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Selection of magnetic anion exchange resins for the removal of dissolved organic and inorganic matters

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Abstract

Four magnetic anion exchange resins (MAERs) were used as adsorbents to purify drinking water. The effect of water quality (pH, temperature, ionic strength, etc.) on the performance of MAER for the removal of dissolved organic matter (DOM) was also investigated. Among the four studied MAERs, the strong base resin named NDMP-1 with high water content and enhanced exchange capacity exhibited the highest removal rate of dissolved organic carbon (DOC) (48.9% removal rate) and UV-absorbing substances (82.4% removal rate) with a resin dose of 10 mL/L after 30 min of contact time. The MAERs could also effectively remove inorganic matter such as sulfate, nitrate and fluoride. Because of the higher specific UV absorbance (SUVA) value, the DOM in the raw water was found to be removed more effectively than that in the clarified water by NDMP resin. The temperature showed a weak influence on the removal of DOC from 6 to 26°C, while a relatively strong one at 36°C. The removal of DOM by NDMP was also affected to some extent by the pH value. Moreover, increasing the sulfate concentration in the raw water could decrease the removal rates of DOC and UV-absorbing substances.

Key words: magnetic anion exchange resins; dissolved organic matter; inorganic anions; water quality

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Introduction

Dissolved organic matter (DOM) in water is a mixture of aromatic and aliphatic hydrocarbon structures with attached functional groups (Leenheer and Croué, 2003; Leenheer, 2007; Xie et al., 2012). DOM can add color, taste and odor to raw drinking water (Christman and Ghassemi, 1966); contribute to biological re-growth in the distribution network (Van der Kooij et al., 1995; Vrouwen-velder et al., 2000) and produce undesirable disinfection byproducts (DBPs) after chemical disinfection (Minear and Amy, 1996; Reckhow et al., 1990; Humbert et al., 2007; Yan et al., 2007; Zhang et al., 2009). Thus, DOM has adverse effects on drinking water treatments and the quality of produced water (Ates et al., 2007; Gao and Yue, 2005; Liu et al., 2005).

Anion exchange is a potential strategy for removing DOM from raw drinking water and controlling the formation of DBPs (Singer and Chang, 1989). The mechanism for the removal of DOM is the exchange between DOM acids and other ions such as chloride ions, rather than physical adsorption (Tan, 2005). In a recent study, Bolto et al. (2004) investigated the performance of 19 anion exchange resins (AERs) for the removal of DOM in synthetic waters. Strong base AERs were found to be

the most efficient (59%–99% UV-absorbance removal) and presented relatively short equilibrium time ranging from 6 to 42 min (Bolto et al., 2002). The conventional implementation of ion exchange must be as a fixed bed. However, magnetic anion exchange resins named MIEX after special modification can be used to remove dissolved organic carbon (DOC) from natural water in a slurry form in completely mixed continuous-flow reactors (Boyer and Singer, 2006; Slunjski et al., 2002). MIEX is a macroporous, strong base anion exchange resin with ammonia functional groups, consisting of 150–180 mm beads of polyacrylic structure (Mergen et al., 2008; Singer and Bilyk, 2002). Magnetic iron oxide is incorporated into the resin matrix to aid in agglomeration and settling. The diameter of MIEX resin particles is 2–5 times smaller than traditional ion exchange resins, resulting in an increase in the specific surface area and a decrease in the resistance to solid-phase mass transfer (Singer and Bilyk, 2002; Boyer and Singer, 2005). Depending on the characteristics of the treated water, pre-treatment with a magnetic ion exchange resin can remove from 30% to over 70% of the DOC from the water (Tan et al., 2005; Slunjski et al., 2002; Wert et al., 2005). Bench-scale testing of MIEX illustrated the rapid removal of DOM, with the majority of UV-absorbing organics removed in the first 10–20 min (Singer and Bilyk, 2002).

MIEX could be used as adsorbent to remove both DOM

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and other inorganic anions. Thus, nitrate, sulfate, etc. (Humbert et al., 2005; Kitis et al., 2007) could be removed effectively by MIEX. For all selected source waters, 17%–42% nitrate and 9%–24% sulfate removals were obtained at a resin dose of 10 mL settled resin/L and a contact time of 10 min (Kitis et al., 2007). The removal efficiency of these compounds depends on the anion competition for exchange sites (Neale and Schäfer, 2009).

Performances of AERs for DOM removal are influenced by the inner characteristics of the resins (strong or weak base AER) and the water quality (pH, ionic strength, etc.) (Humbert et al., 2008). Weak base resins remove less DOM as compared to strong base ones (Bolto et al., 2002). The water content of resins is another important factor influencing DOM removal. Resins with high water content can remove more DOM due to a more open structure allowing a better entry of larger compounds (Gottlieb, 1995). The effectiveness of the ion exchange process can be strongly influenced by the pH value. At high pH, ion exchange is the dominant mechanism, whereas physical adsorption also plays a role at neutral pH (Croué et al., 1999). Besides the pH value, the presence of anions may also affect the ion exchange process. Sulfate and nitrate can be rapidly and almost completely removed by ion exchange and reduce DOM removal due to ion exchange competition (Boyer and Singer, 2006; Hongve et al., 1999).

