Desalination and Water Treatment
www.deswater.com

1944-3994/1944-3986 © 2012 Desalination Publications. All rights reserved
doi: 10/5004/dwt.2012.3262

Taylor & Francis
Taylor & Francis Group

45 (2012) 215–221
July

Turbidity removal improvement for Yangtze River raw water

Chin Nang Lei[a], In Chio Lou[a,b,*], Heng Un Song[b], Pei Sun[b]

[a]*Department of Civil and Environmental Engineering, Faculty of Science and Technology, University of Macau, Av. Padre Tomás Pereira, Taipa, Macau SAR*
[b]*Sino French Water Development Co. Ltd., 718 Avenda do Conselheiro Borja, Macau SAR., P.R.China*
Tel. +853 8397 8469; Fax: +853 2883 8314; email: iclou@umac.mo

Received 9 September 2011; Accepted 8 November 2011

ABSTRACT

Coagulation-flocculation followed by sedimentation and filtration is the most commonly used water treatment process, in which turbidity or particle removal is strongly dependent on proper coagulant dosage, flocculation mixing time, mixing intensity (Gt), and effective size (ES) of filter media. Jar tests and filtration column tests were preformed in this study to evaluate the turbidity removal of the Yangtze River raw water that has medium turbidity and low dissolved organic matters. The new internal standard of 1 NTU for settled water and 0.2 NTU for outlet water were targeted. Operational conditions of primary flocculation (coagulant amount, mixing time and Gt), secondary flocculation, and filter media ES, were tested. Results showed that under the same amount of coagulant, longer flocculation time and higher Gt with tapered mixing can enhance the turbidity removal. The optimal dosage and Gt were estimated as 12 mg l^{-1} PACL and 29,000, respectively. Secondary flocculation further reduced the turbidity of settled water by 80%, suggesting that the smaller particles retained in the primary settled water was focculable. Compared to using 0.95 mm ES, using 0.65 mm ES as filter media obtained higher turbidity removal and can lower the residual turbidity to 0.15 NTU.

Keywords: Coagulation; Filtration; Optimization; Turbidity; Particle size; Yangtze River

1. Introduction

Today, increasing regulatory pressure, cost competition and occurrence of process upset require that the water business units consider more thoroughly on the treatment process, ensuring that each water parameter can meet the regulation with the lowest amounts of chemicals and power consumed. Turbidity is the principle parameter, which is caused by the suspended matters or impurities, interfering with the clarity of the water. Positive correlation between turbidity and pathogens has been reported in previous studies, and high residual turbidity in the treated water may promote the regrowth of pathogens in the distribution system, leading to waterborne disease outbreaks [1,2]. Thus the US regulatory limit for treated water turbidity has reduced from 1 NTU in 1989 to 0.3 NTU in 2002, and some water utilities are even committed to a lower internal guideline of less than 0.1 NTU to guard against pathogen contamination [3]. However, inefficiency of turbidity removal in conventional water treatment process (coagulation-flocculation-filtration) is occasionally observed, particularly in the developing countries.

Coagulant dosage and hydrodynamic environment are the two important factors affecting the efficiency of coagulation-flocculation [4]. The amount of coagulant added is determined by the levels of pH, salts and

---

*Corresponding author.

alkalinity in raw water, while the degree or extent of flocculation is controlled by the applied velocity gradients (*G*) and the time of flocculation (*t*) [3]. If the mixing is too mild, it is difficult for the flocs to grow and requires a longer flocculation time; if the mixing is too intensive, the already formed flocs may re-disperse again [5–7]. In practice, jar test is usually carried out to determine the optimal coagulant amount and mixing intensity (Gt) required.

To further remove residual turbidity before filtration, a secondary flocculation for the primary settled water can be considered to produce an effluent with lower suspended solids concentration [8]. During secondary flocculation, the surface charge of the small particles can be neutralized and larger particles may be formed. However, additional secondary flocculation tank with pumping and mixing accessories is necessary to be installed in the plants.

Another factor controlling the turbidity removal is ES of the filter media. The performance of the filtration process depends on two distinct steps: (1) the transport of the particles to the surface of the solid-liquid interface of the media and (2) attachment of these particles onto the media or other particles which have previously been deposited on the media [9,10]. The transport mechanisms of the particles within the filter media include interception, diffusion and sedimentation, and the size of the particles to be removed is a dominant parameter determining the transport mechanism of the particles [11]. For this reason, changing media size and/or particle size may enhance the transport mechanism [12]. Filter aids are sometimes added to increase the size of the particles by inter-bridging the particles [13].

