Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 21(2009) 1059–1065
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Impact of dynamic distribution of floc particles on flocculation effect

NAN Jun*, HE Weipeng, SONG Xinin, LI Guibai

State Key Laboratory of Urban Water Resource and Environment, School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, China. E-mail: nanjun11@163.com

Received 11 September 2008; revised 02 December 2008; accepted 17 December 2008

Abstract

Polyaluminum chloride (PAC) was used as coagulant and suspended particles in kaolin water. Online instruments including turbidimeter and particle counter were used to monitor the flocculation process. An evaluation model for demonstrating the impact on the flocculation effect was established based on the multiple linear regression analysis method. The parameter of the index weight of channels quantitatively described how the variation of floc particle population in different size ranges cause the decrement of turbidity. The study showed that the floc particles in different size ranges contributed differently to the decrease of turbidity and that the index weight of channel could excellently indicate the impact degree of floc particles dynamic distribution on flocculation effect. Therefore, the parameter may significantly benefit the development of coagulation and sedimentation techniques as well as the optimal coagulant selection.

Key words: particle size distribution; particle counter; index weight; flocculation process

DOI: 10.1016/S1001-0742(08)62382-7

Introduction

As the most generally adopted water treatment technology, removing wastes by flocculation and solid-liquid separation, to a large extent, will impact the treatment effect in subsequent processes, the quality of outflow, and the operation costs (Yang *et al*., 2003). Therefore, the research on the flocculation process has become an essential part in water treatment industry (Wang *et al*., 2006). The flocculation process is considered to change the dynamic distribution of suspended particles in water, i.e., to gather smaller particles into a larger ones and to remove those in certain size ranges by settlement and filtering (Wang and Tambo, 2000). In such process, turbidity refers to an optical measurement of light dispersion due to various densities, sizes, shapes, colors, surface characteristics of suspended particles in water (Yang *et al*., 2007). Particle counting refers to the calculation of the number of suspended particles in water and the measurement of their sizes. The variation of experimental theories results in a poor correlation between turbidity and particle population within some size ranges (Wang and Chen, 2003). It is proven that the particle counter is an effective instrument for studying the dynamic distribution of floc particles because it is more sensitive to the delicate changes of suspended particles and thus can provide more information about their microscopic characteristics (Cui *et al*., 2004). Thereby, particle counter can be used to support turbidimeter (Luo *et al*., 2000). Combining those two instruments can efficiently demonstrate the effect of water treatment and guarantee water safety.

Particle counting is employed in this study to monitor online the dynamic distribution of suspended particles in water. Experimental results proved that the floc particles in different size ranges contributed differently to the decrement of turbidity. Using the multiple linear regression analysis model, a parameter was proposed to quantitatively describe the impact degree of floc particles dynamic distribution on flocculation effect, and the effect of the parameter also discussed. The study will have great significance for the development of highly efficient coagulants and the optimization of flocculation technology.

1 Experimental design and analysis

1.1 Instruments and reagents

Instruments used in this study included PCX2200 particle counter (Hach, USA), MICRO TOL online turbidimeter (HF, USA), RW20 N-type multiple velocity agitator (Ika, Germany), rectangular flocculating reactor (with effective volume of 18 L) and industrial computer monitor.

Kaolin suspension solution was prepared as testing sample (SO_2, 46%; Al_2O_3, 39%; burning loss, 20%). Polyaluminum chloride (PAC) was selected as the coagulant (analytical reagent; content > 99.0%; pH 4.9; basicity 82.4%; water insoluble 0.95%).

* Corresponding author. E-mail: nanjun11@163.com

1.2 Preparation of coagulant and synthetic water

PAC water solution (1%) was prepared. Kaolin clay was soaked before experiment and mixed with tap water in the rectangular reactor to obtain 18 L synthetic water with 100 NTU turbidity. The turbidimeter and the particle counter were switched on to collect samples at a speed of 100 mL/min. Once the turbidity reading is stabilized, the experiments performed as a sequence of dosing, rapid stirring, slow stirring and sedimentation.

1.2.1 Experiment procedures

The stirring method is employed to determine the impact of dynamic distribution of floc particles on flocculation effect.

The optimal PAC dosage 10 mg/L was obtain by changing the coagulant dosage and using infinite approximation method. At PAC 10 mg/L, the residual turbidity at 20 min after sedimentation was compared to evaluate the orthogonal test results. To obtain the optimal hydrodynamic conditions with the orthogonal test, three different levels with different rapid stirring speeds (200, 250, 300 r/min), rapid stirring time (10, 20, 30 s), slow stirring speeds (60, 90, 120 r/min) and slow stirring time (10, 15, 20 min), respectively, were performed. The optimal rapid stirring speed was 250 r/min, rapid stirring time 10 s, low stirring speed 60 r/min and low stirring time 20 min.