This present work compared the performances of four selected strong anion exchange resins (MIEX from Orica Pty. Ltd., Australia; NDMPs from Nanjing University, China) for the removal of DOM and mineral anions (sulfate, nitrate and fluoride). DOM was monitored by measurement of UV-absorbing substances and DOC. Moreover, the influence of treatment conditions on the kinetics of DOM removal by a selected mganetic AERs (MAERs) resin was investigated.

1 Materials and methods

1.1 Characteristics of the studied waters

The raw water sample was collected from the Tongyu River, which is a branch of the Yangzi River, the most important source of drinking water in China. Now the Tongyu River serves almost 720,000 people in Dafeng City. The raw water was coagulated using polyaluminium chloride (PACl) at a concentration about 10 mg/L without adjusting the pH. Then the coagulated water was settled, sand-filtered, and chlorinated. The physicochemical characteristics of the raw water are as follows: total organic carbon (TOC) 4.0–4.4 mg/L; DOC 3.5–4.0 mg/L, UV absorbance at 254 nm (UV_{254}) 0.10–0.14 cm^{-1}, $SUVA_{254}$ 3.4–3.9 L/(mg·m), pH 6.5–7.0, total hardness 140–170

as $CaCO_3$ mg/L, alkalinity 120–130 as $CaCO_3$ mg/L, turbidity 20–40 NTU, sulfate 40–60 mg/L, nitrate 0.5–1.0 mg/L, fluorine 0.02–0.03 mg/L and chloride 40–50 mg/L.

1.2 Characteristics of magnetic anion exchange resins

Four MAERs were selected on the basis of the research results in references (Bolto et al., 2002, 2004). The total ion exchange capacity is connected with the amount of functional groups on the resins, which is expressed as the total number of chemical equivalents available per unit volume of resin. The water content is associated with the functional groups (on and in the ion exchange resins) and the adsorbed water on the outer surface of the resin particles (Cornelissen et al., 2008).

All selected anion exchange resins had a macroporous structure (Table 1). The NDMP resins are composed of polyacrylic particles with sizes of 80–100 μm (Shuang et al., 2012).

1.3 Ion exchange kinetics

These tests were conducted on the raw water using MAERs. The reaction kinetics of the resins was studied in order to assess the maximum removal of DOC and UV_{254} after contact times shorter than an hour. It was found that the maximum removal of the UV_{254} and DOC was achieved by the resin dose of 10 mL/L with 30 min of contact time. In the preliminary experiments, two liters of the water to be tested was added into 2 L square jars along with the desired resin dose, mixed for 60 min at 150 r/min, and then allowed to settle for 20 min at room temperature. The MAER procedures were based on previous research by Singer and Bilyk (2002). During mixing, 20 mL samples were taken at 2, 5, 10, 20, 30 and 60 min for DOC, UV_{254} and inorganic ion analysis. The samples were vacuum filtered through a pre-rinsed 0.45 μm membrane filter and refrigerated at 4°C in the dark.

To investigate the impact of water quality (pH, temperature, ionic strength, etc.) on NDMP performance, the NDMP procedure was carried out under different conditions. The jar-tests were carried out at various temperatures. The pH value was changed by adding concentrated sodium hydroxide or hydrochloric acid to the raw water. A concentrated spiking solution was prepared and mixed with the raw water. The spiking solutions were prepared by dissolving a predetermined mass of sodium sulfate in the raw water.

1.4 Multiple-loading jar tests

In order to evaluate the performance of MAERs in a continuously operated process, a multiple-loading test was performed using a series of successive jar experiments on the same resin for a number of repetitions. The multiple-

Table 1 Characteristics of the resins

Resin	Types	Pores	Structure	Particle size (μm)	Total exchange capacity (mmol/mL)	Water content (%)
NDMP-1	Strong base	Macropore	Acrylic	80–100	0.98	65
NDMP-2	Strong base	Macropore	Acrylic	80–100	1.32	59
NDMP-3	Weak base	Macropore	Acrylic	80–100	1.55	60
MIEX	Strong base	Macropore	Acrylic	150–180	0.52	65

loading test covered the whole service range of typical resins for the MAER process. After the kinetic tests, 10 mL settled resin/L was selected as the resin dose and 30 min as contact time for all multiple-loading jar tests. This first step was conducted at a loading of 100 bed volume (BV), i.e. the treated water volume was 100 times the volume of the resin dose. After 30 min of mixing and 20 min of settling, samples from the supernatant were taken and filtered for DOC and UV$_{254}$ measurements. For the subsequent steps, another liter of raw water was added to the beaker containing 10 mL settled NDMP resin and stirred for 30 min. The above operation step was repeated 10 times until a loading of 1000 BV was achieved.

