Research on micro-particles distribution character in water treatment processes
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ABSTRACT
In this paper we studied the particle size and distribution (PSD) character during conventional water treatment process. By measuring the particle size and distribution of raw-water, settled water and filtered water, we developed a log-log model between particle diameter and amount, which can be described as $ln \ n = -\beta \ ln \ D_p + K$. The value of collision frequency factor $\beta$ in the PSD log-log model can represent the particles' dynamic behavior, and can provide a foundation to choose a more suitable coagulation mode in accelerating particles aggregation. At the same time, we deduced the relationship $ln \ V = bK+C$ between the value of parameter $K$ and the total particles volume $V$. Lots of experiments proved the conclusion’s validity. $K$ is defined as particle volume exponent, which can represent the total volume of particles. $K$’s depression degree shows the removal efficiency of potable water treatment units.

Key words | micro-particles, particle size distribution (PSD), particles collision frequency factor $\beta$, particle volume exponent $K$

INTRODUCTION
In natural water and potable water treatment processes, there are many kinds of particles which have heterogeneity and dispersing. These particles are not only the carrier of micropollution in flow and transference, but also the lodging of many chemical reaction and form transformations. As important objects for investigation in water quality science, particles in aquatic systems have quite an expansive conceptual range, which includes minerals, organisms and living matter, such as poly-molecules, colloids, suspended particles and bacteria, alga, protozoa etc. Therefore, particle removal during water treatment has a great connection with potable water safety and has gradually become a more and more important problem for water supply enterprises. Recently, studies on mechanism and character of particles’ stability and aggregation in aquatic system has become the most active field (Tang Hongxiao et al. 2000).

In general, study of particle size distribution has gone through two stages. The first generation technique involves the representation of the data in terms of total count. Normally this is done as “counts per ml $> 2 \mu m$”. This technique is adequate to describe changes in water quality. Unfortunately, it loses its ability to indicate how the particles are distributed over the different size fractions in water. The second generation technique is the use of power law coefficients to represent the count and count distribution of particles in suspensions. This is probably the most popular method of data reduction among researchers (Willczak et al. 1992).

PSD’S POWER LAW MODEL
As a micro-particles suspension system has high heterodispersity, the number of particles of a certain size increases with the quantity of total particles. Particle amount $N$ and the homologous size $D_p$ (particle diameter or eigenlength)
have some relationship. Particle size and distribution line drawn from particles’ amount and size relationship is called the PSD function.

In general, particle size (or surface area or particle volume) is defined as the PSD function’s independent variable. Friedlander (1997) defined the PSD function as Equations (1). The slope or derivative at any point of such a distribution, \( \frac{dN}{d(D_p)} \), is known as the PSD function, usually given the symbol \( n(D_p) \).

\[
\frac{dN}{d(D_p)} = n(D_p)
\]  

(1)

where \( dN \) is the particle amount between \( D_p \) and \( D_p + d(D_p) \), \( D_p \) is particle’s diameter, \( n \) is PSD function which means the rate of change of particle amount when \( D_p \) changes round a certain value. O’Melia (1980) considered that the PSD function follows a power law model according to some experimental formulas. It can be written as:

\[
\frac{dN}{d(D_p)} = k(D_p)^{-b}
\]

(2)

Taking the logarithm of both sides we can get

\[
\ln n = -b \ln D + K
\]

(3)

where \( K = \ln k \). Some researchers had investigated the values of \( b \) in different water bodies and obtained \( b \) is 3.43 in effluent of activated sludge process, 4.14 in sludge generating in bio-chemical process, 2.5 in Lake Zurich and 3.3 in Creek Lake. The meaning of \( b \) and \( K \) could not be clarified apparently, so the practical function isn’t remarkable in describing particles behavior and character.

Friedlander & Wang (1966) defined \( b \) as particle collision frequency factor on the basis of the discrete particles coagulation kinetics equation and the Smoluchowski formula. He found the \( b \) value changed from 2 to 5. Results from many investigators show that in heterotrophic coagulation dominated by Brownian motion, \( b \) is 2.5, 4.0 in fluid shear and 4.5 in differential settlement (Paojiu & Tengrui 2000). These conclusions have been widely accepted.