The results showed that flocculation process was largely affected by slow stirring speed. The experiment simulated the variation of hydrodynamic conditions by changing the slow stirring speed and studied the correlation between particle population and residual turbidity.

The multiple linear regression model was used to evaluate the flocculation effect and the index weight of channel to quantitatively describe how the decrease of turbidity is affected by floc particles in different size ranges.

1.2.2 Characterization

Clear liquid was collected at 10 cm below the free surface of the reactor. The flocculation effect was reflected by residual turbidity at 20 min after sedimentation.

Particle counter was used to monitor the variation of dynamic distribution of floc particles over the flocculating time and to microscopically observe the gathering and growth of flocs in different size ranges. For the channels (i.e., particle size ranges) of the particle counter, the particle size ranges are shown in Table 1. It was found that the particles mainly distributed in CH1 through CH5.

Table 1 Particle size ranges in particle counter

Channel	CH1	CH2	CH3	CH4	CH5	CH6
Min. size (μm)	2	5	10	18	25	40
Max. size (μm)	5	10	18	25	40	750

2 Results and discussion

2.1 Variation of residual turbidity and floc particle population with different dosages

Experiments were done by changing the coagulant dosage under optimal hydrodynamic conditions. The variations of residual turbidity at 20 min after sedimentation and particle population when slow stirring stopped are shown in Fig. 1. When the coagulant dosage increased from 3 to 10 mg/L, both residual turbidity and floc particle population decreased and the flocculation effect improved. However, once PAC dosage exceed 10 mg/L, the flocculation effect deteriorated with the addition of coagulant. Both residual turbidity and particle population decreased to various extent.

At optimal dosage 10 mg/L both residual turbidity and particle population reached minimal level and flocculation effect turned out the best. The PAC dosage related to the function of charge neutralization, the absorption bridging mechanism, and the sufficiency of flocculating cores as well, which stimulate effective flocculation in treated water (Tang *et al*., 2005). In other words, under the same hydrodynamics condition, a little PAC can distribute instantly in water, forming very few flocculating cores and free particles can be captured. Consequently, the flocculation effect will become poor.

As PAC dosage increases, the flocculating cores will relatively increase, triggering the increase in aggregation points and the formation of large flocs. Thus flocculation effect improved. When the dosage is further increased, as an inorganic polymer coagulant, PAC will form a protective coating on the exterior surface of the colloid particles, making them disperse rather than coagulate. Under certain hydrodynamic conditions, the growth of floc particles is also limited. When the flocs become excessively large, their ability to withstand the shear force of water flow will become weaker. The flocs will break and turn into suspended particles which can not settle easily. Consequently, both residual turbidity and floc particle population will increase.

When PAC dosage increased to 40 mg/L, small flocs formed out of large broken ones were partially dehydrated even though the floc particle population increase continuously. Consequently, the floc density increased while the residual turbidity decreased.

The relationship between residual turbidity and floc particle population under different dosages is shown in Fig. 2. Under optimal hydrodynamics, when PAC dosage

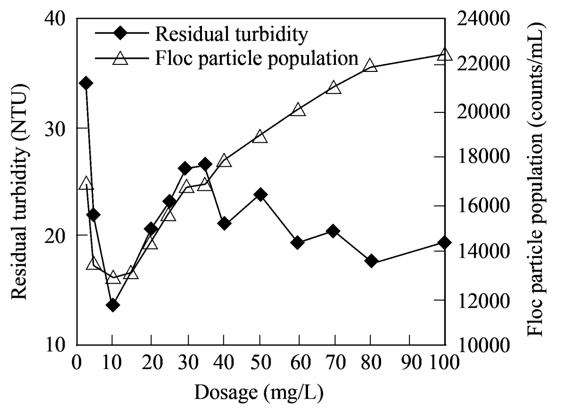

Fig. 1 Variation of residual turbidity and floc particle population under different dosages.

increased from 3 to 35 mg/L, residual turbidity increased with increasing particle population (Fig.2a). In the dosage range 40–100 mg/L, residual turbidity decreased with the increase of the particle population (Fig. 2b). However, there was poor relationship in both cases, with R^2 0.7804 and 0.4802, respectively.

