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Flocculation control study based on fractal theory*

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Abstract: A study on flocculation control based on fractal theory was carried out. Optimization test of chemical coagulant dosage confirmed that the fractal dimension could reflect the flocculation degree and settling characteristics of aggregates and the good correlation with the turbidity of settled effluent. So that the fractal dimension can be used as the major parameter for flocculation system control and achieve self-acting adjustment of chemical coagulant dosage. The fractal dimension flocculation control system was used for further study carried out on the effects of various flocculation parameters, among which are the dependency relationship among aggregates fractal dimension, chemical coagulant dosage, and turbidity of settled effluent under the conditions of variable water quality and quantity. And basic experimental data were obtained for establishing the chemical coagulant dosage control model mainly based on aggregates fractal dimension.

Key words: Aggregates, Flocculation control, Fractal dimension, Image analysis, Turbidity
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INTRODUCTION

Among methods used for flocculation control by chemical coagulant dosage, are mathematical model, on-site test equipment simulation, stream current measurement, aggregates equivalent diameter detection, etc. (Li and Wilkinson, 2005; Werner *et al.*, 2001); and many apparatus such as zeta potentiometer, stream current detector, photometric dispersion analyzer, particle size analyzer, etc. (Chakraborti *et al.*, 2003; Huang, 2005; Rossi *et al.*, 2002; Swift *et al.*, 2004) were applied. However, the development tendency of flocculation control is presently focused on the aggregates characteristic parameter method and the digital image analysis technology.

The digital image analysis technology is mainly by means of CCD (Charge-Coupled Device) linked with a computer to capture the digital image of aggregated particles, wherein their geometrical properties and size distributions are collected, with the information collected being important enough to be introduced from the image analysis for flocculation control as the major control characteristic parameter of aggregates. And the vital factor is considered to have favorable dependence relationship with the settled effluent turbidity. Based on this relationship, the analysis of its variation is used for determining the chemical coagulant dosage to achieve stable and good quality of settled effluent, and the objective decreasing both dosage and operation costs will be achieved.

The congregation from small particles to larger ones is a process of considerable importance. The resulted aggregated particles have a random and complicated structure with low average density. Such particle systems are often described by qualitative terms such as wispy, ramified, or tenuous. Moreover, recent study showed that, in reality, the aggregates consist of multi-branched structure that is not con-

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sistent with the description by the classical Euclidean geometry. In the past 2~3 decades, a new geometry, namely fractal geometry, developed by Mandelbrot for understanding and describing many of these random structures and processes (Chakraborti *et al*., 2003). Fractal geometry is concerned with geometric scaling relationships and the symmetries associated with them. It has been used to embellish the morphology of highly irregular objects imbedded onto two and three-dimensional space and is defined here as two and three-dimensional fractal dimensions. The fractal concept has provided a new way for describing aggregates geometry and physical properties such as density, porosity, and settling velocity (Kostoglou and Konstandopoulos, 2001; Tang *et al*., 2000). Thus, aggregates and their formation are described quantitatively.

In this study advanced image capturing and recognizing technologies were employed. Image analysis was used to help calculation of the fractal dimension of aggregates while their configuration and structure are directly and numerically denoted. In the interest of aggregates fractal dimension regarded as the major control characteristic parameter for flocculation control, the correlation between the parameter and the turbidity of settled effluent was investigated at different dosages of chemical coagulant. And their variations under different conditions of water quality and quantity were further investigated. The main goal of this study was through experimental study to determine the feasibility of applying aggregates fractal dimension for flocculation control and to determine settled sediment evolution with variable water quality and quantity. Based on the test results, the developed chemical coagulant dosage control model and its automatic-adding system are proposed to be used in the flocculation process.

METHODS

Quality of source water

The source water used in this test was taken from a reservoir in Shenzhen, China, characterized by low turbidity, high algae content and organic micro-pollutants, as shown in Table 1.

Table 1 Quality of source water (sampled from June 2003 to June 2004)

Parameter	Max.	Min.	Ave.
Temperature (°C)	31.0	14.5	22.3
pH	7.44	6.86	7.12
Turbidity (NTU)	21.60	1.70	7.95
,Alkalinity* (mg/L)	28.80	5.71	24.66
,TP (mg/L)	0.29	0.02	0.16
,NH_3-N (mg/L)	0.27	0.02	0.14
NO_2^--N (mg/L)	0.046	0.004	0.021
NO_3^--N (mg/L)	3.60	0.30	2.13
,TN (mg/L)	3.8	0.5	2.1
,Algae ($\times10^4$ L^{-1})	2580	297	1217
,DO (mg/L)	9.72	6.44	8.00
,BOD_5 (mg/L)	3.5	<2.0	−
,IMn (mg/L)	3.20	0.90	1.80
,UV_{254} (cm^{-1})	0.1294	0.0240	0.0488