Lawler (1997) analyzed particles’ rectilinear collision and curvilinear collision model through experiment on basis of the formers’ investigation. He drew the conclusion that the collision mechanism of different size particles is different. The particle size range of different collision mechanism was also established by him as Figure 1 shows. By coagulation of latex micro-spheres (2.85\( \mu \)m) in a Jar-test (paddle-mixing) device, Li & Logan (1997) found that fluid shear rate (\( G \)) and the aggregate fractal dimension (\( D \)) affected the collision frequency function (\( \beta \)) between fractal aggregates and small particles, resulting in \( \beta \sim G_1 - 0.33D \). His study on marine waters’ particle size distribution dynamics also shows that steady-state PSD can be achieved after a period of simulation regardless of the initial conditions which follows a power-law function and the slope of PSD varies from – 3.5 to – 1.2 (Li et al. 1997). The power-law function has three linear regions after log–log transformation, with different slopes corresponding to the three collision mechanisms: Brownian motion, fluid shear and differential sedimentation. Lee et al. (2000) established the coalesced fractal sphere (CFS) assumption based on particle aggregates fractal structure. And his simulations with the fractal cases indicated that both \( D_f \) and \( \beta \) significantly affected the evolution of PSD, and that with lower values of \( D_f \) and \( \beta \), the model predicted a trend of PSD similar to that of the Euclidean case. Ceionio & Haarhoff (2005) gave modification on \( \beta \)’s express pattern of PSD power law function, indicating that there is some relationship between \( \beta \) and particle size. It’s obvious that

![Dominant regions for collisions by each mechanism in rectilinear and curvilinear models.](https://iwaponline.com/ies/article-pdf/8/1/25/418736/25.pdf)
the conception of $\beta$ in terms of collision frequency factor has already been accepted widely and undergoing further investigation. But it hasn’t led to any reports about parameter $K$ in PSD power law function so far.

In this paper, we studied the particle size and distribution (PSD) character at different stages of conventional water treatment processes on the basis of previous studies. By measuring raw-water, settled water and filtered water particle size and distribution, we developed the power law function of micro-particles’ size and distribution between particle diameter and amount. We considered particles collision frequency factor $\beta$, which is used to denote the difference of particles collision mechanism under different PSD condition. At the same time, we defined the meaning of $K$ in PSD power law function, and proved the feasibility of $K$ to represent the total particles’ volume. So $K$ has a significant guidance meaning on behalf of the particles removal efficiency at different stages of potable water treatment processes.

**METHODS**

Particle counting instruments can be used to measure particles’ PSD, when equipped with more precise laser diode as ray resource (as Figure 2). Each particle through the beam give rise to a voltage pulse signal, and the amount of pulse signals can reflect the amount of particles. In contrast to turbidity, the result of particle counting can directly reflect particles’ physical parameters, such as amount and PSD.

In order to find $K$’s meaning in the PSD’s power law function, we carried out analysis as follows. About close system of suspended micro-particles, we proposed three assumptions: (1) particles are all regular spheres; (2) particles have discrete distribution, with diameters presumed as $D_1, D_2, \ldots D_i, D_{i+1}, \ldots D_m$; (3) micro-particles are in kinetic equilibrium, thermodynamic disequilibrium and congregative equilibrium. That is, the gravity and flotation acting on particles were equal, so the particles are in steady suspended state. Particles keep in a consecutive movement because of the effect of Brownian motion and fluid turbulence, and they had nonlinear collisions. The probability of particles’ adhesion because of collisions between each other is low, and particle’s have a high congregative stabilization. Then, for particles sized $D_i$, which amount is $n_i$, the volume $V_i$ can be expressed as follows:

$$V_i = n_i \frac{\pi}{6} D_i^{-3}$$

and the total particles’ volume is:

$$V = \sum_{i=1}^{m} V_i = \sum_{i=1}^{m} n_i \frac{\pi}{6} D_i^{-3}.$$  \hspace{1cm} (5)