2.2 Variation of residual turbidity and particle population under different slow stirring speeds

The variations of residual turbidity at 20 min after sedimentation and floc particle population when slow stirring stopped under the optimal dosage of 10 mg/L are shown in Fig. 3 . The flocculation effect is largely determined by particle characteristics and hydrodynamic conditions. Figure 3 shows that the hydrodynamic conditions change have a major impact on the residual turbidity. The PAC coagulant stimulated the formation of floc particles in various size ranges in water. At certain slow stirring speed, the chances for particle collision will increase when small particles gather into large ones and prevent large flocs from excessive damage. When particle aggregation and breakup reach a dynamic balance, the water will contain a small number of large-size and high-density particles of excellent gradation and settling characteristics that can better withstand the damages in subsequent processes (Jarvis *et al*., 2005a). Therefore, suspended particles will be removed easily during subsequent solid-liquid separation and the quality of outflow will be improved.

As the slow stirring speed increase, the flow turbulence becomes tenser in the reactor, increasing the chance for particle collision. If taking no account of the inevitable particle breakage in practice, even larger size and higher intensity floc particles will be formed (Jarvis *et al*., 2005b). Increasing the slow stirring speed will active the flow movement in the reactor, forming more larger vortices with less intensity. The shear force of the vortices cause greater damage to formed large flocs, tearing the binding tissues and breaking large flocs into scattered ones (Yukselen and Gregory, 2004). As a result, the small size particles will increase in water and broken flocs have weaker binding capability (Li *et al*., 2004). Even if the broken flocs can lump with small particles again, causing particle population to decrease slightly as the slow stirring speed increases, as shown in Fig. 3, the quality of outflow will get poorer since the remaining floc particles have low density and poor settling characteristics. Therefore, the residual turbidity will increase when the slow stirring speed increases.

Under optimal dose and selected slow stirring speeds, the relationship between residual turbidity and floc particle population was poor and R^2 was merely 0.7984 (Fig. 4).

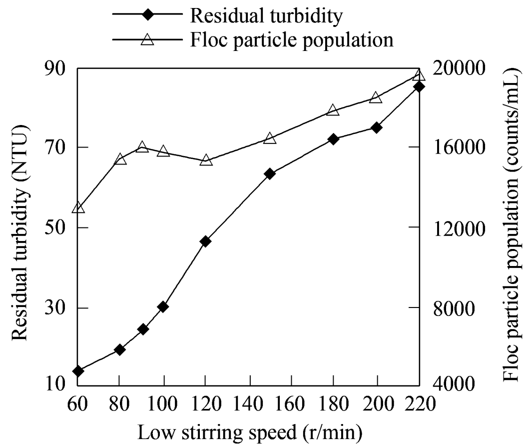

Fig. 3 Variation of residual turbidity and floc particle population under different slow stirring speeds.

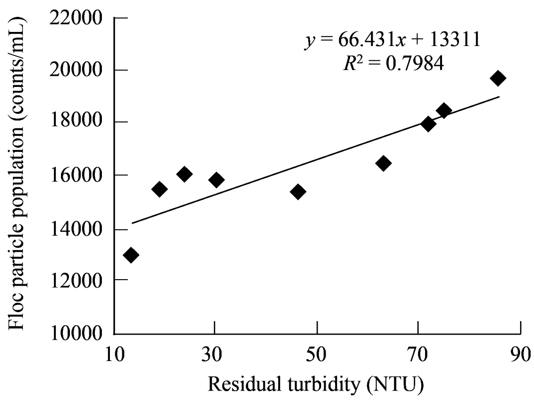

Fig. 4 Relationship between residual turbidity and floc particle population under different slow stirring speeds.