* were calculated in terms of $CaCO_3$; TP: Total phosphorus; TN: Total nitrogen; DO: Dissolved oxygen; BOD_5: Biochemical oxygen demand (5 d)

Pilot plant

The trial was carried out in a pilot plant with capacity of 3.0 m^3/h. The pilot-scale plant consisted of mixing basin, perforated and rotational flow flocculation basin, and tube type lamellar settler, as shown in Fig.1. Poly-aluminum chloride (PAC, in which Al_2O_3 content accounted for 10% in weight) was dosed in the mixing basin entrance, and then mixed with the influent from the hydrodynamic and mechanical modes. The whole mixing time was about 6 s. The flocculation basin was separated into six compartments that take multilevel serial arrangements. The flocculation basin effective depth was 0.72~1.01 m, and the whole flocculation time was 23 min. In the tubular settler, the up-flow rate of the clear-water area was 1.38 mm/s; that in the tube was 1.60 mm/s, and

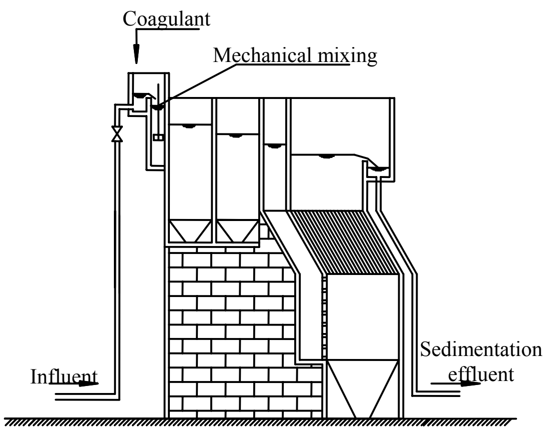

Fig.1 Process flow diagram of pilot plant

the sedimentation time was 36 min. The chemical sludge was discharged from the funneled bottom. The main units of the pilot plant used during the trial are listed in Table 2.

In these units, video frequency photo-fittings were applied to collect the optical reproduction of the aggregates image in the water. And then the digital information of the image was transmitted through the DH-CG 400 block into a computer processing, image signal translation, and analysis. Photographs of aggregates were displayed on-line and their fractal dimensions in real-time were calculated. The video frequency photo-fittings were set at 20 cm below water level in the flocculation basin. The application of the above units enables dynamic analysis of the aggregates structure and monitoring of the flocculation process.

Computational methods

To make use of aggregates photograph, a parameter, namely two-dimensional fractal dimension (D_f) was derived from the logarithmic correlation between their projection areas (A) and perimeters (P). D_f represents average significance of all aggregates in the photograph. The correlation equations were as follows:

$$A \propto P^{D_f} \quad (1)$$

$$\lg A \propto D_f \lg P \quad (2)$$

In Eq.(2), D_f is calculated as the slope of a plot of lg$A$ divided by lg$P$. According to fractal theory, the geometry character of aggregates differs from an ordinary area-perimeter relationship only in that the power coefficient D_f is no longer limited to integers.

The photograph of aggregates taken by video frequency photo-fittings is shown in Fig.2, and the corresponding coordinate drawing from the fractal dimension calculation is shown in Fig.3.

RESULTS AND DISCUSSION

Influence of PAC dosage

The evolution of aggregates fractal dimensions with flocculation time for different PAC dosages is shown in Fig.4.

In the flocculation process initial phase, particles collided with one another to form micro-aggregates, the structure of which was compact because of the strong stream turbulence. Consequently, the aggregates acquired bigger fractal dimension. With the advance of reaction time, the flow velocity was grad-

