Removal of natural organic matter for controlling disinfection by-products formation by enhanced coagulation: A case study

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ABSTRACT

Increasingly stringent drinking water standards raise challenges to many drinking water treatment plants (DWTPs) currently treating seriously polluted source waters. This plant-scale field study investigates the feasibility and technological strategies for process improvement for the Luwen (LW) DWTP, a typical plant with conventional processes employed to treat source water heavily polluted by natural organic matter (NOM). Originally, the LW DWTP exhibits DOC removal efficiency as low as 14.4% for filtration effluents; and COD_{Mn} concentrations continually exceed the required (<3 mg/L) for half a year. High doses of chlorine during pre- and post-chlorination at this DWTP lead to the formation of high-level total trihalomethane (TTHMs). Decreasing the dosages of chlorine during pre-chlorination from 3.5 to 2 mg/L obviously inhibit TTHMs formation from 0.98 to 0.54 for influents of this plant, but showed limited efficiency for its effluents due to the high chlorine demand of this source water. The combined use of KMnO₄ and FeCl₃ significantly enhanced COD_{Mn} removal, and the removed COD_{Mn} quantity by coagulation increased from 0.60 to 2.22 mg/L whereas that by chlorination decreased from 1.66 to 0.67 mg/L. In other words, the contributive ratios of chlorination on COD_{Mn} removal decreased from 73.5% to 23.2%. This enhanced coagulation strategy also reduced the required dosages of chlorine from 6.26 to 4.85 mg/L, and the formation of TTHMs decreased by 24.8% accordingly.

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1. Introduction

Natural organic matter (NOM) holds significance due to its reactivity to chlorine and the formation of disinfection by-products (DBPs) [1–3]. NOM is different from various chemicals which may be controlled by minimizing the discharge of wastewater; however, it is widely present in various drinking water sources such as lakes, rivers, reservoirs and so on. The control of NOM-related DBPs is a great challenge to many drinking water treatment plants (DWTPs) in different countries [4–6].

In China, the conventional treatment processes of coagulation, sedimentation, filtration, and disinfection are widely used. Many of these plants using conventional treatment processes were designed and constructed several decades ago under less stringent regulation. At that time, water sources had higher water quality and the drinking water standards were not as stringent as they are today. However, the newly issued National Drinking Water Standard required increasingly strict requirements on water quality [7]. For example, this standard has required that the concentrations of as many as 16 DBPs species [i.e., trihalomethanes (THMs), haloacetic

acids (HAAs)] be below the MCLs levels. Additionally, under normal conditions the concentration of chemical oxygen demand (COD_{Mn}) in DWTPs effluents is required to be below 3 mg/L. In case the COD_{Mn} concentrations in source water are above 6 mg/L, the COD_{Mn} values should be lower than 5 mg/L. These requirements raise technical challenges to many DWTPs such as the Luwen (LW) DWTP in China. At the LW DWTP, effluent levels of COD_{Mn} and the total trihalomethane (TTHM) exceeded the regulatory standard by 27–40% and 60–110%, respectively. The enhanced removal of NOM (i.e., DBPs precursors) is important for these DWTPs to meet the water quality standards of both COD_{Mn} and DBPs.

The removal of NOM by enhanced coagulation is defined by the U.S. EPA as the best available technology to control the formation of DBPs in conventional treatment processes. This strategy may be achieved by significantly increasing the dosages of coagulant, adjusting pH to optimum ranges, and introducing pre-oxidation [8]. However, very few studies focused on the introduction of another coagulant to enhance the removal of NOM and control DBPs formation, rather than increasing the dosage of the originally-used coagulants. Basically, the different coagulant species shows critically different behaviors towards colloids and NOM, with different dominant mechanisms involved in. On the other hand, in cases where pre-chlorination resulted in the significant formation of