1.5 Analytical methods

UV$_{254}$ was measured using a UV-1800 spectrophotometer (Shimadzu, Japan). TOC was measured using a TOC-V CSH (Shimadzu, Japan). DOC was operationally defined as the organic carbon concentration of a sample filtered through a 0.45 μm membrane filter. Every TOC measurement was repeated three times and the average value was recorded, as long as the relative percent error was less than 5%. Turbidity was measured using an AQ3010 Turbidity Meter (Thermo Fisher Scientific Inc., USA). Chloride, fluoride, sulfate, and nitrate were analyzed using ion chromatography in accordance with Method 300.0 (US EPA, 1993). The samples were analyzed on a liquid chromatograph LC-10AD (Shimadzu, Japan) using an IC-GA2S guard column and IC-A2S analytical column (Shimadzu, Japan).

2 Results and discussion

2.1 Kinetics of the removal of organic and inorganic matters

2.1.1 DOC and UV$_{254}$ analyses

Figure 1 provides the kinetics of the removal of DOC and UV$_{254}$ from the raw water sampled in April 2011 by 10 mL/L MAERs including NDMPs and MIEX. Similar experiments were conducted for the raw waters collected at different periods. The results show that UV$_{254}$ absorbance

and DOC content decreased rapidly with increasing contact time on any resin used. After 30 min of contact time, DOC content dropped from 4 mg/L to less than 2.6 mg/L on each resin, indicating that all kinds of MAERs displayed fast DOC and UV$_{254}$ removal. This finding is attributed to the small bead size (Singer and Bilyk, 2002; Boyer and Singer, 2005). For every resin, about 10% of the initial DOC was eliminated after 5 min of contact time. After 30 min of contact time, the remaining DOC and UV$_{254}$ tended to approach a low residual and achieve pseudo-equilibrium. As a general observation for all resins, the removal of UV absorbing substances is more important than the removal of DOC, indicating a preferential sorption of aromatic type molecules (Ates et al., 2007; Humbert et al., 2005).

With the resins NDMP-1 and MIEX, about 48.9% and 39.3% of the initial DOC was eliminated after 30 min of contact time. Within the same time, only 36.5% and 32.5% of the DOC were removed using NDMP-2 and NDMP-3, respectively. The removal of both DOC and UV$_{254}$ reached a maximum (pseudo-equilibrium) after 30 min on each of the resins. For all resins, the DOC remaining after 30 min of contact time was found to be extremely low (2.0–2.6 mg/L depending on the resin), and the removal of UV absorbing substances was 82.4% after 30 min of contact time, while the removal of DOC by NDMP-1 was 48.9%. The removal of UV absorbance was almost 33% more than the DOC removal, which confirmed that MAER could remove the aromatic matters more effectively.

The better performance of NDMP-1 compared to NDMP-3 was attributed to the different type of resins. The effect of the quaternary ammonium group in NDMP-1, which is positively charged, gave it a greater affinity for hydrophobic counter ions because of the larger size and lower charge density of the –NMe$_3^+$ sites (Bolto et al., 2004; Jensen and Diamond, 1965). Although the weakly basic resins are effective for the removal of organics (Boening et al., 1980), their performance was found to be not as good as that of the strong base resin (Bolto et al., 2004; Boyer and Singer, 2008). With the increased exchange capacity of NDMP-1, it exhibited higher removal of DOM than MIEX with the same quaternary ammonium group
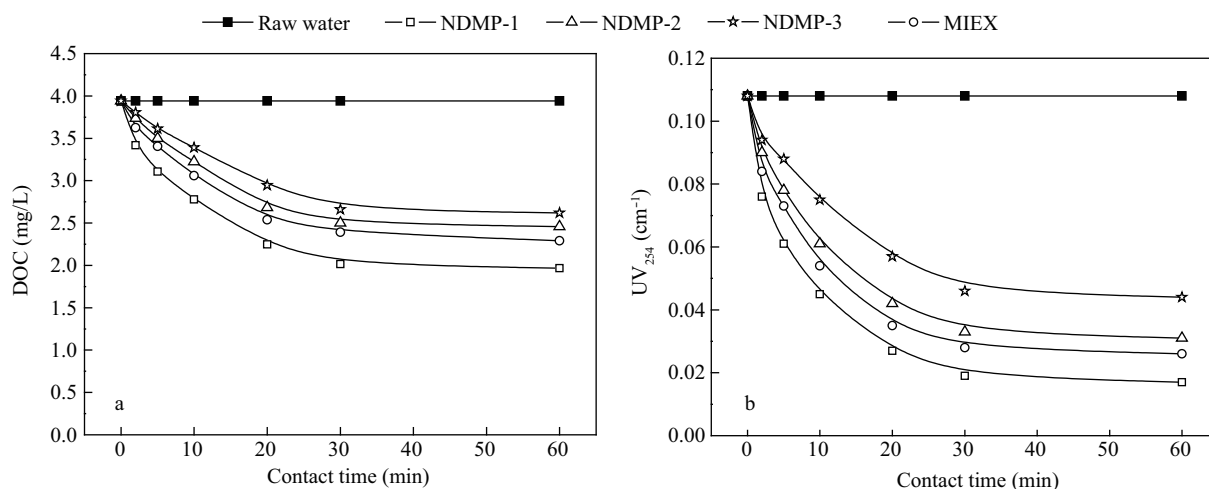

