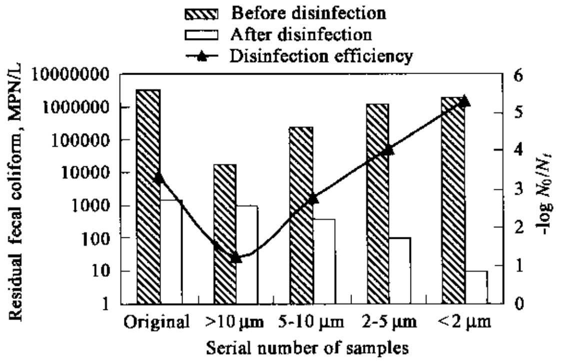

Fig.3 Effect of particle size on UV disinfection

of effluent ($D\geq10$ μm) consistently produced a lower efficiency than the smaller fractions (D: 5—10 μm and D: 2—5 μm), and the efficiency of three were 1.23, 2.78 and 4.1 log respectively. The free F.C. was the easiest to be disinfected, and the efficiency of which was more than 5.28 log. Although particles $D\geq$ 10 μm associated F.C. were 1.7×10^4, about justly 0.5% of all F.C. of effluent (Table 2), this part F.C. was important for the tailings of F.C. inactivation curve. The result is close to the research of Emerick *et al.* (1999). Total F.C. after UV disinfection was 1.5×10^3 MPN/L, and the F.C. from $D\geq10$ μm particles was 10^3 MPN/L, about 66.7% of all. So for UV disinfection process, it is important to control particle concentration, especially $D\geq10$ μm fraction.

Even through SS concentrations of different effluent samples were similar, the particle distribution of them will have significant differences because of the different treatment processes before disinfection. Therefore, the influence of particle size may explain why traditional solid measurements (total weight of suspended solid measurements) do not provide accurate prediction of UV disinfection. To ensure the disinfection efficiency in the UV disinfection, the particle counting apparatus is preferable to traditional solid measurement.

2.3 Dose of ClO_2 and UV process alone

Because the lifecycle in water and resistance of F.C. are similar to that of pathogenic intestinal bacteria, F.C. is commonly used to reflect the disinfection efficiency. The F.C. disinfection effects with respective ClO_2 and UV are shown as Fig.4. The disinfection standard is in reference to 1A class standard of Chinese National Integrated Wastewater Discharge Standard (GB81918-20020), which is 1000 MPN/L of F.C. The average of F.C. within effluent before disinfection was 2.4×10^6, the log inactivation was about 3.4 log to satisfy the level of 1000 MPN/L of F.C. Fig.4 shows that ClO_2 disinfection C_Rt (t is contact time, C_R is residual ClO_2 concentration after contract time) for this disinfection effect was 75(mg·min)/L, and relative initial ClO_2 dose was about 5 mg/L. And UV dose with the same disinfection effect was 25 mJ/cm^2.

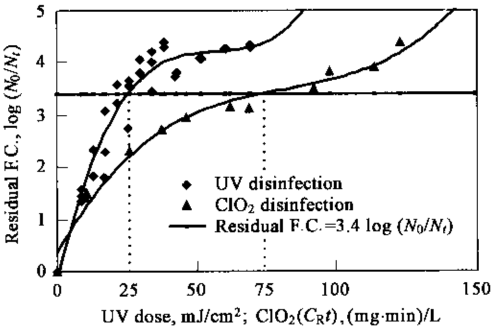

Fig.4 Inactivation of F.C. with respective UV and ClO_2 disinfection

2.4 Dose of ClO_2/ UV combined process

The ClO_2 dose of ClO_2/UV disinfection was in reference to bio-toxicity after ClO_2 disinfection (including ClO_2 disinfection and then completely dechlorination, same in the following of this paper). The toxicity is shown in Fig.2. It can be seen that the bio-toxicity of wastewater at ClO_2 dose of 4 mg/L was increased to 24%, which was close to the upper limit of low toxicity. Therefore, ClO_2 dose of 3 mg/L was used in the ClO_2/UV disinfection process.

The samples were first disinfected with ClO_2 for 30 min, then continued to be disinfected by different doses of UV. The total disinfection results are shown in Table 3. It can be found ClO_2 and UV disinfection dose of 3 mg/L, 6 mJ/cm^2 could meet the selected F.C. standard. Dechlorination was recommended before UV disinfection, not only to avoid the erosion of residual ClO_2 to UV fittings, but to decrease the bio-toxicity of disinfected wastewater.

Table 3 Inactivation of fecal coliform (F.C.) with ClO_2/UV process

ClO_2 dose, mg/L	UV dose, mJ/cm^2	Residual F.C., MPN/L	Inactivation efficiency, -log(N_t/N_0)
0	0	2600000 (N_0)	-
3	2	4600	2.78
3	4	1800	3.19
3	6	700	3.60
3	8	400	3.84
3	10	150	3.27
3	12	40	3.85

Notes: F.C.=2.6×10^6 MPN/L; SS=16 mg/L; T = 26.5℃

2.5 Particle distribution after ClO_2 disinfection

Both the particle size and weight distribution, at the end of 30 min contact after 3 mg/L ClO_2 disinfection, are shown in Table 4.