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DBPs, the substitution of chlorine by other oxidants should be considered [9]. Potassium permanganate (KMnO_4) is another feasible option for oxidation due to its affordability and minimum need for the installation of additional facilities. The *in situ* formed manganese dioxide ($\delta\text{-MnO}_2$) shows adsorptive activity towards NOM, and it may also act as nuclei and aid coagulation by seeding effects to benefit the removal of NOM [10,11]. Generally, the KMnO_4 doses should be below 2 mg/L to avoid side effects such as the elevated levels of color and residual Mn. The introduction of coagulant may enhance the adsorption capability towards organic species. Consequently, the combined use of coagulant and KMnO_4 to substitute pre-chlorination may be valuable to achieve two goals between disinfecting and enhancing NOM removal, and this should be well evaluated before adopting these techniques in practice.

This study focused on source water with high concentrations of NOM, and aimed to: (1) propose feasible technological strategies to enhance the removal of NOM and to minimize DBPs formation; (2) optimize the operational parameters by conducting a plant-scale field study.

2. Materials and methods

2.1. Reagents

Unless specifically noted, all the reagents used in this study were of industrial grade. Commercial poly aluminum chloride (PACl) was purchased from a purification-reagent company in Henan province, China, and used in the LW DWTP as the coagulant. The basicity of this PACl was in the range of 85–95%, and the ratio of active species was above 10% as Al_2O_3 . The other coagulants [i.e., PAFC, CAF001] used in jar tests were provided from other companies.

2.2. Experimental methods

2.2.1. Description of the treatment processes of the LW DWTP

LW DWTP uses water coming from Weishan Lake as its source. The main water properties are presented in Table S1. Raw water is pumped at the 1st pump station and enters the plant after about 12 h. The LW DWTP, with the designed treatment scale of 200,000 m^3/d , includes the main processes of static mixing, coagulation, laminar sedimentation, quartz sand filtration, and post-chlorination. The exact treatment scale is adjusted by the water level of the clean water basin, and the normal scale is in the range from 85,000 to 120,000 m^3/d .

2.2.2. Jar tests

Batch jar experiments were conducted in glass beakers with rapid-mixing (160 rev/min, 2 min). Soon after dosing reagents at desired dosages, this was followed by slow-mixing (40 rev/min, 15 min) and static settling for 30 min. In order to simulate the addition of reagents (i.e., FeCl_3 , KMnO_4 , and chlorine) at the 1st pump station, the water was kept still for 12 h after dosing these reagents. After that, jar tests were conducted in aforementioned procedures.

While investigating the dynamic variation of flocs diameter, the procedures of rapid-mixing (200 rev/min, 1 min) and the subsequent slow-mixing (40 rev/min, 10 min) were preceded. The samples were continuously withdrawn at 10 mm below the water level with a peristaltic pump for on-line measurement of the particles diameter. In this experiments, the aluminum chloride (AlCl_3 , A.G.), ferric chloride (FeCl_3 , A.G.), and KMnO_4 (A.G.) were used.

2.2.3. Fractionation of the organic matter in water

Raw water and filtration effluent were analyzed for molecular weight distribution after filtering through 0.45 μm membrane filters. These two samples were fractionated into six fractions using a stirred ultrafiltration cell device (Model 8200, Amicon, Millipore) with nominal molecular weight cutoffs of 3, 10, 30, 100, and 300 kDa regenerated cellulose membranes (PL, 63.5 mm, Millipore). Fractionation methodology followed the procedure of Kitis et al. [12]. The DOC and UV_{254} values of each size fraction were also measured; and the specific UV absorbance at 254 nm (SUVA) was obtained by dividing UV_{254} by DOC.

2.2.4. DBPs formation potential

Prior to the addition of chlorine, all water samples were adjusted to $\text{pH } 7.0 \pm 0.2$. After dosing 20 mg/L of chlorine, samples were capped and kept in an incubator at 20 °C for 72 h. After 72 h, all samples were found to have measurable residual free chlorine. The THMs and HAAs in these samples were also measured, and then the THM formation potential (THMFP) and HAA formation potential (HAAFP) were calculated by dividing the measured THMs and HAAs by DOC.