Fig. 1   DOC (a) and UV$_{254}$ absorbance (b) removal by NDMPs and MIEX resins with dose of 10 mL/L in raw water within 60 min of contact time.

and water content. The removal extent of UV absorbance by NDMP-1 was 8% more than that by MIEX after 30 min of contact time. The removal mechanism of DOM is mainly due to ion exchange reactions. Thus the higher removal of DOM by NDMP-1 compared to MIEX could be explained by its increased ion exchange capacity, as shown in Table 1. As compared to NDMP-1, NDMP-2 with lower water content led to a lower removal percentage. It was found that water content had a remarkable effect on the DOC removal (Bolto et al., 2002). AERs with high water content were found to be very efficient for the removal of any charged aquatic DOM, due to a more open structure allowing a better entry of larger compounds (Bolto et al., 2002; Gottlieb, 1995; Cornelissen et al., 2008).

SUVA (L/(mg·m)), the ratio of the UV absorbance at 254 nm (UV_{254}, cm^{-1}) to the DOC concentration (mg/L) multiplied by 100, is reported to be directly correlated with the aromatic carbon content and molecular weight of DOM (Chin et al., 1994; Weishaar et al., 2003). The SUVA value reduction by NDMP-1 was 65.7% after pseudo-equilibrium, the results of which confirm the preferential removal of DOM with higher aromatic character by MAERs (Humbert et al., 2005). The percentage SUVA reductions were 57.3% by MIEX, 51.8% by NDMP-2 and 36.9% by NDMP-3.

The results confirmed the inferences suggested by previous publications (Bolto et al., 2002; Boyer and Singer, 2008; Anderson and Maier, 1979; Fu and Symons, 1990), i.e. the strong-base anion exchange resins with high water content and extensive exchange capacity are most effective for DOC removal.

2.1.2 Removal of mineral ions

Figure 2 presents the evolution of chloride, fluoride, nitrate and sulfate during the treatment of the raw water (April 2011) with MAERs. As compared with the DOM removal, all resins showed the same trend with regard to the removal of fluoride, nitrate and sulfate. A similar pattern was also found in all resins, i.e. the anions such as fluoride, nitrate and sulfate decreased progressively with prolonged contact time followed by an increase in chloride content. All AERs were used in chloride form, and the anions were easily exchanged with the chloride of the resin (Humbert et al., 2005).

The resins rapidly eliminated all three anions and reached pseudo-equilibrium after 30 min. Fluoride, sulfate and nitrate concentrations dropped from 0.02 to 0.008 mg/L, 23.6 to 1.8 mg/L and 0.9 to 0.17 mg/L after 30 min of contact time with NDMP-1, respectively. A greater reduction of fluoride was obtained with NDMP-1 (63.1%) and MIEX (57.8%) compared to NDMP-2 (53.2%) and NDMP-3 (48.5%). The reduction of nitrate was greater with NDMP-1 (81.4%) and MIEX (76.6%) than with NDMP-2 (70.2%) and NDMP-3 (58.3%). The sulfate removal was also greater with NDMP-1 (92.2%) and MIEX
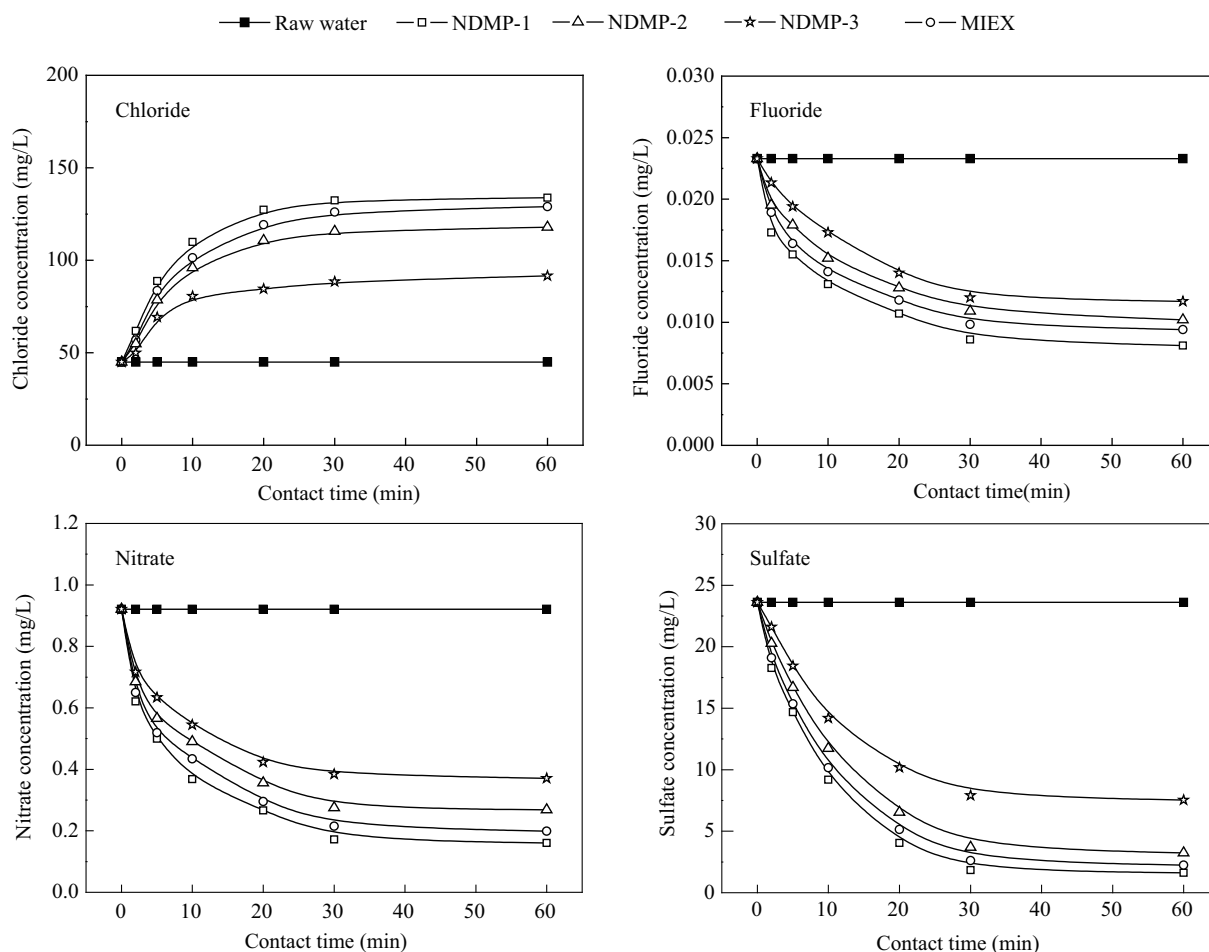