Due to the new Chinese National Drinking Water Quality Standard (GB 5749-2006), in which a more stringent monitoring scheme for turbidity and microbiological risk parameters was established, the coagulation-flocculation-filtration process of Changshu WTP was evaluated in this study in order to improve the turbidity removal of Yangtze River raw water, for complying with the new internal guideline set for the Chinese Subsidiaries of Suez Environment, 1 NTU for settled water and 0.2 NTU for outlet water. The amount of coagulant, flocculation mixing time and intensity, secondary flocculation, and the ES of filter media were investigated.

2. Materials and methods

2.1. Changshu full-scale WTP

Changshu WTP, located in the downstream of Yangtze River, is a subsidiary of SUEZ Environment WTP and also the largest WTP in Changshu city, with a maximum daily production capacity of 400,000 m^3 d^{-1}. The raw water has medium turbidity and low dissolved organic matter, and is treated with the conventional coagulation-flocculation-sedimentation-filtration process. Polyaluminum Chloride (PACl) is used as coagulant, and the flocculator is designed to be in four compartments to provide different mixing strengths, with the approximate Gt value of 14,500. Filter media with an 0.95 mm ES are currently used.

2.2. Jar tests

Coagulation jar tests were conducted in 1 l plexiglass beakers using a programmable jar testing apparatus, Model ZR4-6 (Zhongrun, China), and operated under several mixing scenarios that mimicked different slow mixing scenarios. Mixing intensity was quantified by the Gt value. Liquid PACl with Al_2O_3 content of 10–11% and 70–75% in base saturation degree (Tianshu Purification Material Co. Ltd, Tianjin), were used as coagulant and a stock solution of 10,000 mg l^{-1} PACl was prepared before the test. Supernatant samples were withdrawn at 2 cm below the water surface. Coagulation dosage was measured by a calibrated pipette.

2.2.1. Determination of optimal coagulant dosage

The mixing simulated the in-practice operation by using a 3 min rapid mixing followed by 20 min slow mixing, with the corresponding fixed rotation speeds of 250 rpm ($G = 102.5\ s^{-1}$) and 40 rpm ($G = 11.9\ s^{-1}$), respectively. The Gt value for the flocculation (slow mixing) was about 14,500. The samples were then allowed to stand for 20 min after mixing and the supernatant was taken for turbidity analysis for particle number and size distribution. PACl dosages of 8, 12, 16, 20, 24, 28 mg l^{-1} were used by diluting the stock solution.

2.2.2. Flocculation under different flocculation time using 60 rpm

The PACL dosage was maintained as 12 mg l^{-1} in this test and the slow mixing speed used was 60 rpm ($G = 20.5\ s^{-1}$) with Gt value of 29,000, i.e., twice of that using 40 rpm. The flocculation time examined varied from 5 min to 30 min. The samples were then allowed to settle for 20 min before analysis.

2.2.3. Flocculation under different slow tapered mixing

Instead of using the fixed velocity gradient, the slow tapered mixing was introduced in this scenario to simulate the WTP flocculation operation, in which four descending velocity *G* were used in the four corresponding compartments for the whole slow mixing process. The operation of the slow tapered mixing was shown in Table 1. The samples were then settled for 20 min before analysis.

Table 1
Operation of the slow tapered mixing

Duration (s)	Impeller speed of the jar tester (rpm)		
	Gt = 14,500	Gt = 21,750	Gt = 29,000
300	60	80	100
300	45	60	75
300	30	45	55
300	18	25	35
Fixed impeller speed (rpm) of equivalent Gt	40	–	60

2.2.4. Secondary flocculation

The settled water from the WTP was collected before the test and stirred at 60 rpm for 40 min, with the PACl of 1, 2, 4, 6, 8 mg l^{-1} added into the beaker, respectively. Samples were then allowed to settle for 20 min before analysis.