2.2.5. Plant-scale field study

There was no substantial change to the treatment processes within this DWTP during plant-scale field study except the installation of two facilities for the preparation and dosing of chemicals, i.e., KMnO_4 , FeCl_3 . These two reagents were dosed simultaneously at the suction well of the 1st pump station, and were well mixed inside the pumps. The doses of KMnO_4 and FeCl_3 were 0.6–0.8 mg/L as KMnO_4 and 0.5–1.0 mg/L as Fe, which were adjusted according to the water quality in effluents of sedimentation and filtration processes.

2.3. Analysis and instruments

THMs and HAAs samples were measured following U.S. EPA Methods 551 and 552.3 [13] using a gas chromatograph (6890 N, Agilent) with an electron capture detector (ECD). The total THM (TTHM) was calculated according to Eq. (1). National drinking water standards require that TTHM values should be below 1 [7].

$$\text{TTHMs} = [\text{CHCl}_3]/0.06 + [\text{CHCl}_2\text{Br}]/0.06 + [\text{CHClBr}_2]/0.1 + [\text{CHBr}_3]/0.1 \quad (1)$$

Turbidity was determined with a 2100 N turbidity meter (Hach Co., USA). The COD_{Mn} concentrations were measured according to the standard methods (State Environment Protection Bureau, 1997). Chlorine concentrations were determined by the *N,N*-diethyl-*p*-phenylenediamine (DPD) titrimetric method [14]. A laser particle size analyzer 2000 (Malvern, UK) was used to monitor the dynamic variation of particle size distributions (PSD) of the flocs.

3. Results and discussion

3.1. Characterization of individual components of DOM in raw water

Table 1 illustrates the main characteristics of the organic species in the source water of the LW DWTP. The high DOC level of 6.38 mg/L indicated serious contamination of the DWTP source water. The molecular weight distribution was 29.0, 15.7, 20.2, 16.1, and 8.4% for >100, 30–100, 10–30, 3–10, and <3 kDa, respectively. The species with molecular weight of >30 kDa, which was normally considered to be easily removed by coagulation, constituted 40.8% of the total DOC. However, the species with a molecular weight below 10 kDa were 41.7% of the total DOC.

Table 1

Characterization of individual components of DOM in raw water (Sampling time: April, 28th, 2009).

	DOC		UV ₂₅₄	SUVA	THMsFP	HAA5FP
	mg/L	%	cm ⁻¹	L/cm tmg	μg/mg C	
Raw water (kDa)	6.38	–	0.110	1.72	19.55	17.95
>100	1.85	29.0	0.033	1.78	17.22	15.90
30–100	1.00	15.7	0.017	1.70	18.79	14.36
10–30	1.29	20.2	0.028	2.17	22.30	16.92
3–10	1.03	16.1	0.020	1.94	18.47	17.54
<3	1.81	28.4	0.031	1.71	17.78	18.35

Additionally, the raw water had a SUVA value of 1.72 L/cm mg and the formation potential of THMs and HAAs were 19.55 and 17.95 μg/mg C, respectively. The DOM species with molecular weights in the range of 10–30 KDa exhibited the highest SUVA value of 2.17 L/cm mg and the maximum THMFP of 18.79 μg/mg C. However, the species with molecular weight below 3 KDa showed the maximum HAAFP of 18.35 μg/mg C and contributed to significant formation of HAAs.

3.2. Description of the operation of the LW DWTP before adopting process adjustment

3.2.1. Characteristics of individual components of DOM after sand filtration

Table 2 lists the main water properties after sand filtration at LW DWTP. The high DOC concentration of 5.46 mg/L corresponded to a low DOC removal efficiency of 14.4% after the treatment processes of pre-chlorination, coagulation, sedimentation, and filtration. Additionally, the ratio of low-molecular species (i.e., <10 KDa) increased from 41.7% to 54.0%. This was ascribed to the removal of high-molecular species by coagulation and the formation of DOM species with low molecular weight after chlorination.