Combining Equations (2) and (5), we can obtain

$$V = \sum_{i=1}^{m} k D_i^{-\beta} \frac{\pi}{6} D_i^{-3} = \frac{\pi}{6} \sum_{i=1}^{m} D_i^{-\beta - 3}$$

For a certain micro-particle suspended system, $-\beta$ is the slope of PSD’s log-log model and can be regarded as a constant according to Equation (3). Therefore, total volume of particles $V$ and intercept $K$ have a relationship of linear in Equations (6), which can be simplified as:

$$V = cK$$

(7)
That is,

\[ \ln V = \ln k + \ln c = K + \ln c \]  

where \( c \) is the function of \( \beta \) and \( D \) which are determined in certain aquatic systems; then \( c \) can be considered as constant.

According to the form of Equation (7), we give a presumption which describe the relationship of \( V \) and \( K \) as:

\[ \ln V = bK + C \]  

where \( b \) is a coefficient, \( C = \ln c \). For different aquatic systems, there may be some difference in \( c \) because of \( \beta \) and \( D \)'s variety and \( C \) is different too. But there also we have the linear relationship of \( \ln V \) and \( K \). We define vertical intercept \( K \) in PSD log-log model (Equations 3) as Particle Volume Exponent, which denotes the particles’ total relative volume in micro-particles suspended system.

**RESULTS AND DISCUSSION**

The conclusions above are acquired under ideal conditions with three hypothesises. In order to give a higher reliability, we have experimented with natural water containing particles which include clay, powder sand, dross and bacteria etc with complex surface character and irregular shape. Experiments were carried out in the S water plant of Harbin with traditional water treatment processes, including machine mix coagulation, inclined pipe settlement, V type filter and chlorine disinfection. Particle diameter ranged from 2 to 50 \( \mu \)m and they were measured by an America HIAC-9703 model particle counting instrument. Samples were taken from raw water, settled water and filtered water. Figure 3 reveals the experimental results of one day during the experimental period. In the figure, the abscissa is defined as particle diameter’s logarithm and the ordinate is defined as particle amount’s logarithm. The line shows the relationship and function between particle size and amount and the line expressed the PSD log-log function.

The following can be concluded from Figure 3. With natural water as the research subject, the particle size and amount fit log-log linear relationship in

\[ \ln n = -\beta \ln D + K \]

which means that particle diameter and amount meet the power law function and the correlation reaches more than 0.97. Thus it can be seen that the existence and distribution of micro-particles with different size in certain aquatic system are well regulated. Amount of specified particle size will never be larger or smaller infinitely. The cause may be that suspended micro-particle in aquatic system keeps in a stable state. Particles show nonlinear and irregular motion because of the effects of the surrounding environment and their own physiochemical surface character. Therefore, bigger particles dispersion and smaller particles aggregation take place simultaneously and the former keeps in a dynamic balance with the latter.

**Particles collision frequency factor \( \beta \)**

In PSD log-log model obtained from experiment, \( \beta \) is the negative of line’s slope. According to Friedlander’s (1997) conclusion, change of particles collision frequency factor \( \beta \) predict collision and aggregation mechanisms of particles which included Brownian motion, fluid shear and settlement. In order to give a further explanation of numerical value stability and variety rule of \( \beta \), we took a continuous measurement of PSD of raw water, settled water and filtered water from July to August in 2003. Figure 4 reveals the value of \( \beta \) acquainted from PSD log-log model.

Within the 23 groups, particle size and amount were all fitted for log-log model and the correlation were all no lower than 0.95. For raw water with high concentration of particles, the value of \( \beta \) is larger obviously, none less than 3.2 and almost in the range of 3.5 ~ 4.0. This demonstrates that fluid shear takes a dominant role in 2 ~ 50 \( \mu \)m particles collision in raw water. The \( \beta \) of settled water and filtered water were all less than 3.2.
between 2.5 and 3.0, which demonstrates that Brownian motion takes a dominant role in micro-particles collision. Fluid shear and settlement have a weak effect. Comparing the values of settled water and filtered water, we can see the latter is a little bigger than the former. Along with water filtration, particles of 20 ~ 50\( \mu m \) are removed more completely, and 2 ~ 5\( \mu m \) particles have a higher proportion (Liu Guangqi et al. 2006). So fluid shear and settlement give the lowest effect on particles collision and \( b \) value decrease. For settled water and filtered water, a smallest \( b \) means more large particles in aquatic system and weaker dependence of particles collision on fluid shear and settlement.