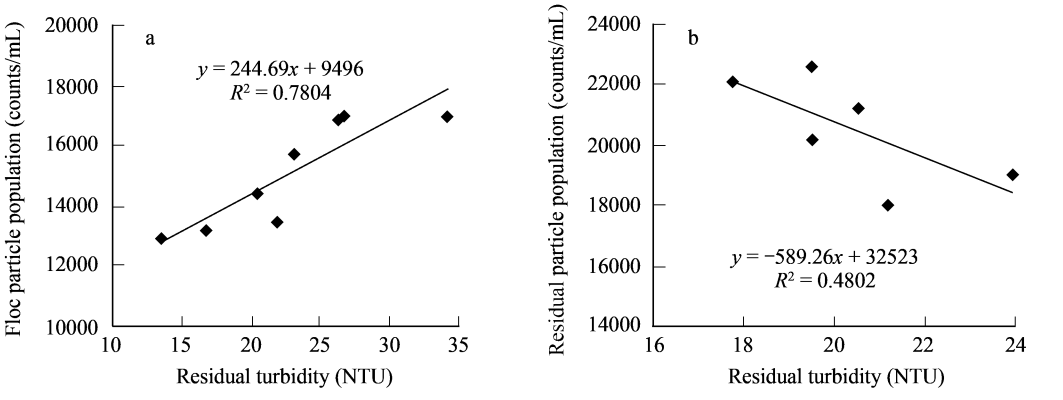

Fig. 2 Relationship between residual turbidity and floc particle population under different dosages. PAC dosage ranged from 3 to 35 mg/L (a) and from 40 to 100 mg/L (b).

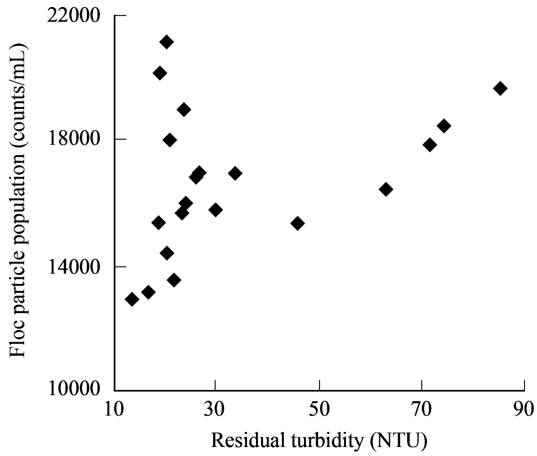

Fig. 5 Relationship between residual turbidity and floc particle population.

3 Evaluation model for impact on flocculation effect

3.1 Model establishment

As shown in Fig. 5, there was no one-to-one correspondence between residual turbidity and floc particle population. In the flocculation process, floc particles were distributed loosely, settled hardly and broken easily, so that particles of various size ranges will be formed in water when the flocculation conditions change (Fig. 6). Floc particles in various size ranges contribute variously to the residual turbidity, thereby the flocculation effect turned out remarkably different.

Such interdependent relationship between residual turbidity and particle size range can be reflected by the multiple linear regression analysis model.

Suppose y, the dependent variable, representing the variation in the number of studied object, and x_i (i = 1, 2, ..., m), the independent variable, representing the variation in the number of the ith object related to y.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_m x_m + \varepsilon \quad (1)$$

where, β_0 means the intercept of the multiple linear regression equation. β_i (i = 1, 2, ..., m) means the degree of impact of x_i (i = 1, 2, ..., m) on the variation of y, or the regression coefficient.

Suppose $\varepsilon \sim N(0, \sigma^2)$, ε or the error item an immeasurable random variable with mean value of 0 and $\sigma^2 > 0$.

The relationship between residual turbidity and floc particle population of each channel can be quantitatively expressed by Eq. (1). Suppose y_i the variation of residual turbidity in the ith flocculation experiment and x_{ij} (j = 1, 2, 3, 4, 5) the variation of particle population of channel j in the ith flocculation experiment, the result of the nth experiment can be expressed as (y_i, x_{i1}, x_{i2}, x_{i3}, x_{i4}, x_{i5}) (i = 1, 2, ..., n).

All n times of flocculation experiment satisfy the Formula (1):

$$\begin{cases} y_1 = \beta_0 + \beta_1 x_{11} + \beta_2 x_{12} + \beta_3 x_{13} + \beta_4 x_{14} + \beta_5 x_{15} + \varepsilon_1 \\ y_2 = \beta_0 + \beta_1 x_{21} + \beta_2 x_{22} + \beta_3 x_{23} + \beta_4 x_{24} + \beta_5 x_{25} + \varepsilon_2 \\ \cdots\cdots\cdots \\ y_n = \beta_0 + \beta_1 x_{n1} + \beta_2 x_{n2} + \beta_3 x_{n3} + \beta_4 x_{n4} + \beta_5 x_{n5} + \varepsilon_n \end{cases} \quad (2)$$

where, ε_1, ε_2, ..., ε_n are independent values subject to $N(0, \sigma^2)$ distribution.