This process contributed to a more significant decrease of UV₂₅₄ values with a UV₂₅₄ removal efficiency of 38.2%, in comparison to the removal efficiency of DOC. The species with a molecular weight of >100 KDa also showed this trend, where the DOC concentration decreased from 1.85 to 0.99 mg/L (removal efficiency of 46.5%) and the UV₂₅₄ decreased from 0.033 to 0.008 cm⁻¹ (removal efficiency of 75.8%). The DOM species with higher molecular weight exhibited a larger decrease in UV₂₅₄ than those with lower molecular weight. For example, the species with a molecular weight of >30 KDa showed UV₂₅₄ removal efficiency of 66.0%, whereas those species with a molecular weight of <10 KDa exhibited removal efficiency rates as low as 13.7%. The combined effects of DOC and UV₂₅₄ decreased SUVA, THMsFP, and HAAsFP, especially for DOM species of higher molecular weight.

3.2.2. Removal of turbidity and COD_{Mn} in the LW DWTP

Fig. 1 shows the variation of turbidity and COD_{Mn} in the LW DWTP before process modification. The original water treatment processes showed good capability of removing turbidity (Fig. 1a).

Table 2

Characterization of individual components of DOM after sand filtration (Sampling time: April, 28th, 2009).

	DOC		UV ₂₅₄	SUVA	THMsFP	HAA5FP
	mg/L	%	cm ⁻¹	L/cm mg	μg/mg C	
Filtration effluents (kDa)	5.46	–	0.068	1.25	14.39	13.33
>100	0.99	18.1	0.008	0.81	9.03	8.80
30–100	0.78	14.3	0.009	1.15	10.87	11.96
10–30	1.16	21.2	0.016	1.38	13.87	13.84
3–10	1.05	19.2	0.014	1.33	18.24	13.62
<3	1.90	34.8	0.030	1.58	17.89	18.11

Fig. 1. Variation of (a) turbidity and (b) COD_{Mn} in the LW DWTP before adopting process adjustment (April 1st, 2009 to May 27th, 2009).

The average turbidity in influents was relatively low at 3.30 NTU, and further decreased to 1.33 NTU after sedimentation and 0.25 NTU after filtration. The average removal efficiency of turbidity was 59.5% and 81.0% for the units of sedimentation and filtration.

However, the original process exhibited limited removal efficiency towards COD_{Mn} (Fig. 1b). The influents of the LW DWTP showed an average COD_{Mn} value of 4.73 mg/L, with the highest and lowest values being 5.41 and 4.02 mg/L, respectively. From April 1st to May 27th, 2009, all effluents exceeded the regulatory standard of COD_{Mn} below 3 mg/L. The only exception was April 20th, when the COD_{Mn} was 2.91 mg/L. The average COD_{Mn} concentration in effluents was 3.36 mg/L, with an average removal efficiency of 29.0% by these unit processes of coagulation, sedimentation, filtration, and post-chlorination. It was noted that the dosing of chlorine in the 1st pump station contributed to the average COD_{Mn} removal efficiency of 15.5% after the 12-h transportation of source water.

3.2.3. DBPs formation at different units of the LW DWTP

From April 1st to May 27th, 2009, the average dosages of chlorine during pre-chlorination and post-chlorination were 2.86 and 3.38 mg/L, and the total dosage was as high as 6.25 mg/L as chlorine. The high doses of chlorine inevitably lead to the formation of elevated levels of DBPs, although it also resulted in a decrease in COD_{Mn} concentrations. Fig. 2 below indicates the formation of

Fig. 2. THMs formation in different units of the LW DWTP before adopting process adjustment (October 24th, 2008 to May 20th, 2009).

TTHMs at different points in the LW DWTP. Pre-chlorination at the 1st pump station resulted in TTHMs formation levels as high as 0.74. Following the unit processes of coagulation, sedimentation, and filtration, TTHMs exhibited a slight increase to 0.77. Post-chlorination further enhanced the formation of TTHMs, which increased to 1.19 in effluents and to 1.46 in the distribution system.