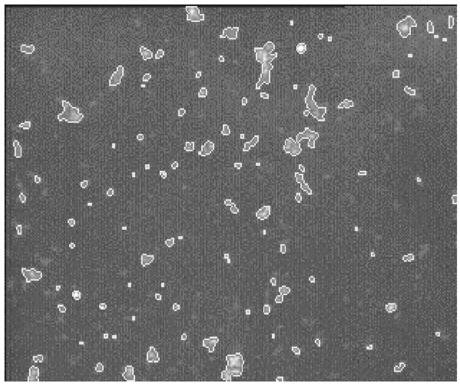

Fig.2 Photograph of aggregates

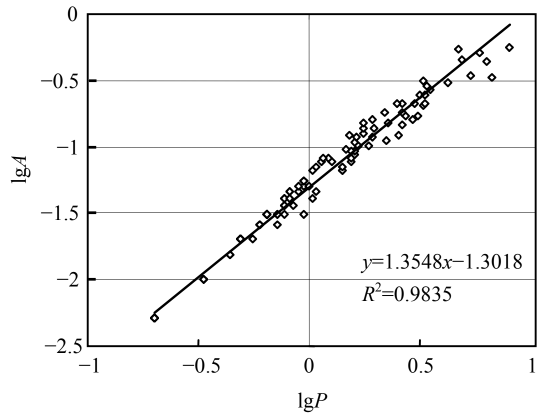

Fig.3 Fractal dimension calculation

Table 2 Main units of pilot plant

Number	Name	Specification	Remark
1	Dosage pump	LMI P046-3587	LPH 2.2, BAR 17.3
2	Mixer	JJ-90	0~2, 600 r/min
3	Turbidity meter	HACH 1720D	
4	Video frequency photo-fittings		Design and made by us
5	Image block	DH-CG 400	
6	Computer		On-line monitoring and image analysis

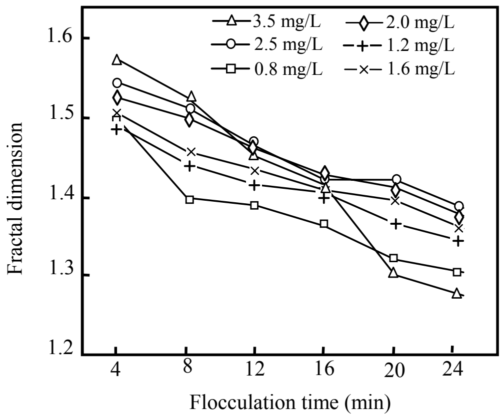

Fig.4 Fractal dimension evolution with flocculation time for variable PAC dosages

ually reduced while the colloid particles began to agglomerate and grow. The bigger the aggregates size, the lower their density. In the final phase of the flocculation process, the bigger and more open aggregates had smaller fractal dimension which gradually decreased, and its evolution clearly reflected the variation of aggregates structure during the course of flocculation. Furthermore, the fractal dimensions of aggregates exhibited the same evolutions for variable PAC dosages.

It is also obvious from Fig.4 that with the increase of PAC dosage these curves gradually rose, but fell sharply at dosage point of 3.5 mg/L resulted from the excessive dosage of PAC and its fractal dimension of final-forming aggregates was even below that of the least chemical coagulant dosage of 0.8 mg/L. Correspondingly, the structures of aggregates went through a course of development from more closed to looser with the increase of PAC dosage. According to this development, higher density aggregates were formed when the PAC dosage was increased to a certain extent. As a result, the aggregates were characterized by higher settling velocity necessary for achieving high turbidity removal. When the PAC dosage was increased over the appropriate limit, the structure of aggregates became extraordinarily loose.

Statistical analysis of the moving ranges of fractal dimensions related to different PAC dosages are shown in Table 3. For this reservoir source water, the fractal dimensions of aggregates were typically 1.2255~1.5251.

In the flocculation process, the different structures of aggregates are attributable to the different reaction mechanism. When the dosage of PAC did not reach the excessive point of 3.5 mg/L, the formation of aggregates mainly depended on the actions of adsorption and electron neutralization; when PAC was excessively dosed, the wrapping and sweeping actions were the chief mechanisms that caused the formation of reticulate-structure aggregates that led their fractal dimensions decreasing to a great extent. This was proved in other numerical and experimental studies (Meakin, 1988; Thieme and Niemeyer, 1996). Therefore, the fractal dimension can be used as an identification parameter to predict the turning point of aggregates formation and structure variation.

The evolutions of aggregates fractal dimension and settled effluent turbidity for different PAC dosages are shown in Fig.5. In the test, when the video frequency photo-fittings were installed in the fourth flocculation basin, the best fluid state was achieved in terms of steady stream and timely renewal. Therefore, the fractal dimension of aggregates from the fourth flocculation basin was used for studying the correlation between aggregates fractal dimension and settled effluent turbidity.