2.3. Filtration column test

The filtration column is made of PVC cylinder that has 50 mm in diameter and 300 mm in height. Sand was used as media, filled up to 90 mm high in the column. The turbidity removal by 0.65 mm ES and 0.95 mm ES media were examined in this test, with the addition of 2 mg l^{-1} and 4 mg l^{-1} of filter aid (PACl), mixed under 100 rpm ($G = 40.7\ s^{-1}$) for 3 min, before the test. The sand media was backwashed with tap water before the test, and filtration velocity was maintained as 7.5 m h^{-1}. The first sample taken for turbidity analysis was collected after 1000 ml of water was filtered to minimize the effect of the backwash water. Sample was taken every 500 ml thereafter.

2.4. Analytical methods

Turbidity and particle size measurement were measured using a HACH 2100AN turbid-meter (Hach Company, USA) and an IBR particle counter (IBR, USA), respectively. Only the particles with sizes larger than 2 μm can be measured. Dissolved oxygen (DO), pH, and conductivity were determined using HACH LDO probe (Hach company, USA) meter, DKK-TOA HM-30R pH meter and DKK-TOA CM-30R conductivity meter (DKK-TOA corporation, Japan), respectively. Dissolved organic carbon (DOC) was analyzed using UV-persulfate technique and the infrared carbon dioxide analyzer (Phoenix 8000), and calibrated with potassium hydrogen phthalate as standard. UV-254 was measured by following the organic constituents' procedure using the DR/2010 spectrometer (Hach Company, USA). Ammonia and chemical oxygen demand (COD) measurement followed standard procedures of the Chinese Environmental Protection Bureau [14].

3. Results and discussion

3.1. Water characteristics of the WTP

Samples of the raw water and treated water were obtained from May to August, 2009 and the characteristics were measured and summarized in Table 2. The results showed that the turbidity of the raw water in Yangtze River was about 40 NTU, which was considered as low to medium turbidity, and the value is a bit lower than the previous results reported from other research groups [15,16]. It is considered to be difficult to treat the raw water with low turbidity using the traditional coagulation-flocculation process, as the concentration of particles in the water is too low to cause effective particle collision and aggregation [17,18]. The DOC, UV254, and specific ultraviolet absorbance (SUVA) values were 1.53 mg l^{-1}, 4.06 m^{-1}, and 2.65 l $(mg\ m)^{-1}$, respectively, indicating that the water has a low potential to form the disinfection by products [19]. Thus this type of raw water may not cause a disinfection problem when chlorine is used. The removal efficiency of COD_{Mn} (COD measurement

Table 2
Raw water and treated water characteristics of WTP (average ± standard deviation)

	Turbidity (NTU)	pH	COD_{Mn} (mg l^{-1})	Conductivity (μs cm^{-1})	Total alkalinity (mg l^{-1} as $CaCO_3$)
Raw water	40.3 ± 10	7.84 ± 0.13	2.65 ± 0.76	323 ± 50	91 ± 5
Treated water	0.3 ± 0.06	7.66 ± 0.10	0.96 ± 0.26	317 ± 25	86 ± 3

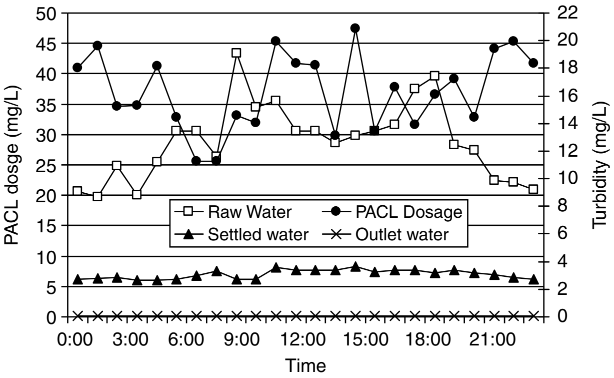

Fig. 1. Hourly PACL dosage and turbidity of raw water, settled water and outlet water.

using Potassium Permanganate Method) in the WTP was about 60%, which suggests that the organic matters in raw water can be removed by this conventional treatment process. The typical hourly PACl dosage and turbidity of raw water, settled water and outlet water are shown in Fig. 1. It has to be noted that the settled water and outlet water residual turbidity was above 2 NTU, and 0.15 NTU respectively, which can meet the current Chinese regulation. However, the coagulant dosage was as high as 40 mg l^{-1}. To comply with the new internal guidelines and the microbiological parameters closely related to turbidity, as well as to reduce the chemical costs, further improvement and optimization in turbidity removal are necessary.