If

$$X = \begin{bmatrix} 1 & x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ 1 & x_{21} & x_{22} & x_{23} & x_{24} & x_{25} \\ \vdots & & \ddots & & & \vdots \\ 1 & x_{n1} & x_{n2} & x_{n3} & x_{n4} & x_{n5} \end{bmatrix}$$

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_5 \end{bmatrix} \quad \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}$$

Equation (2) can be obtained as:

$$Y = X\beta + \varepsilon \quad (3)$$

where, ε is the n-dimensional random error vector and $\varepsilon \sim N(0, \sigma^2 I_n)$. I_n is the identity matrix of n order. $\sigma^2 > 0$ is unknown.

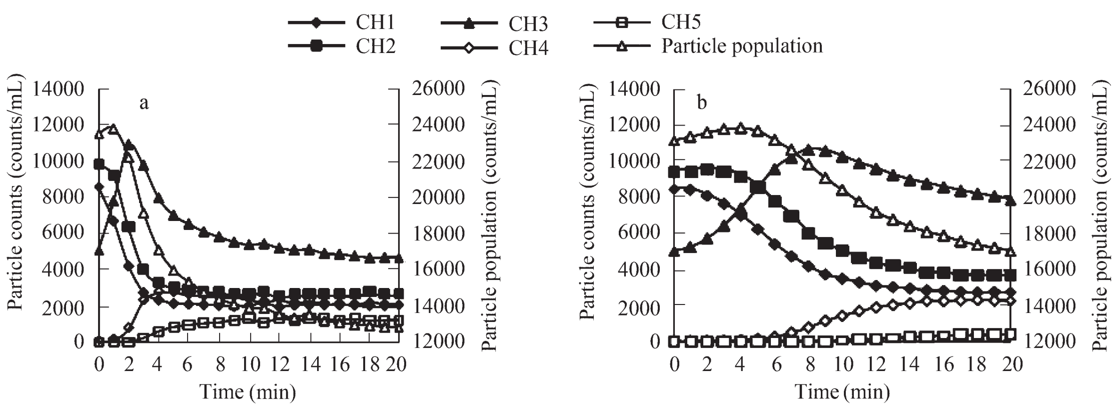

Fig. 6 Variation of floc particle distribution over time. PAC dosage and residual turbidity were 10 mg/L and 13.58 NTU (a) or 3 mg/L and 34.17 NTN (b), respectively.

In Eq. (3), Y is the observation vector and X is the design matrix whose values can be obtained with the flocculation experiment; β is an estimated parametric vector. Since the random variable ε_i (i = 1, 2, ..., n) can not be obtained in the experiment and β, unable to obtain directly, can be calculated from the least square estimation of regression coefficient β_j (j = 0, 1, 2,..., 5). First, the residual sum of squares is calculated as:

$$Q = \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_{i1} - \beta_2 x_{i2} - \beta_3 x_{i3} - \beta_4 x_{i4} - \beta_5 x_{i5} - \varepsilon_i)^2 = \|Y - X\beta\|^2 \tag{4}$$

Equation (4) reflects the total degree of error of the n times of flocculation experiment. To obtain the first-order partial derivative of Q by β_j (j = 0,1,2, ...,5) and set the derivatives at 0.

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_5 \end{bmatrix} = (X^T X)^{-1} X^T Y \tag{5}$$

The regression coefficient β_j (j = 0, 1, 2, ..., 5) is obtained. To evaluate the results, make

$$\Delta Y_i = y_i \qquad i = 1, 2, ..., n \tag{6}$$

$$\Delta X_i = |\beta_1|\, x_{i1} + |\beta_2|\, x_{i2} + |\beta_3|\, x_{i3} + |\beta_4|\, x_{i4} + |\beta_5|\, x_{i5} \quad i = 1, 2, ..., n \tag{7}$$

The linear relationship between ΔY and ΔX is studied. If there is a good linear relationship between them, $|\beta_j|$ will be defined as index weight of channel j (j = 1, 2, ..., 5) to indicate the degree of impact on residual turbidity when particle population in channel j varies and to distinguish the impact of particle population (i.e. the number of particles in various size ranges) in each channel on decrement of turbidity so as to describe quantitatively their impact on the flocculation effect. The bigger the value of $|\beta_j|$, the greater the residual turbidity will be affected by the particles in channel j.