3.3. Technological strategies for enhanced removal of COD_{Mn} and control of DBPs formation

3.3.1. The reduction of chlorine dosages during pre-chlorination to reduce DBPs formation

The reduction of chlorine dosage during pre-chlorination is a strategy to minimize the formation of DBPs. During the period from May 3rd to May 27th, the LW DWTP began to decrease the dosages of chlorine during pre-chlorination (Fig. S1). Fig. 3 compares the TTHMs formation after reducing chlorine dosages. It indicated that the dosages during post-chlorination should be increased to maintain the residual chlorine levels at the end-points in the distribution system. The total chlorine dosages decreased slightly from 6.36 to 6.10 mg/L accordingly. The positive effect of decreasing chlorine dosage on the control of TTHMs formation was also observed. The TTHMs levels at different points correspondingly decreased from 0.98 to 0.54 for influents, from 1.24 to 1.15 for effluents, and from 1.59 to 1.38 for the sampling points in distribution system. It was noted that the COD_{Mn} concentrations still exceed 3 mg/L after reduction of the chlorine dosages during chlorination.

3.3.2. Enhanced coagulation by combined use of FeCl_3 and KMnO_4

Bench scale study: Table 3 illustrates the effects of KMnO_4 and FeCl_3 on the removal efficiency of COD_{Mn} by three different coagulants of PACI, PAFC, and CAF001. It was observed that the combined use of KMnO_4 and FeCl_3 were beneficial in the removal of COD_{Mn} by coagulation, further contributing to an increase in removal efficiency. Quantitatively, PACI at 10 mg/L contributed to a removal efficiency of 7.8%, which increased to 14.4% and 11.8% due to the addition of 1 mg/L of KMnO_4 and 3 mg/L of FeCl_3 . The combined use of KMnO_4 and FeCl_3 further increased the removal efficiency to 23.4%. The elevated removal efficiency of COD_{Mn} was also observed for other coagulants as PAFC and CAF001.

Fig. 3. The decrease of chlorine dosages during pre-chlorination (a) and its effects on TTHMs formation (b).

Table 3

Enhanced coagulation for NOM removal by combined use of FeCl_3 and KMnO_4 .

KMnO_4 (mg/L)	FeCl_3 (mg/L)	Coagulants and dosages	Residual COD_{Mn} (mg/L)	COD_{Mn} removal (%)
–	–	10PACI*	5.46	7.8
1	–	10PACI	5.07	14.4
–	3	10PACI	5.22	11.8
1	3	10PACI	4.59	23.4
–	–	15PACI	3.92	30.0
0.6	3	15PACI	3.28	41.4
–	–	10PAFC	5.04	8.7
0.6	3	10PAFC	4.40	20.3
–	–	15CAF001	5.23	5.3
0.6	3	15CAF001	4.53	17.9

* Note: 10PACI means 10 mg/L of PACI.

The enhanced removal of COD_{Mn} was first ascribed to the positive effects of KMnO_4 and FeCl_3 on the formation of larger flocs. In the coagulation by AlCl_3 at 1 mM, the average diameter [$d(0.5)$] of flocs was 317.3 μm . The introduction of 0.05 mM FeCl_3 increased the $d(0.5)$ to 352.2 μm , and the additional KMnO_4 at 0.0165 mM further increased the $d(0.5)$ to 393.6 μm , accordingly. The flocs with larger diameters were more easily removed in the subsequent unit processes of sedimentation and filtration than the smaller size flocs [11]. On the other hand, the Fe(III) hydroxide precipitates and the MnO_2 from KMnO_4 reduction showed different adsorption behaviors towards NOM from Al precipitates, therefore favoring the removal of the NOM species that could not be removed by Al coagulation.