3.2. *Jar tests to determine the optimal coagulant dosage and slow mixing condition*

3.2.1. *Determination of optimal coagulant dosage*

A preliminary jar test was conducted for the inlet water to determine the optimal dosage of coagulant. Water samples were taken from the inlet of the WTP and the initial turbidity was measured as 52 NTU. Results showed that the residual turbidity and particle number decreased as the PACl dosage increased (Fig. 2). Under PACl dosage of 8 mg l^{-1}, colloid suspension was observed in the supernatant after 20 min settling and the residual turbidity was 5.3 NTU, which was beyond the current internal standard of 3 NTU for the settled water. When PACl dosage increased to 12 mg l^{-1} or more, larger flocs were formed after 5 min slow mixing and clearer supernatant was observed. The turbidity and particle numbers (> 2 μm) decreased to 2.9 NTU and 10,000 particle ml^{-1}, respectively at PACl dosage of 12 mg l^{-1}. At PACl dosage of 28 mg l^{-1}, the residual turbidity could be lowered to 0.91 NTU, and no re-stabilization was observed within the range of the PACl dosage change. Considering the chemical costs as well as operational performance, PACL dosage of 12 mg l^{-1} was considered as the dosage for optimization in the following further studies.

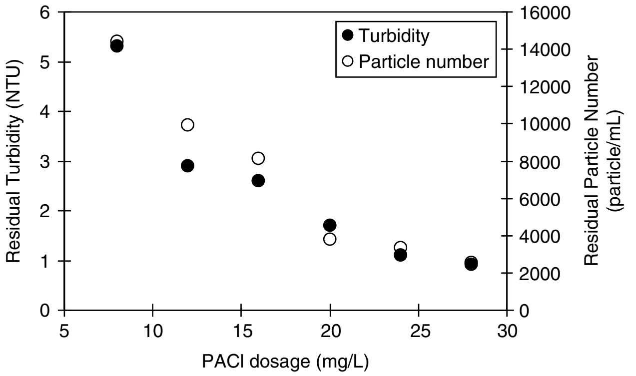

Fig. 2. Residual turbidity and particle at different PACl dosage.

3.2.2. *Flocculation under different flocculation time using 60 rpm*

Effect of flocculation time on the removal of turbidity was explored. Using different flocculation time, it showed that the residual turbidity decreased linearly as the flocculation time increase from 5 min to 20 min (Fig. 3), which suggests that a certain flocculation time was essential for maintaining satisfactory flocculation. When the flocculation time is too short, there may not be sufficient collision between particles for flocs formation. When the time reached 20 min, the residual turbidity was approximately 1 NTU, which can meet the new internal standard of Suez Environment. Besides, as the slowing mixing time increased to more than 20 min, the turbidity did not decrease much. Even though the higher velocity *G* would induce more turbulence in water, leading to more collisions among the particles within a given time, there would be an ultimate floc size due to a continuous breakdown of the large flocs, and thus there will be a limiting flocculation time beyond which floc particles will not grow (Bratby 2006). Compared to the tests using 40 rpm, under the same PACl dosage, the turbidity

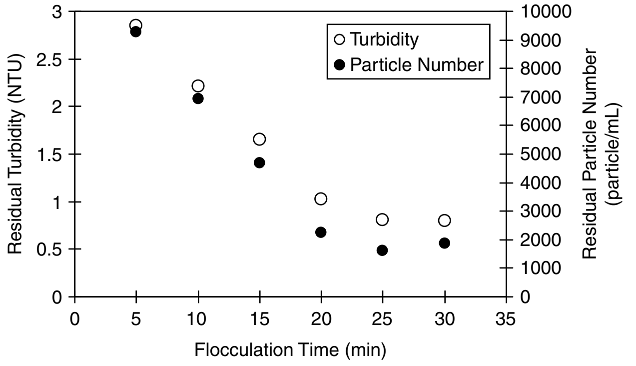

Fig. 3. Residual turbidity under different flocculation time.

removal using 60 rpm in this test increased from 2.9 NTU to 1 NTU. Considering the power consumption, the optimal flocculation time was taken as 20 min.