3.2 Levels of impact under different flocculation conditions

3.2.1 Variation of index weight under different dosages

Under optimal hydrodynamics, the flocculation experiment was done for n times (n = 14) under different dosages. The variation of residual turbidity y_i was studied based on the difference between the residual turbidity of raw water of settled water. The variation of particle population x_{ij} (i = 1, 2, ..., 14; j = 1, 2, ..., 5) was studied based on the difference between the particle population of each channel in raw water and that when slow stirring stopped. The results are shown in Table 2. The value of β was calculated using Eq. (5):

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \end{bmatrix} = \begin{bmatrix} 71.0631 \\ 0.0067 \\ -0.0086 \\ 0.0107 \\ -0.0247 \\ 0.1066 \end{bmatrix} \tag{8}$$

The value of ΔY_i and ΔX_i (i = 1, 2, ..., 14) was calculated using Eqs. (6) and (7). The linear relationship between ΔY and ΔX is shown in Fig. 7. ΔY and ΔX showed good linear relationship under different dosages and R^2 = 0.9044. The index weight of CH1, CH2, CH3, CH4 and CH5 was 0.0067, 0.0086, 0.0107, 0.0247 and 0.1066, respectively.

Based on the results of $|\beta_j|$ (j = 1, 2, ..., 5), the impact of particle population in each channel on residual turbidity under different dosages was shown as CH5, CH4, CH3, CH2 and CH1 in a descending order.

3.2.2 Variation of index weight under different slow stirring speeds

Under the optimal dosage, the flocculation experiment was done for n times (n = 9) under different slow stirring speeds. The variation of residual turbidity y_i was studied based on the difference between the residual turbidity of raw water of settled water. The variation of particle population x_{ij} (i = 1, 2, ..., 9; j = 1, 2, ..., 5) was studied based on the difference between the particle population of each channel in raw water when slow stirring stopped. Results are shown in Table 3. The value of β was calculated using Eq. (5):

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \end{bmatrix} = \begin{bmatrix} 71.4323 \\ 0.0358 \\ -0.0321 \\ 0.0108 \\ 0.0121 \\ -0.1002 \end{bmatrix} \tag{9}$$

The value of ΔY_i and ΔX_i (i = 1, 2, ..., 9) was calculated using Eqs. (6) and (7). The linear relationship between ΔY and ΔX was then studied (Fig. 8).

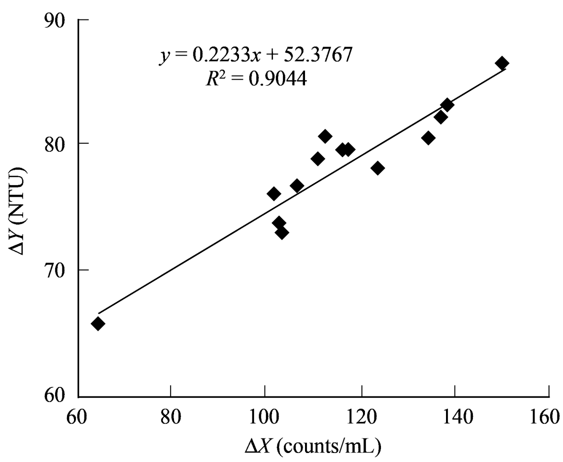

Fig. 7 Relationship between ΔY and ΔX under different dosages.

Table 2 Decrement of turbidity and particle population under different coagulant dosages

Dosage (mg/L)	Turbidity decrement (NTU)	Particle population decrement (counts/mL)				
		x_{i1}	x_{i2}	x_{i3}	x_{i4}	x_{i5}
3	65.83	3375.2	4677.6	1018.6	–227.4	–38.6
5	78.11	5339.6	7040.0	3202.4	–100.4	–43.4
10	86.42	6358.0	8004.2	4015.0	–30.0	–26.6
15	83.26	5603.2	7547.2	3825.8	–70.0	–28.4
20	79.46	5276.8	6725.2	2743.0	–145.0	–29.4
25	76.82	4787.6	6048.6	2274.0	–52.2	–4.8
30	73.72	4227.0	5985.0	2337.0	–66.2	–6.6
35	73.30	4169.8	5969.2	2378.4	–32.6	–6.0
40	78.87	3343.8	5891.0	3422.2	28.0	5.2
50	76.10	2618.4	5468.0	3260.0	56.8	7.6
60	80.52	2334.6	5701.6	4126.4	101.2	10.2
70	79.52	2352.6	6182.8	4298.2	73.4	1.6
80	82.29	2971.2	7034.0	5034.4	90.4	6.8
100	80.52	2432.6	6977.6	5111.2	101.0	7.8

Table 3 Decrement of turbidity and particle population under different slow stirring speeds