From Fig.5, it is found that with the increase of PAC dosage the fractal dimension of aggregates gently ascended while the turbidity of settled effluent de-

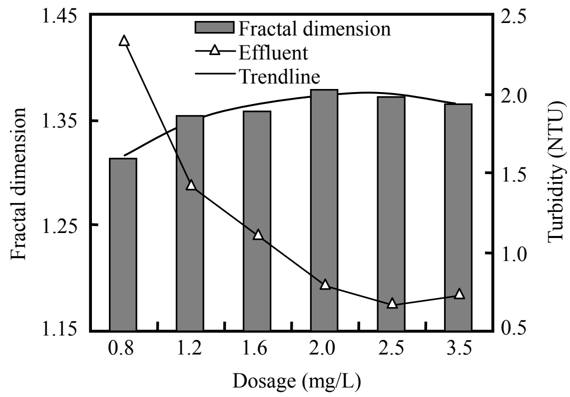

Fig.5 Fractal dimension and turbidity evolutions for variable PAC dosages

Table 3 Fractal dimensions for different PAC dosages

Dosage (mg/L)	0.8	1.2	1.6	2.0	2.5	3.5
Range	1.2553~1.4503	1.2950~1.4392	1.3107~1.4564	1.3251~1.4755	1.3359~1.4958	1.2255~1.5251

scended remarkably from 2.325 NTU at PAC dosage of 0.8 mg/L to 0.660 NTU at PAC dosage of 2.5 mg/L. And when the PAC dosage was excessive, the fractal dimension declined and the settled effluent turbidity rose. Accordingly, there existed the good dependency relationship between the fractal dimension of aggregates and the turbidity of settled effluent. Namely, the more closed the structure of aggregates, the lower the settled effluent turbidity, and vice versa.

Corresponding to the optimal removal of turbidity, the removal of other water quality parameters is listed in Table 4. The optimal removal effect was achieved at 2.5 mg/L PAC dosage, while the fractal dimension of aggregates was 1.3722.

Table 4 Water quality data at optimal turbidity removal

Parameter	Influent	Settled effluent	Removal efficiency (%)
Turbidity (NTU)	6.620	0.660	90.0
IMn (mg/L)	1.64	1.03	37.2
UV_{254} (cm^{-1})	0.0492	0.0226	54.1
TOC (mg/L)	2.22	1.56	29.7
Algae ($\times 10^4$ L^{-1})	214	36	83.2
pH	6.98	7.13	–

TOC: Total organic carbon

The above test and analytical results showed that the fractal dimension can favorably reflect aggregates flocculation degree and settling characteristics. Furthermore, the good correlation between fractal dimension and settled effluent turbidity was found for different dosages of chemical coagulant. By analysis of the fractal dimension variation, the optimal chemical coagulant dosage was found to occur simultaneously with the formation of more compact aggregates and higher turbidity removal.

Influence of water quantity

During the test period, the evolutions of aggregates fractal dimension obtained from the fourth flocculation basin and settled effluent turbidity are shown in Fig.6 and Fig.7 under the conditions of variable water quantity, which were the designed water flow rate of ±10%, ±20%, ±30%.

In this part of the test, there were two different cases for PAC dosing under different water quantity. The first one, as shown in Fig.6, varied water quantity while total PAC dosage was kept constant. In this case, the PAC concentration was subject to change. The second case, as shown in Fig.7, varied water quantity while PAC concentration was kept constant. In this case, its dosing amount was correspondingly altered with the variation of water quantity. The dosing of chemical coagulant PAC was employed to implement aim of 1.0 NTU of the settled effluent. And relevant to this objective, the adding amount and concentration of PAC was 32 ml/min and 1.6 mg/L, respectively, on the design scale of 3.0 m^3/h.

Fig.6 and Fig.7 show obviously that the fractal dimension of aggregates near the design scale was lower, but varied with the increase and decrease of water quantity. The fractal dimension went through an evolution valley with the water quantity variation from –30% to +30% of design scale. It implied that aggregates have tighter structure denoted by fractal dimension with water quantity variation. However, the tendency of fractal dimension variation had some differences for the two PAC dosing cases. It was found that the location of the valley basically occurred at the middle of 3.0 m^3/h and 3.3 m^3/h in Fig.6 while it occurred at around 2.7 m^3/h in Fig.7. Moreover, the turbidity of settled effluent followed the va-

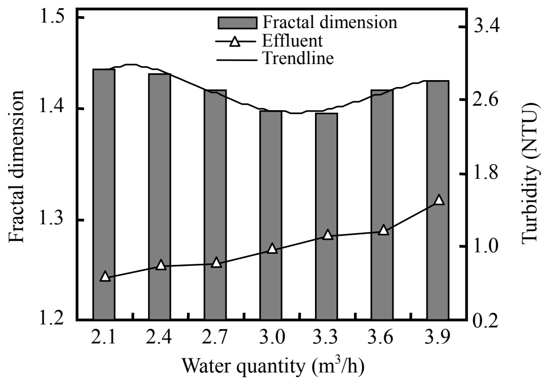

Fig.6 Fractal dimension and turbidity evolutions for variable water quantity and PAC concentrations