3.2.3. Flocculation under different slow tapered mixing

Using different types of slow tapered mixing and PACl dosage, it showed that the residual turbidity decreased as Gt or PACl dosage increased (Fig. 4). Compared to fixed rate mixing that produce the settled water of 2.9 NTU when Gt of 14,500 was applied (Fig. 1), the tapered mixing can further reduce the residual turbidity to 2.5 NTU. This result was consistent with previous studies [20] that tapered mixing helps the flocculation process, as the bigger the particle aggregates form, the more gentle agitation is required to avoid breaking up the existing aggregates. While keeping the PACl dosage of 12 mg l^{-1}, increasing the mixing Gt value to 29,000 that has the same value using fixed 60 rpm can further lower the turbidity to below 1 NTU.

3.2.4. Secondary flocculation

A secondary flocculation test was conducted to study the flocculability of the settled water after primary flocculation. The settled water with water turbidity of 2.4 NTU, was used to investigate the flocculation possibility, thus to further increase the turbidity removal for the remaining small particles, before filtration. It showed in Fig. 5 that the residual turbidity decreased from 2.4 NTU to 1 NTU after addition of second coagulant aid of 6 mg l^{-1} PACl, suggesting the secondary flocculation can solve the high turbidity problem in settled water to meet the new internal guideline of 1 NTU before filtration. It was also reported that secondary flocculation can improve the removal efficiency of algae and dissolved organic matters [8].

3.2.5. Correlation between particle numbers and turbidity

Large particles are more easily than small particles to form aggregate and would first settle in the sedimentation process, while the small particles form colloids are still in the settled water. Thus turbidity is a good indicator representing the particle number in the water. Fig. 6 showed that there are strong correlation between residual particle numbers and turbidity that measured in the previous tests. Besides, under the same particle number, the turbidity in the primary flocculation was higher than that in the secondary test, implying the very small particles (<2 μm) that was not detected by the particle counter and contributed to the turbidity, can be removed during the secondary flocculation, assuming the light-scattering properties of small particle suspension in both tests were the same.

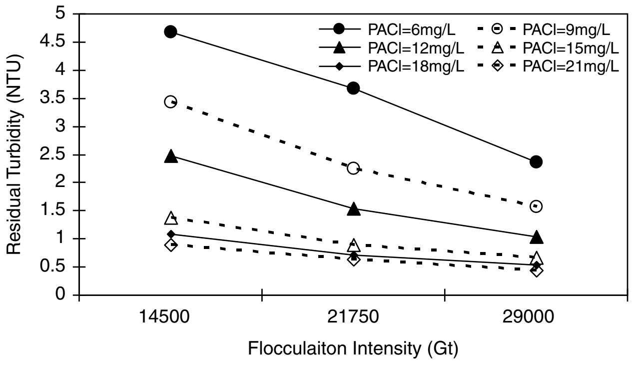

Fig. 4. Residual turbidity under different Gt value and PACl dosage.

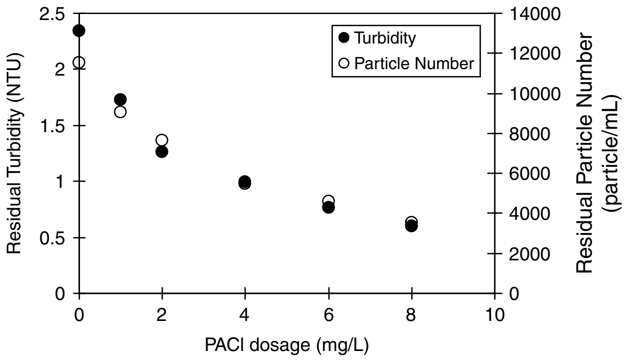

Fig. 5. Residual turbidity and particle number under different PACl dosage in the secondary flocculation test.

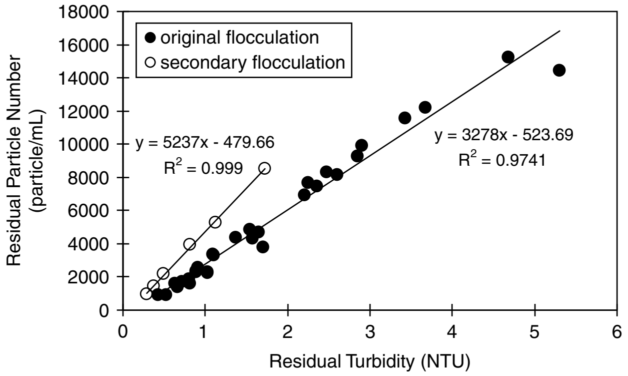

Fig. 6. Correlation of particle number and residual turbidity in the tests (Notes: in original flocculation, water samples were from the raw water while in secondary flocculation, the water samples were from settled water after the primary flocculation).