Moreover, the pre-chlorination process may be substituted by the combined use of KMnO_4 and FeCl_3 with respect to the removal of COD_{Mn} (Table S2). This technological strategy avoided the addition of chlorine in raw water and minimized the potential formation of disinfectant by-products as much as possible. Considering the low levels of microorganisms (i.e., total bacteria, total coliforms, thermotolerant coliforms) present in the source water (Fig. S2), this strategy would not lead to increased risks.

Plant-scale field study: Based on the aforementioned considerations, the KMnO_4 and FeCl_3 were simultaneously dosed at the suction well of the 1st pump station as a surrogate pre-chlorination strategy for process improvement. In the long-term field study, the dosages of KMnO_4 and FeCl_3 were adjusted at intervals to evaluate the efficiency and to optimize this process. Table 4 compared the removal of COD_{Mn} by different unit processes, along with the contributive ratios of chlorination after process improvement adoption.

Before adoption of process improvement using KMnO_4 and FeCl_3 , pre-chlorination contributed to an average COD_{Mn} removal efficiency of 15.7%, which corresponded to 0.88 mg/L as COD_{Mn} . The average COD_{Mn} concentrations in influents and effluents of the LW DWTP was 4.74 and 3.36 mg/L, and the treatment processes of coagulation, sedimentation, filtration, and post-chlorination contributed to the COD_{Mn} removal efficiency of 29.0%. The entire process removed a total of 2.26 mg/L of COD_{Mn} , and the contributive ratio of chlorine was as high as 73.5%.

In comparison, during the field study periods after adopting process improvement, the COD_{Mn} level in raw water increased slightly to 5.79 mg/L. The combined use of KMnO_4 and FeCl_3 resulted in a removal efficiency of 12.2%, and the COD_{Mn} concentration in influents at 5.09 mg/L. After that, the COD_{Mn} concentrations in effluents of sedimentation and filtration decreased to 3.91 and 3.58 mg/L. Post-chlorination further reduced the COD_{Mn} concentration to 2.91 mg/L. The whole process altogether removed 2.89 mg/L of COD_{Mn} , and the total removal efficiency of COD_{Mn} increased from 40.2% to 49.8%. Additionally, the chlorine played a less

Table 4The removal of COD_{Mn} by different unit processes, and the contributive ratios of chlorination after process improvement adoption.

		Raw water	Inf.	After Sed.	After Fil.	Eff.	Total
Before adopting process improvement	Residual COD _{Mn} (mg/L)	5.62	4.74	N.A.	N.A.	3.36	–
	Removal efficiency (%)	–	15.7%	N.A.	N.A.	29.0%	40.2%
	Removed COD _{Mn} (mg/L)	Pre-chlorination		Coag. + Sed. + Fil.			2.26
		0.88		1.38			
	Contributive ratio of chlorine (%)	–	–	–	–	–	73.5%
After adopting process improvement	Residual COD _{Mn} (mg/L)	5.79	5.09	3.91	3.58	2.91	–
	Removal efficiency (%)	–	12.2%	23.1%	8.4%	18.8%	49.8%
	Removed quantity (mg/L)	KMnO ₄ + FeCl ₃		Coag. + Sed.	Fil.	Post-chlor.	2.89
		0.71		1.17	0.33	0.67	
	Contributive ratio of chlorine (%)	–	–	–	–	–	23.2%

important role in COD_{Mn} removal, with the contributed ratio decreasing to as low as 23.2%.

This process improvement demonstrated increased efficiency for the enhanced removal of NOM and the control of DBPs formation. The rate of COD_{Mn} meeting the State regulation requirement of (<3 mg/L) increased from 0.9% in the control periods to 90.1% in the field-study periods. In addition, the improved processes reduced the average dosages of chlorine from 6.26 to 4.85 mg/L, along with reducing TTHMs formation by 24.8%.