The difference between Table 2 and Table 4 shows that (1) SS concentration decreased slightly from 18 to 16 mg/L after chlorination; (2) the total number of particles D>2 μm was decreased from 30100 to 19643 particle/L; and the numbers of large particles decreased more evidently than the small ones. The total number of D>10 μm decreased by 65% (from 1330 to 450 particle/L), but the total number of particles D<10 μm decreased 33% (from 28770 to 19193 particle/L). The size of main particles of samples before chlorination is 3—5 μm, however that after chlorination is 2—3 μm. It can be explained that pre-ClO_2 addition can oxidize the organic matters within the particles, and made them split into small ones and then made the relatively smaller particles decomposed to dissolved state. As a result, both the total number of particles and the large ones descend, and the larger particles influencing on UV disinfection was reduced.

Table 4 Particle distribution and weight after ClO_2 addition

Particles size, μm	<2	2—3	3—5	5—10	10—20	20—30	30—50	>50	Total
SS distribution, mg/L	9	3	3	2	-	-	-	-	16
Particle counting, particle/L	-	10661	6182	2350	300	130	20	0	28770
Particle counting ratio, %	-	54.3	31.5	11.9	1.5	0.6	0.1	0	100

Notes: F.C.=3.3×10^6 MPN/L; SS=18 mg/L; T = 24.5℃

2.6 Resistance to particle loadings of combined disinfection process

A serial of samples with different particle concentrations before overflow weir of secondary clarifiers were selected, and SS effect on the three disinfection processes was studied and the result is shown in Fig.5. Although particle counting parameter was preferred to adjust the disinfection dose, SS parameter was used to reflect the total content of the particles within the effluent here. Fig.5 shows that UV disinfection efficiency decreased with the increase of SS, and both the disinfection efficiencies of ClO_2 and ClO_2/UV processes were similar which had a little variation. It is obvious that the resistance ability to particle loadings of ClO_2/UV disinfection process was better than UV process alone.

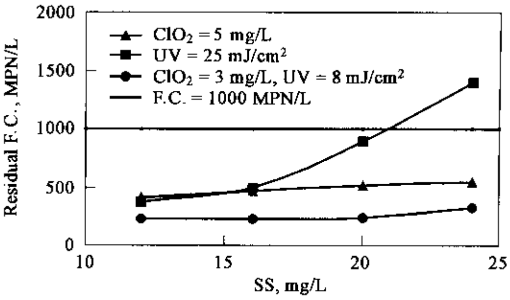

Fig.5 Effect of SS on three disinfection processes
F.C.=3.4×10^6 MPN/L; T = 26.5℃

2.7 Economic analysis

The economic analysis of ClO_2 disinfection, UV, and combined ClO_2/UV disinfection was calculated in Table 5. The disinfection objective was 1000 MPN/L, and disinfection doses were all from laboratory results. Capital cost includes the expense of equipments and relative buildings, and operational cost includes chemical disinfectants expense, manpower expense and equipment depreciation. The results show that the combined ClO_2/UV disinfection process is more expensive than UV process alone, but inexpensive than ClO_2 disinfection with the same disinfection results.

Table 5 Economic analysis of ClO_2/UV disinfection process

Process	Dose	Capital construction fund, USD	Operational fund, USD/a	Operational cost [a], USD/m^3
ClO_2	5 mg/L	50620	294190	0.0110
UV	25 mJ/cm^2	28100	18300	0.0005
ClO_2/UV	3 mg L^{-1}/6 mJ cm^{-2}	28400/17800[b]	177400/12800	0.0070

Notes: a. Dechlorination cost was not included in the capital construction fund, operational fund, but in the calculation of operational cost, experiential equation: $S_{ClO_2\ \mathrm{disinfection/dechlorination}} = 1.4\ S_{ClO_2\ \mathrm{dininfection}}$ was used to revise the results; b. the left and right of "/" were the respective cost for ClO_2 and UV of combined process

3 Conclusions

Suspended solid size has a major impact on UV disinfection efficiency, and the large particle size fraction of effluent consistently produced a lower efficiency than the smaller ones. In order to ensure high disinfection efficiency, wastewater disinfected UV process should prefer particle counting apparatus to traditional solids measurements. Pre-ClO_2 addition oxidizes the organic matters within the particles, and make large particles decrease to small ones and then the relatively smaller particles are further transformed into dissolved state. As a result, the total number of particles in effluent decreases.

The combined ClO_2/UV disinfection process has a higher resistance ability to particle loadings than UV process alone, and its bio-toxicity is much lower than ClO_2 process with same disinfection efficiency. Even though the operational cost of combined process is less than that of ClO_2 process. Furthermore, the combined process is easy to establish in the constructed and operated wastewater plants as well as those to be constructed and operated. For the wastewater plants that have constructed ClO_2 process, UV lamps can be installed at the end of dechlorination contact facilities, and need no other units. For a newly constructed wastewater treatment plant, the combined process requires less footprint and capital cost than that of traditional ClO_2 process, and has better disinfection efficiency than UV process.

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