3.3. Filtration column test

Settled water with the turbidity of 3.23 NTU and the particle number of 8886 particles ml^{-1}, was used as influent for filtration. The results (Fig. 7) showed that more than 60% of the initial turbidity can be removed for both

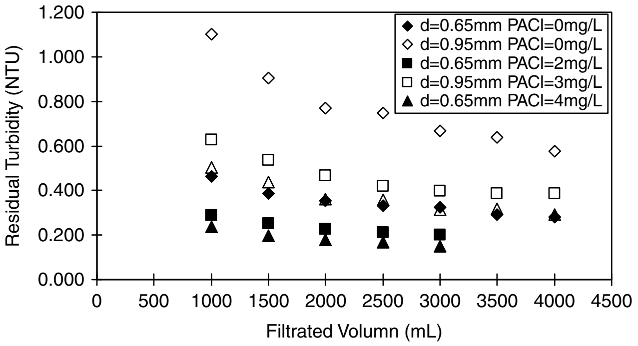

Fig. 7. Residual turbidity in the filtrate under different filter media size and coagulant dosage.

sizes of filter media. Without filter aid addition, the residual turbidity after 1000 ml water filtration was 1.1 NTU for 0.95 mm ES and 0.48 NTU for 0.65 mm ES. The 0.95 mm ES filter has 20% less turbidity removal efficiency than 0.65 mm ES filter. However, the smaller the grain size is, the slower the water moves through the media and the smaller amount of water that can be filtered, reducing the filtration flow rate, i.e., if equal amounts of water is filtered, small ES media increases the head loss and thus requires more frequent backwash. These are disadvantage using smaller ES media, even though it can increase the turbidity removal. In addition, as the filtered volume increase the difference of removal efficiencies became less and reached only 10% (0.58 NTU for 0.95 mm ES filter and 0.28 NTU for 0.65 mm ES filter), after the 4000 ml filtrated volume. Furthermore, addition of filter aid would greatly improve the turbidity removal, e.g., using 2 mg l^{-1} of PACl the residual turbidity after the first 1000 ml filtrated volume, the turbidity was 0.50 NTU for 0.95 mm ES filter and 0.29 NTU for 0.65 mm ES filter, which was only about one half of that without PACl addition. It was also noted that the 0.65 mm ES combined with the PACl dosage of 4 mg l^{-1}, the final residual turbidity can be reduced to 0.15 NTU, which meet the new internal standard of 0.2 mg l^{-1} for the outlet water.

To further understand the filtration mechanism of both filters, water samples after 1500 ml, 3000 ml and 4000 ml filtrated volume, were collected to determine the corresponding particle numbers and floc sizes (Fig. 8), from which the particle and turbidity removal efficiencies can be calculated (Fig. 9). The tests were performed without addition of coagulant aids. It was observed that the residual turbidity and particle numbers decreased with increasing the filtrated volumes. Large particles have high removal efficiency than small particles. 0.65 mm ES filter have higher particle and turbidity removal than 0.95 mm ES filter that after 1500 ml of water sample was filtered, more than 90% of particles can be removed using the 0.65 mm ES. Using the