Fig. 2   Impact of resin treatment on inorganic species. Resin dose: 10 mg/L.

(89.0%) compared to NDMP-2 (84.4%) and NDMP-3 (66.5%) after 30 min of mixing time. The sulfate in raw water showed the highest removal efficiency by MAERs due to its high selectivity. Thus, high alkalinity and sulfate content in raw water could limit the competition by other anions (Humbert et al., 2005).

2.2 Multiple-loading jar tests of a series magnetic ion exchange resins

2.2.1 DOC and UV$_{254}$ analyses

In the multiple-loading jar tests (Fig. 3), the DOC level achieved 2.0 mg/L and 2.4 mg/L at 100 BV loading (i.e., the first jar step or treated water volume 100 times the volume of resin used) when the raw water was treated by NDMP-1 and MIEX, respectively, whereas the DOC levels achieved were 2.6 and 3.0 mg/L at a loading of 1000 BV. The removal of DOC by both of the resins was decreased by about 0.6 mg/L at a loading of 1000 BV compared to the fresh resin. At a load of 1000 BV, the DOC level achieved was 3.3 mg/L by NDMP-2 and 3.5 mg/L by NDMP-3, which implied a decrease of about 0.8 mg/L in the DOC removal compared to the fresh resins. In addition, the UV absorbance removal showed the same trend as the DOC removal. The results demonstrated that the NDMP-1 and MIEX resins showed higher DOM removal and better performance than NDMP-2 and NDMP-3 during the continuously operated process.

2.2.2 Removal of mineral ions

In the multiple-loading jar tests shown in Fig. 4, the removal of fluoride achieved was 63.0% and 57.4% at 100 BV loading and 43.0% and 38.3% at 1000 BV when treated by NDMP-1 and MIEX, respectively. The removal of fluoride by both resins was decreased by about 20% at a loading of 1000 BV as compared to the fresh resins, whereas the removal of fluoride by NDMP-2 and NDMP-3 was decreased by 22% and 28%, respectively. At a loading of 1000 BV, the removal percentages of nitrate by NDMP-1, MIEX, NDMP-2 and NDMP-3 were 49.4%, 44.1%, 34.9% and 23.1%, respectively. The removal percentage of nitrate was decreased by 32% with NDMP-1 and MIEX, while it was decreased by 35% with NDMP-2 and

NDMP-3.

The removal percentages of sulfate by NDMP-1 and MIEX were 92.2% and 89.1% at the loading of 100 BV, while 59.8% and 55.4% at 1000 BV loading, respectively. The sulfate removal was decreased by about 37% with NDMP-2 and NDMP-3 at a loading of 1000 BV when compared to the fresh resin. As shown in Fig. 3, the removal of DOM by a series of resins appeared to follow a similar trend as for the removal of fluoride, nitrate and sulfate during the continuously operated process. A corresponding result was found in the change of chloride content in the treated water. It was noticed that the variation of chloride was dependent on the removal of DOM and inorganic ions by all resins in the multiple-loading process. With the increase of the DOM removal by the series of resins, the content of chloride in the treated water was also increased. And when the resin has been used a number of times, the chloride content in treated water was decreased along with the lower removal of DOM.

2.3 Influences of treatment conditions and water quality

In order to better explore the capability of NDMP for DOM removal, dose response experiments were conducted with waters of different quality. The previous results confirmed that among ion exchange resins, strong-base anion exchange resins with high water content and exchange capacity have been shown to be the most effective ones for DOC removal. Among the four MAERs tested, NDMP-1 was selected because of its high efficiency for the removal of DOM and inorganic matter.