Slow stirring speed (r/min)	Turbidity decrement (NTU)	Particle population decrement (counts/mL)				
		x_{i1}	x_{i2}	x_{i3}	x_{i4}	x_{i5}
60	86.42	6358.0	8004.2	4015.0	–30.0	–26.6
80	80.97	6326.2	7862.4	3142.2	–178.6	–33.4
90	75.76	5157.6	6612.2	2702.2	–250.4	–43.4
100	69.86	5590.2	6693.8	923.0	–683.4	–97.4
120	53.68	4551.8	5476.2	–384.6	–1326.2	–165.0
150	36.77	5175.4	6148.4	–2011.8	–1940.0	–221.2
180	28.06	5510.6	6042.0	–3671.2	–2227.8	–186.6
200	25.22	4970.4	5516.8	–3453.0	–1995.2	–129.6
220	14.59	5116.2	5485.8	–4695.0	–1912.8	–105.8

As shown in Fig. 8, ΔY and ΔX showed good linear relationship under different slow stirring speeds and R^2 was 0.8506. The index weight of CH1, CH2, CH3, CH4 and CH5 was 0.0358, 0.0321, 0.0108, 0.0121, and 0.1002, respectively.

Based on the results of $|\beta_j|$ (j = 1, 2, ..., 5), the impact of particle population of each channel on residual turbidity under different slow stirring speeds was shown as CH5, CH1, CH2, CH4 and CH3 in a descending order.

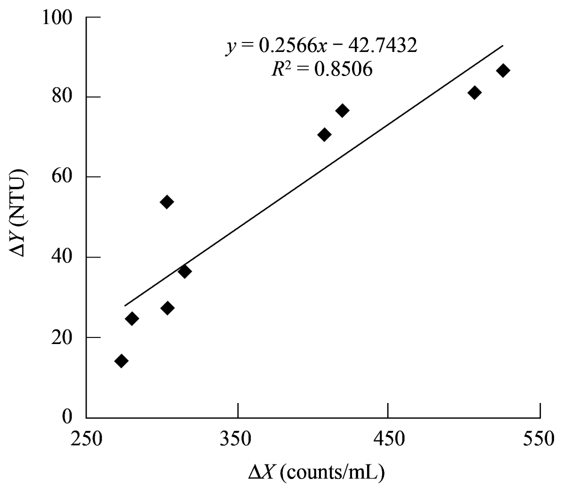

Fig. 8 Relationship between ΔY and ΔX under different slow stirring speeds.

3.3 Significance of the evaluation model in engineering

Based on previous experiments, the synthetic water of turbidity 50, 160, 215 and 270 NTU was also adopted to study the impact on flocculation effect by calculating the index weight of each channel under different dosages and different slow stirring speeds. The results showed good linear relationship between ΔY and ΔX at different turbidities as well. R^2 was 0.8901, 0.9328, 0.9152 and 0.9274 respectively under different dosages and 0.9135, 0.8790, 0.8617 and 0.9021 under different slow stirring speeds.

Tables 4 and 5 show that the values of index weight of channel changed similarly in a descending order from CH1, CH2, CH3 to CH4 at different turbidities under different dosages and slow stirring speeds. In addition, the value of index weight was always the greatest in CH5 regardless of experiment conditions and varies largely from the values of other channels.

Table 4 Index weight of channel at different turbidity values under different PAC dosages

Turbidity (NTU)	CH1	CH2	CH3	CH4	CH5
50	0.0074	0.0069	0.0131	0.0186	0.1102
100	0.0067	0.0086	0.0107	0.0247	0.1066
160	0.0065	0.0063	0.0156	0.0284	0.1238
215	0.0058	0.0097	0.0210	0.0193	0.1197
270	0.0061	0.0073	0.0203	0.0236	0.1265

PAC dosages are the same as presented in Table 2, under optimal hydrodynamics.

Table 5 Index weight of channel at different turbidity vales under different slow stirring speeds

Turbidity (NTU)	CH1	CH2	CH3	CH4	CH5
50	0.0275	0.0252	0.0107	0.0104	0.1238
100	0.0358	0.0321	0.0108	0.0121	0.1002
160	0.0310	0.0295	0.0136	0.0154	0.1177
215	0.0341	0.0366	0.0117	0.0193	0.1359
270	0.0332	0.0309	0.0143	0.0205	0.1201

Slow stirring speeds are the same as presented in Table 3, under the optimal dosage.

In a sophisticated multi-variable evaluation system, each variable or the index weight varies in its importance and the evaluation result is determined by proper selection and application of such variables. When studying the impact of floc particles on the flocculation effect, $|\beta_j|$ is defined as the index weight of channel j (j = 1, 2, ..., 5) to distinguish the impact of particles of different size ranges on decrement of turbidity. The experiment results proved that the evaluation model was viable and effective.