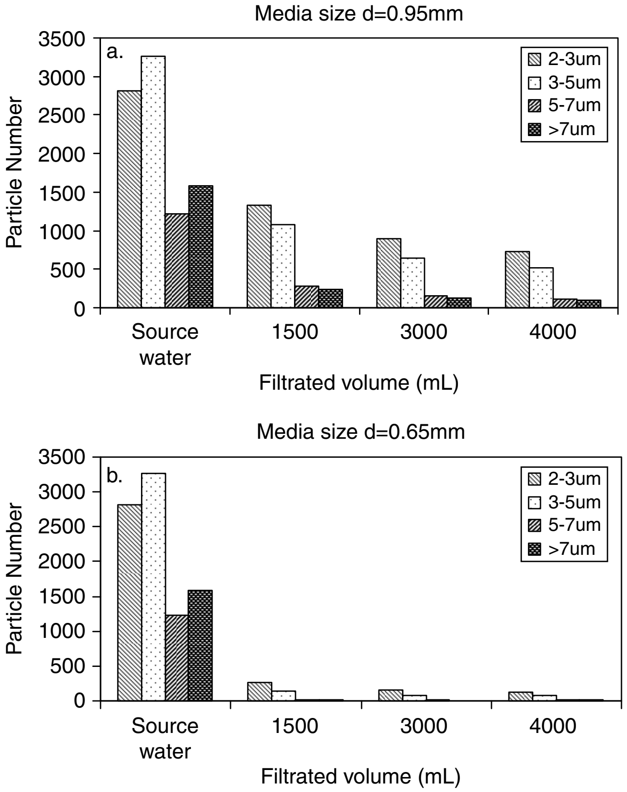

Fig. 8. Particle numbers and size distribution in the filtrate for (a) media size d = 0.95 mm and (b) media size d = 0.65 mm.

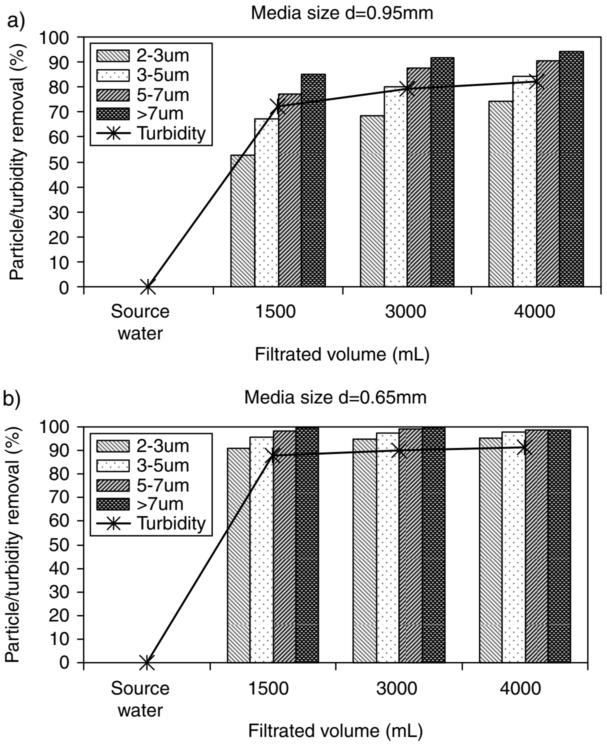

Fig. 9. Particle and turbidity removal percentages in the filtrate for (a) media size d = 0.95 mm and (b) media size d = 0.65 mm.

0.95 mm ES, the removal efficiency of larger particles (>7 µm) was much higher than that of smaller particles (2–3 µm) at the beginning of the test, with the removal efficiencies of 85% and 53%, respectively. However, when the filtration proceeded, the removal efficiency of smaller particles increased to 74% after 4000 ml filtrated volume. These results supported the mechanisms of straining, sedimentation and interception in the filtration, as small ES media has small openings that retain the particles.

Comparing the residual turbidity and the particle removal efficiencies (Fig. 9), it was found that using both media the turbidity removal was lower than the removal of particles with sizes greater than 3 µm, suggesting that small particles contributed to turbidity more than large particles. As the particle counter can only determine the number of particles greater than 2 µm, the diffusion mechanism applied to small particles (typically <2 µm) cannot be verified in the studies. However, using 0.95 ES media, the 2–3 µm particles removal efficiency is lower than the turbidity removal efficiency, which can be hypothesized that some portion of the small particles less than 2 µm was removed by other mechanism, probably by diffusion. The mechanism of diffusion will be systematically investigated in the future study. Thus, to increase the turbidity removal in filtration, addition of coagulant acid to increase particle sizes, and using the smaller media filter will be the effective approaches.

4. Conclusions

Jar tests and filtration column tests were performed to improve the turbidity removal of the conventional coagulation-flocculation-filtration process in Changshu WTP to meet the new internal standard for turbidity with reducing chemical and power consumption. The parameters investigated were coagulant dosage, flocculation mixing time, tapered mixing and filter media size. The results showed that using PACl dosage of 12 mg l^{-1} with the tapered mixing for 20 min (Gt = 29,000), or implementing an additional secondary flocculation process with 6 mg l^{-1} PACl, can reduce the settled water turbidity to 1 NTU. Secondary flocculation process can further remove the smaller particles that retained in the settled water. However it would need more space for construction additional settling tank. It was found that there were strong correlation between turbidity and particles. Besides, small particles contributed to turbidity more than large particles in the filtration, and compared to 0.95 mm ES, 0.65 mm ES with 4 mg l^{-1} PACl filter aid can reach the residual outlet water to below 0.15 NTU. The approaches will be further studied in the full-scale Changshu WTP.

