Desalination 354 (2014) 116–124

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Effect of particle size distribution on turbidity under various water quality levels during flocculation processes

Meng Yao, Jun Nan *, Ting Chen

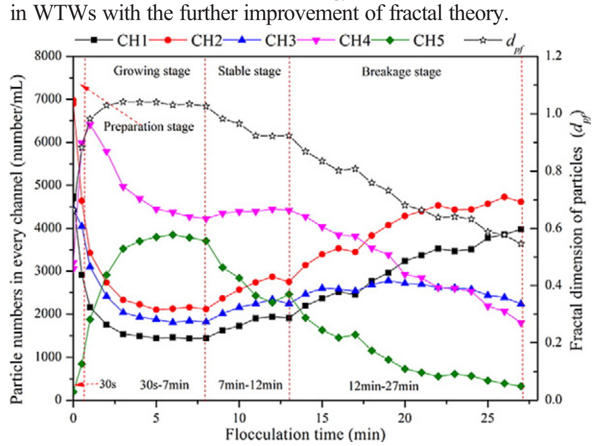
State Key Laboratory of Urban Water Resource and Environment, School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, China

HIGHLIGHTS

- Large particles formed through combining smaller flocci and monomeric particles.
- Larger particles have prominent contribution on water turbidity.
- Fractal dimension of particles was used to evaluate smaller particle number.
- Flocculation process was divided into four stages.

GRAPHICAL ABSTRACT

Dynamic analysis on the variation of particle size distribution was characterized by the on-line particle counter. The flocculation process was divided into four different stages on the basis of the variation of d_{pf} over the flocculation time, since the value of d_{pf} was able to conduct real-time detection and be more extensively used in WTWs with the further improvement of fractal theory.



ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form 22 September 2014
Accepted 23 September 2014
Available online 8 October 2014

Keywords:
Particle size distribution
Turbidity
Fractal dimension of particles (d_{pf})
First derivative of d_{pf}
Block theory

ABSTRACT

The dynamic relationship between particle size distribution and water turbidity was characterized using online real-time monitoring devices to explore the impact of particle size distribution on water quality. Particle amount was proportional to water turbidity in the range of 0–40 NTU, whereas the correlation was rather poor in the range of 40–100 NTU. The number of particles smaller than 5 μm ($N_{d<5}$) should be strictly monitored and controlled in water treatment works (WTWs) due to their complex behaviors. The fractal dimension of particles (d_{pf}) is well suited to characterize particle size distribution under different water turbidities. The first derivative of d_{pf} was firstly used to explain the relationship between d_{pf} and the percentage of $N_{d<5}$, and the turbidity and d_{pf} values could be used together to monitor the temporal evolution of the number of smaller particles. A new block method for analyzing flocculation processes was proposed based on the change in d_{pf}. The particle counting method was more sensitive to the evolution of particle size, which allowed a better understanding of the impact of particle size distribution on water turbidity.

* Corresponding author. Tel.: +86 451 86084169; fax: +86 451 86283001.
E-mail address: nanjun_219@163.com (J. Nan).

http://dx.doi.org/10.1016/j.desal.2014.09.029

1. Introduction

The aggregation of small particles into larger particles is a well-established method of removing turbidity, color and other organic and inorganic materials in water treatment works (WTWs) [1]. Solid/liquid separation processes in drinking water treatment usually begin with flocculation, which is followed by sedimentation and filtration [2]. Turbidity is the most widely used parameter for monitoring the quality of treated water and evaluating the effectiveness of treatment processes; it is used in almost all WTWs because of its low cost and easy application. Water turbidity is usually measured by passing an incident beam through the sample, which is scattered at right angles when it interacts with the particles. The suspended particles then absorb the light energy and re-radiate light in all directions [3]. Lower levels of turbidity are generally considered to indicate high water quality and thus a lower likelihood of transmitting gastrointestinal disease [4,5]. However, for low-turbidity water, the turbidity value does not perfectly represent the number of particles in water, providing only partial information on the efficacy of the treatment process [6].

As sedimentation and filtration processes can only remove particles in specific size ranges, the flocculation process, in which small particles are aggregated into larger flocs, is crucial [7–9]. Therefore, directly measuring and monitoring the particle size distribution (PSD) is very important in such solid/liquid separation processes. Particles of various sizes are present in natural water, but colloids (0.01 and 0.1 μm) and small solids (10 and 100 μm) are the main particles removed. An online particle counter device can monitor the particle size distribution and quantify the number of particles. Such devices are widely employed for the real-time determination and characterization of the PSD at WTWs. However, no studies to date have reported on the relevance of particle number and water turbidity. Relative to turbidimeters, particle counters can provide better particle characterization information on the micro-scale, and the measured results are more accurate due to their higher sensitivity to small particles. McCoy and Olson [10] concluded that there was no predictable relationship between bacteriological quality and water turbidity after investigating the relationship among turbidity, particle number and bacteriological quality. However, the application of particle counting for the determination of the removal of small particles from drinking water still provided the best public sanitary conditions [11,12]. Particle counting was considered an effective diagnostic method for operating conditions during flocculation processes. Moreover, the use of a particle counter in combination with a turbidity device to monitor and control water treatment operation has been increasingly used in WTWs [5].