As drinking water is having stricter quality standards and higher demand on the turbidity of outflow, ordinary water treatment technology can hardly or no longer meet such requirements (Cernio and Haarhoff, 2005). The turbidity of settled water has become a critical parameter for monitoring the effect of water treatment and the addition of water treatment reagent. The study showed that the floc particles in various size ranges had different impact on the residual turbidity of settled water.

The quantitative description of the impact of dynamic particle distribution on flocculation effect will enable improve the control of floc particle population in size ranges with higher index weight or greater impact on the turbidity by improving the flocculation and sedimentation techniques (e.g., to remarkably reduce the turbidity of settled water by controlling the floc particle population in CH5 that has the greatest value of index weight which varies largely from the values of other channels), so that the water quality of outflow will meet the relevant requirements and to achieve the optimization of technique design, dosage reduction and automatic control of coagulant addition.

Furthermore, for developing and selecting the optimal water treatment reagent, the flocculation effect of the coagulant can be quantitatively evaluated based on the particle population in various size ranges. The randomness of selection will thus be reduced. Therefore, the study holds great significance for engineering development and scientific research.

4 Conclusions

Under different flocculation conditions, the residual turbidity of settled water changed in a similar way as the floc particle population did but there was no one-to-one correspondence between them. When the flocculation condition changed, particles of different size ranges contributed differently to the variation of residual turbidity of settle water.

Based on the multiple linear regression analysis model, a quantitative parameter was proposed to demonstrate the impact of dynamic distribution of floc particles on flocculation effect, i.e., the index weight of channel. The index weight could excellently indicate the degree of impact of floc particles in various size ranges on flocculation effect. The study may beneficial for the development of flocculation and sedimentation technology as well as the optimization of coagulant selection.

The particle counter can be used to support the turbidimeter. Combine the two instruments can effectively demonstrate the effect of water treatment and guarantee water safety.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 50678047), the National High Technology Research and Development Program of China (No. 2006AA06Z305) and the National Science and Technology Project of Eleventh Five Years (No. 2006BAJ08B05-2).

References

Cui H M, Zhang S X, Chen K C, Zhou D N, Fan K P, Chen Y S *et al*., 2004. Application of particle counter for the water treatment in Beijing No. 9 water plant. *Water Purification Technology*, 23: 32–37.

Cernio A D, Haarhoff J, 2005. An improvement on the power law for the description of particle size distributions in potable water treatment. *Water Research*, 39: 305–313.

Jarvis P, Jefferson B, Parsons S A, 2005a. Breakage, regrowth and fracal natural organic matter flocs. *Environmental Science & Technology*, 39: 2307–2314.

Jarvis P, Jefferson B, Gregory J, Parsons S A, 2005b. A review of floc strength and breakage. *Water Research*, 39: 3121–3137.

Li X Y, Zhang J J, Lee J H, 2004. Modelling particle size distribution dynamics in marine waters. *Water Research*, 38: 1305–1317.

Luo Y P, Li N, Li J G, 2000. Testing and controlling suspended particles in drinking water. *Water & Wastewater Engineering*, 26: 26–31.

Tang S, Preece J M, Mcfarlane C M, Zhang Z, 2005. Fractal morphology and break age of DLCA and RLCA aggregates. *Journal of Colloid and Interface Science*, 221: 114–123.

Wang Z G, Xu Y P, Cui F Y, Liu G Q, 2006. Analysis on parameters of particle size distribution in drinking water treatment. *China Water & Wastewater*, 22: 50–52.

Wang D S, Chen Y S, 2003. Application of on-line laser particle counter in water treatment. *China Water & Wastewater*, 19: 29–31.

Wang X C, Tambo N, 2000. A study on the morphology and density of floc (I): the fractal structure of floc. *Acta Scientiae Circumstantiae*, 20(3): 257–263.

Yang Y L, Li X, Liu M Z, Zhang H, Zhang L L, Chen X, 2007. Evaluation on particle removal effect with combination of particle counting and turbidity. *Journal of Beijing University of Technology*, 33: 1199–1202.

Yang Y L, Li X, Cong L, Li G B, 2003. Optimizing of water quality monitoring and removal of pathogenic protozoa in water works. *Water & Wastewater Engineering*, 29: 22–26.

Yukselen M A, Gregory J, 2004. The effect of rapid mixing on the break-up and re-formation of flocs. *Journal of Chemical Technology and Biotechnology*, 79: 782–788.