At the same time, from Figure 4, we can see that \( b \) of settled water and filtered water have a similarly changing trend. That is, PSD of settled water has an effect on the overall of filtered water in some degree. Therefore, in water treatment systems, a unit process’s running function have a great effect on the overall system. Only if units operated in a stabilized state can the system have an optimized running. In raw water, settled water and filtered water, \( b \)‘s value has a range with the averages \( b_{\text{raw}} = 3.68, b_{\text{settled}} = 2.77, b_{\text{filtered}} = 2.73 \). \( b \) fluctuates only in a narrow range and with a high stability. So it is feasible to use \( b \) to denote particles collision mechanism in potable water treatment systems.

**Particle volume exponent \( K \)**

From Equation (9), we know that vertical intercept \( K \) of the trendline in Figure 3 fits a linear relationship with total particle volume \( \ln V \), which can be described as \( \ln V = bK + C \). In order to validate the deduction, we calculate the particles’ total volume approximately, and take a further analysis between \( \log V \) and \( K \). First, we assumed particles as regular spheres, and we proposed a middle size of channel as the diameter used to calculate; for instance, we took 3\( \mu m \) as the calculated diameter for particles measured from 2 to 5\( \mu m \). Then the total volume of particles sized from 2 to 50\( \mu m \) can be expressed as follows:

\[
V = \sum_{i=1}^{16} n_i \frac{\pi}{6} D_i^3
\]

According to Equation 10, we took a approximate calculation of particle total volume for settled water and filtered water, and obtained the relationship of \( V \) and \( K \), as shows in Figure 5. It can be made out that there is a good linear relationship between \( \ln V \) and \( K \) with the correlation coefficient 0.82. And the expression form fits Equation 9. Then we can consider that \( K \)‘s value may be used to denote total particles relative volume in aquatic system. The changes of \( K \) shows the changes of the total particles volume. It is feasible to use particle volume exponent \( K \) to demonstrate particle removal effect in different units of a water treatment system.

According to the conclusions above and comparing Figure 5 with Figure 6, it can easily found that the raw water \( K \) is the highest and then the total particles volume is also the largest. Filtered water has the lowest \( K \) and smallest total particles volume. Figure 6 shows the value of \( K \) obtained from many times of experiments with the mean value is \( K_{\text{raw}} = 17.21, K_{\text{settled}} = 9.75 \) and \( K_{\text{filtered}} = 8.83 \). The decreasing value of \( K \) from raw water, to settled water to filtered water shows particles’ removal effect of water treatment units. The \( K \) of raw water is obviously higher.
than that of settled water and filtered water shows the unit of coagulation and settlement play a important role on particle removal from aquatic system.

CONCLUSIONS

In the particle size category of our experiments, we obtained differing size micro-particles in certain aquatic system with their distribution well regulated. That is, particle diameter $D_p$ and amount $n$ fit the PSD log-log model:

$$\ln n = 2\beta \ln D_p + K.$$

The changes of particles collision frequency factor $\beta$ are consistent with the changes of PSD. $\beta$ of raw water is the highest and particles collision mostly dominated by fluid shear. $\beta$ of settled water and filtered water lies within 2.5 $\sim$ 3.0, and Brownian motion plays a great effect on particles collision frequency. The value of collision frequency factor $\beta$ in the PSD log-log model can be suited to represent the particles dynamic behavior, and can provide a foundation to choose more suitable coagulation mode in accelerating particles aggregation.

Vertical intercept $K$ of the PSD log-log model fits a linear relationship with total particle volume $\ln V$; we defined $K$ as particle volume exponent. During water's treatment process, the value of $K$ decreases consistent with particles removal gradually. $K$ has a good stability in reflecting total particle volume in aquatic system. The decreasing degree of $K$ from raw water, settled water and filtered water shows particles' removal effect of water treatment units.

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