Acknowledgements

This project was supported by Sino French Water Research Fund, Fundo para o Desenvolvimento das Ciencias e da Tecnologia (FDCT), under grant No. 016/2011/A and Research Committee at University of Macau under grant No. MRG002/LIC/2012. The authors are very grateful to all staffs of Technical Department in Changshu Sino-French Water Supply Co. Ltd., who provided full supports to this research.

References

[1] M.W. LeChevallier and W.D. Norton, Treatments to Address Source Water Concerns: Protozoa. Safety of Water Disinfection: Balancing Chemical and Microbial Risks, G.F. Craun (ed.), ILSI Press, Washington, D.C., 1993.

[2] K.R. Fox, Turbidity as It Relates to Waterborne Disease Outbreaks. Presentation at M/DBP Information Exchange, Cincinnati, Ohio, AWWA white paper, 1995.

[3] J. Bratby, Coagulation and Flocculation in Water and Wastewater Treatment, IWA publishing, London, UK, 2006.

[4] A. Amirtharagjah and C.R. O'Meli, Coagulation Processes: Destabilzation, Mixing, and Flocculation. Water Quality and Treatment: A Handbook of Community Water Supplies, F.W.A.W.W.A. Pontius (ed.), McGraw-Hill, New York, 1990.

[5] K. Miyanami., K. Tojo and Y. Yokota, Effect of mixing on flocculation, Ind. Eng. Chem. Fundam., 21 (1982) 132–135.

[6] W.Y. Sheng, X.F. Peng and D.J. Lee, Coagulation of particles through rapid mixing, Drying Technol., 24 (2006) 1271–1276.

[7] J. Churchill, M.W. Beutel and P.S. Burgoon, Evaluation of optimal dose and mixing regime for alum treatment of Matthiesen creek inflow to Jameson Lake, Washington, Lake Reservoir Manage., 25 (2009) 102–110.

[8] A.W. Timonthy and G.P. Nicholas, Optimizing filter performance, J. New Engl. Water Works Assoc., 3 (1999) 6–21.

[9] K.J. Ives and J. Gregory, Basic concepts of filtration, Proc. Soc. Water Treat. Exam., 16 (1967) 147–169.

[10] C.R. O'Melia and W. Stumm, Theory of water filtration, J. AWWA, 59 (1967) 1393–1412.

[11] K.M. Yao, M.T. Habibian and C.R. O'Melia, Water and waste water filtration: concepts and applications, Environ. Sci. Technol., 5 (1971) 1105–1112.

[12] J.S. Chang, S. Vigneswaran and J.K. Kandasamy, Effect of pore size and particle size distribution on granular bed filtration and microfiltration, Sep. Sci. Technol., 43 (2008) 1771–1784.

[13] H. Zhu, D.W. Smith and H. Zhou, Improving removal of turbidity causing materials by using polymers as a filter aid, Water Res., 30 (1996) 103–114.

[14] CEPB, Analysis Method for Monitoring Water and Waste. Environmental Science Press, Beijing, China, 2002.

[15] A. Halawik, Effect of Aluminium and iron salts in coagulation on turbidity removal of Yangtze River, J. Hehai Univ. (Nat. Sci.), 29 (2001) 114–118.

[16] Y. Zhang, Y.X. Li and J. Jia, Studies on turbidity removal of tiny polluted autumn Yangtze River raw water using composite coagulants of polyaluminum chloride, Fine Chem., 26 (2009) 493–497.

[17] S.K. Dentel and J.M. Gossett, Mechanisms of coagulation with aluminum salts. J. AWWA, 80 (1988) 187–198.

[18] W.P. Cheng, F.H. Chi and C.C. Li, A study on the removal of organic substances from low-turbidity and low-alkalinity water with metal-polysilicate coagulants, Colloids Surf., 312 (2008) 238–244.

[19] US EPA, Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual, United States Environmental Protection Agency, 1999.

[20] M. James, Water Treatment Principles and Design. Wiley-Interscience, John Wiley & Sons, New York, 1985.