2.3.1 Impact of treatment conditions on DOM removal by NDMP

Figure 5 plots the kinetics of the removal of DOC and UV$_{254}$ for raw and clarified waters using NDMP-1 at different doses (1, 4 and 10 mL/L). The results show that DOC content and UV absorbance decreased rapidly with prolonged time for the three doses of NDMP applied. The higher the resin dose, the more reduction of DOC and UV absorbance occurred. After 30 min, the DOC residual remained almost unchanged (pseudo-equilibrium
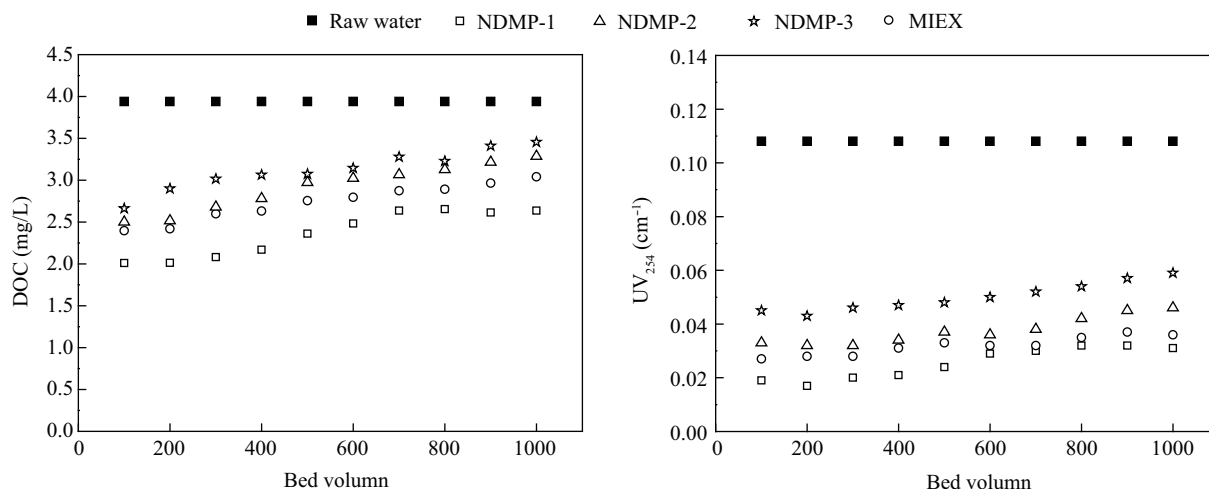

Fig. 3 Multiple-loading jar tests of magnetic ion exchange resins for DOC and UV$_{254}$ removal from the raw water.
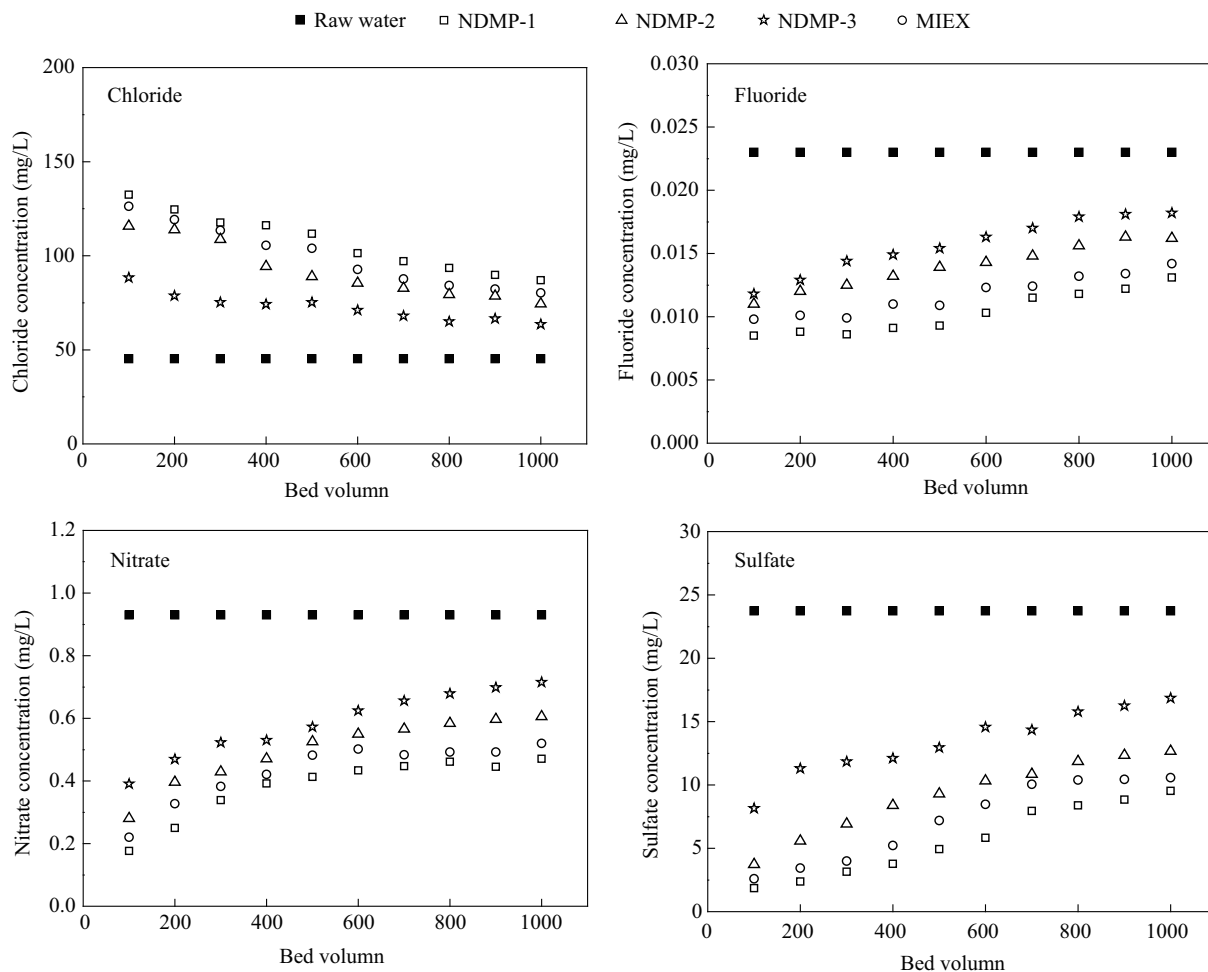
Fig. 4   Impact of multiple-loading jar tests of magnetic ion exchange resins on inorganic species.