4. Conclusions

There are quite a few DWTPs that are facing similar technological challenges to balance the conflicts between more seriously polluted source waters and increasingly stringent drinking water regulations, especially in developing countries. Additionally, the large-scale upgrading of individual unit process within drinking water treatment plants is sometimes inhibited by other factors including inadequate funding. This study indicated the feasibility of resolving the NOM and DBPs issues by unit process improvements such as enhanced coagulation with combined use of KMnO₄ and FeCl₃ and reducing the dosages of chlorine during pre-chlorination. This technological strategy enhances the removal of COD_{Mn} by coagulation rather than by chlorination, and reduces the interactions between NOM and chlorine and the consequent formation of DBPs. However, the molecular weight distribution of NOM in the raw water and effluents should be well evaluated before adopting the enhanced coagulation strategy. Other consideration such as using chloramines as a substituted disinfectant, and using ozonation with granular activated carbon should also be included and evaluated in cases where enhanced coagulation could not resolve these problems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.seppur.2011.07.009](https://doi.org/10.1016/j.seppur.2011.07.009).

References

- [1] P. Roccaro, H.S. Chang, F.G.A. Vagliasindi, G.V. Korshin, Differential absorbance study of effects of temperature on chlorine consumption and formation of disinfection by-products in chlorinated water, *Water Res.* 42 (8–9) (2008) 1879–1888.
- [2] Hua Zhang, Jiuhui Qu, Huijuan Liu, Dongbin Wei, Characterization of dissolved organic matter fractions and its relationship with the disinfection by-product formation, *J. Environ. Sci.* 21 (1) (2009) 54–61.
- [3] C.M.M. Bougeard, E.H. Goslan, B. Jefferson, S.A. Parsons, Comparison of the disinfection by-product formation potential of treated waters exposed to chlorine and monochloramine, *Water Res.* 44 (3) (2010) 729–740.
- [4] E.H. Goslan, S.W. Krasner, M. Bower, S.A. Rocks, P. Holmes, L.S. Levy, S.A. Parsons, A comparison of disinfection by-products found in chlorinated and chloraminated drinking waters in Scotland, *Water Res.* 43 (18) (2009) 4698–4706.
- [5] T. Bond, E.H. Goslan, S.A. Parsons, B. Jefferson, Disinfection by-product formation of natural organic matter surrogates and treatment by coagulation, MLEX® and nanofiltration, *Water Res.* 44 (5) (2010) 1645–1653.
- [6] T.H. Boyer, P.C. Singer, Bench-scale testing of a magnetic ion exchange resin for removal of disinfection by-product precursors, *Water Res.* 39 (7) (2005) 1265–1276.
- [7] Ministry of Health of PR China and Standardization Administration of P.R.China, Sanitary Standard for Drinking Water (GB5749–2006), 2007.
- [8] USEPA. Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual. EPA 815-R-99-012, 1999.
- [9] USEPA. Alternative disinfectants and oxidants guidance manual. EPA 815-R-99-014, 1999.
- [10] R.P. Liu, H.J. Liu, Z.M. Qiang, J.H. Qu, G.B. Li, D.S. Wang, Effects of calcium ions on surface characteristics and adsorptive properties of hydrous manganese dioxide, *J. Colloid Interface Sci.* 331 (2) (2009) 275–280.
- [11] R.P. Liu, Effectiveness and mechanisms of permanganate and permanganate composites removing pollutants through integrated oxidation and adsorption [Doctoral thesis], Harbin Institute of Technology, Harbin.
- [12] M. Kitis, T. Karanfil, A. Wigton, J.E. Kilduff, Probing reactivity of dissolved organic matter for disinfection byproduct formation using XAD-8 resin adsorption and ultrafiltration fractionation, *Water Res.* 36 (15) (2002) 3834–3848.
- [13] USEPA. Methods for the Determination of Organic Compounds in Drinking Water Supplement I. U.S. EPA: Cincinnati, OH, 1990.
- [14] American Public Health Association, American Water Works Association, Water Environment Association. Standard Methods for the Examination of Water and Wastewater, APHA, Washington, DC, 1998.