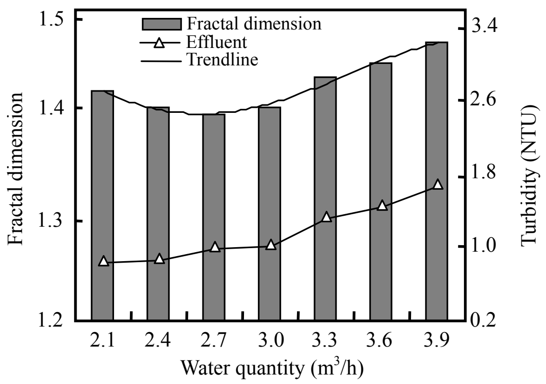

Fig.7 Fractal dimension and turbidity evolutions for variable water quantity and PAC dosages

riation law different from that of the fractal dimension, and gradually increased with the increase of water quantity from –30% to +30% of design scale all along.

For the first case, Fig.6, total PAC dosage was invariable, thus the concentration of PAC increased with the decrease of water flow rate, so that higher fractal dimensions of aggregates were achieved. On the other hand, the decrease of water flow rate resulted in the decrease of settling velocity and the prolonging of sedimentation time. As a result, higher settled aggregates removal efficiency was attained. On the contrary, the water quantity increase that decreased PAC dosing concentration enhanced the flow velocity and mixing intensity, and shortened the sedimentation time. So that aggregates structure became more compact and fractal dimension became bigger when the turbulent current was stronger; but the settled effluent removal efficiency was poor and the effluent turbidity was higher. During the test period, this phenomenon could be clearly observed at the computer interface, in which the sub-aqueous aggregates that were more became brighter with the increase of water quantity.

And the second case, as shown in Fig.7, was that the PAC concentration was constant while water flow rate changed. For this case, the stream intensity in the flocculation basin and deposition condition in the tubular settler was primary influence factors. On the left of Fig.7, the fractal dimension rises slightly, but this trend was not comparatively distinct from and almost reverse to that of the first case. On the right, the decrease of water quantity decreasing current turbulence insignificantly worked on aggregates fractal dimension, whereas the increase of water quantity increase current turbulence greatly influenced on it, which requires further study. Further comparison between Fig.6 and Fig.7 showed that if we eliminate the impact of stream variation induced by altering water quantity, the increase of PAC concentration would increase aggregates fractal dimension.

In this part related to the variation of water quantity, the movement of the aggregates structure and settling characteristics were quantitatively described. Regarding the relationship between them, when reducing water quantity the fractal dimension and settled effluent turbidity exhibited good dependency relationship according to the above mentioned phenomenon that the settled effluent turbidity decreased with increasing fractal dimension. When water quantity was increased their evolution relationship behaved like that with increase of fractal dimension the settled effluent turbidity rose as well. Therefore, flocculation control system based on the fractal dimension of aggregates can be set up as flux control parameter to achieve the target value of fractal dimension for alleviating the influence of water quantity fluctuation. And the feedback from the turbidity of settled effluent should be considered in this control system, too.

CONCLUSION

Based on fractal theory, this study uses two-dimensional fractal dimension to quantitatively describe the configuration and structure properties of aggregated particles of reservoir source water characterized by low turbidity, high algae content, and organic micro-pollutants. For different PAC dosages the variations of fractal dimension all exhibited gradual decrease with flocculation time and were generally 1.2255~1.5251. The fractal dimension typically reflects the flocculation degree of aggregates and their settling characteristics. Moreover, the pilot plant experiment further confirmed that the good correlation exists in the fractal dimension of aggregates and the turbidity of settled effluent for variable PAC dosages: the fractal dimension increases with the increase of PAC dosage restricted to a certain extent (<2.5 mg/L) while the settled effluent turbidity decreases. Accordingly, it is feasible to utilize fractal dimension as the major characteristic parameter in automatic control on the chemical coagulant dosage.

The flocculation control system should primarily consider its adaptability to water quality and quantity fluctuations. The effects of various water qualities on flocculation are directly reflected on the variation of aggregates fractal dimension. Consequently, the single parameter, namely fractal dimension, can accomplish the adjustment and fitting of the variation of water quality. For the variation of water quantity, the fractal dimension control system still requires the flux control parameter and settled effluent turbidity feedback alleviating the variation of deposition running condition.

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