condition) with NDMP for the raw and clarified water. On the other hand, significant improvements were observed when doses were increased from 1 to 10 mL/L. The DOC fractions that remained after NDMP treatment were all about 2.0 mg/L with resin dose of 10 mL/L after 30 min contact time with the raw water and clarified water. The DOC removal by NDMP was 48.3% and 42.6% for raw water and clarified water, respectively, whereas the UV

absorbance reduction was 81.7% by NDMP for the raw water and 76.5% for the clarified water by NDMP with resin dose of 10 mL/L after 30 min of contact time. It is found that the DOM removal in the raw water by NDMP was more effective than that in the clarified water. This could be attributed to the high SUVA value of the treated water, which is more efficient for the removal of DOM by MAERs (Humbert et al., 2005).
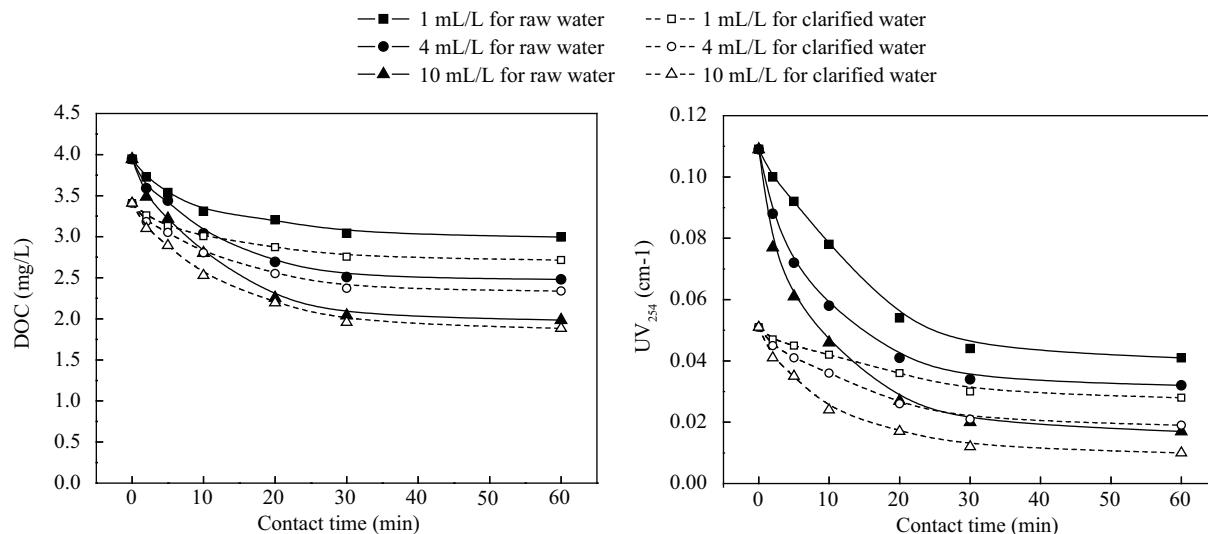

Fig. 5   Impact of NDMP dose on the kinetic removal of DOC and UV_{254} for raw and clarified (PACl, 10 mg/L) waters.