Fractal theory has been widely applied in a variety of research fields to explain randomness and non-linear processes. Recent lectures have focused on solving the equations of coagulation dynamic [13,14], with little research conducted on particle number and particle size distribution in water to illustrate its fractal characteristics. Jin [15] investigated raw humic acid using the image method and concluded that the PSD was normally distributed. To monitor the dynamic particle distribution in water using a particle counter, the fractal characteristics of the particle size distribution were applied to describe the flocculation process, and a new concept of fractal dimension was first proposed [16]. The fractal characterization of PSD was studied by exploring the law of particle size distribution during the flocculation process, which was based on the particle size distribution function and statistical methods. This fractal dimension (d_{pf}) was considered a fundamental index for describing the degree of particle dispersion in water, which could be used to effectively monitor the evolution of the particle size distribution in water.

In this paper, a series of jar-test flocculation and sedimentation experiments were carried out under different raw water qualities to investigate the relationship between PSD and water turbidity. First, the dynamic effect of PSD on turbidity was investigated for different water quality levels over the flocculation period. Next, the relationship between the particle numbers corresponding to various size ranges and turbidities was studied using the correlation analysis. Furthermore, the relationship between the fractal dimension of the particles (d_{pf}) and water turbidity was discussed, and d_{pf} was proposed to characterize the properties of smaller particles. Finally, block theory can be applied to the flocculation process based on the changes of d_{pf} to better understand the impact of particle size distribution on water turbidity. An online turbidimeter was applied to determine the water turbidity, while another online particle counter device was used to measure the particle number throughout the entire flocculation process in every test.

2. Materials and methods

2.1. Suspension

A kaolin clay (Tianjin, China) suspension was used as the water sample because its quality is similar to that of several rivers in the UK. The stock suspension was prepared using a method similar to that described by Yukselen and Gregory [17]. The particles had an average size of approximately 3 μm, as determined by a particle counting device.

To conduct the tests, the stock solution was diluted using tap water from Harbin, China, to specific clay concentrations. Harbin tap water has a moderate total hardness (ca. 160 mg/L as $CaCO_3$) and alkalinity (ca. 115 mg/L as $CaCO_3$) as well as a pH of approximately 7.8. To minimize the disturbance of divalent metal ions, such as Ca^{2+} and Mg^{2+}, in the tap water, a small dose of humic acid (Shanghai, China) was added into the testing sample [17]. The suspension containing 100 mg/L kaolin and 2 mg/L humic acid had a turbidity of approximately 100 NTU, and other turbidities were obtained by diluting the testing water by this stock solution. All of the turbidity values were determined by an online turbidimeter.

2.2. Coagulant

Polyaluminum chloride (PACl) was chosen as the coagulant. Stock PACl solutions (1% w/w) were prepared by dissolving the reagent in deionized water (5 g of reagent to 500 mL of water). This solution was used directly, without further preparation [17,18].

2.3. Apparatus

The test procedure is shown in Fig. 1. A modified version of the standard flocculation test procedure was conducted using an online turbidimeter (HF, USA) and an online 2200PCX particle counter (HACH, USA) to achieve the dynamic characterization of the PSD and water turbidity. The PSD was represented by the particle population and the number of particles in various size ranges. Accordingly, the size ranges corresponding to channels (i.e., CH1–CH6) in the particle counter are shown in Table 1. For dynamic monitoring, the water sample was circulated from the flocculation reactor at a flow rate of 100 mL/min through transparent plastic tubing with a 5-mm internal diameter by a peristaltic pump. This peristaltic pump was placed on the back of the online turbidimeter and particle counter to minimize the breakage of flocs in the pinch part of the pump.

In this paper, an in situ recognition system composed of an automated stroboscopic lamp was employed to illuminate suspended particles in the reactor. A high-speed digital charge-coupled device (CCD) video camera (SVS-VISTEK GmbH, Germany) was used to capture images of the particles, and a process control and image processing software package (FMans 10, China) was used to measure the floc geometrical parameters. The camera was placed on the opposite side of the reactor from the lamp, capturing the backlit shadows of the particles. A personal computer was employed to control the camera and store the particle images [18]. A non-intrusive optical sampling technique was applied to obtain the digital particle images, which were used to characterize the particle size and structural properties. The major advantage of this in situ method is that there is no sample handling during the whole process, as the particle