2.3.2 Impact of temperature on DOM removal by NDMP

The effect of temperature on the kinetics of the removal of DOC and UV_{254} by NDMP-1 was also investigated (Fig. 6). DOC removal was slightly influenced by the temperature between 6 and 26°C. However, a significant effect was observed at 36°C. The removal of DOC and UV-absorbing substance was 45.7% and 77.8% by NDMP at temperature of 6°C after 30 min of contact time, 3% and 5% lower than the reduction at 26°C, respectively. When the temperature was increased to 36°C, higher removal of DOM was obtained. The removal of DOC and UV-absorbing substances was 54.2% and 88.9% by NDMP at temperature of 36°C after 30 min of contact time, 5% and 6% more than the reduction of DOC and UV absorbance at 26°C, respectively. The results showed that temperature has potential effects on the DOM removal. This is because an increase in temperature leads to an augmentation of reaction kinetics (Humbert et al., 2005). On the other hand, NDMP is an ion-exchange resin, and the removal mechanism of DOM is mainly due to ion exchange reaction. It was reported that the major component of DOM was natural organic acids, such as humic, fulvic and tannic acids, and these natural organic acids could dissociate in water. Higher temperature was beneficial to the dissociation of DOM. Thus compared with 6 and 26°C, the removal rate of DOM was the highest at 36°C.

2.3.3 Impact of pH on DOM removal by NDMP

The pH value had a small effect on the kinetics of the removal of DOM by NDMP as shown in Fig. 7, when the pH value varied between 6.5 and 8.5 (the ordinary water treatment temperature). However, the removal efficiency of DOC can be affected by the quality of the raw water. Due to the presence of carboxylic groups (Wert et al., 2005), DOC is in an anionic form within the pH range 4–5. At low pH (< 4) the resin cannot be used to effectively remove DOC. The best applications are in the pH range 6.5–7.5 because it can remove DOC rich in carboxylic groups. The DOC removal was increased slightly as the pH value decreased in the pH range of 6.5–8.5. However, the UV absorbance removal was slightly higher at pH 8.5 than at pH 7.5. This could be explained by the fact that the removal efficiency
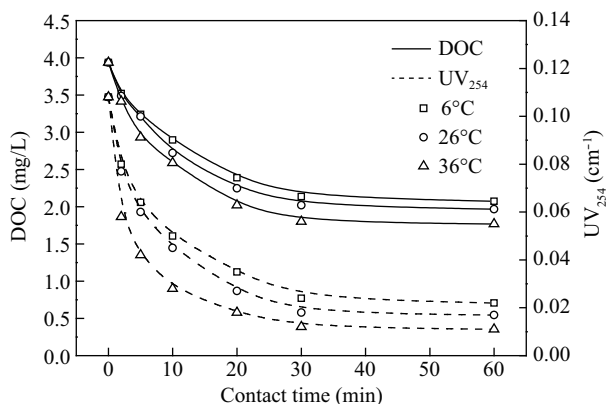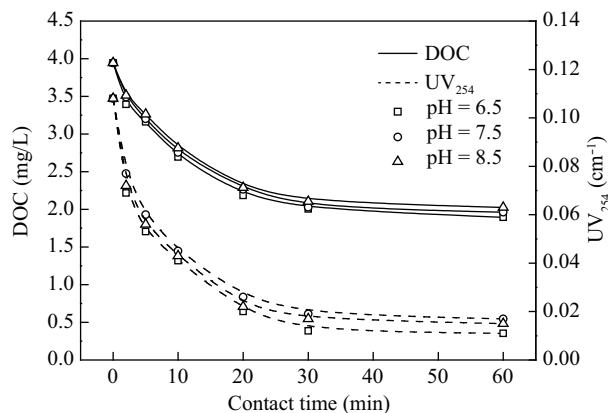

Fig. 7 Effect of pH value on the kinetics of removal of DOC and UV_{254} by NDMP for raw water. Resin dose: 10 mL/L.
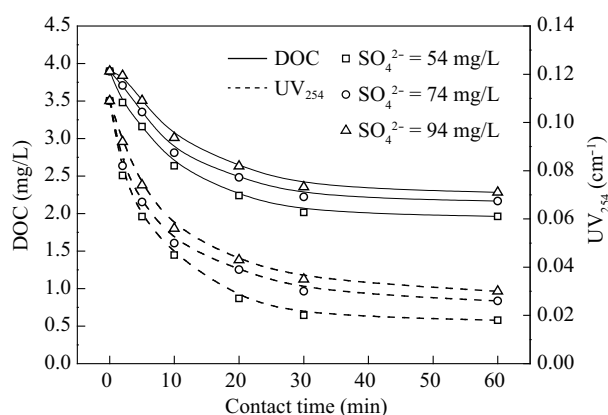

Fig. 8 Effect of inorganic sulfate on the kinetics of removal of DOC and UV_{254} by NDMP for raw water. Resin dose: 10 mL/L.

could be greatly reduced if the raw water came from a source rich in tannins. Tannins primarily contain phenolic hydroxyl groups, which are not in an anionic form until approximately pH 8–9 (Allpike et al., 2005).

2.3.4 Impact of sulfate on DOM removal by NDMP

Figure 8 illustrated the impact of elevated levels of sulfate on the removal of DOM in raw water. It was clear that the removal of DOC and UV-absorbing substances decreased with increasing sulfate concentration. When the sulfate concentration was increased from 54 mg/L to 94 mg/L, the removal of DOC and UV absorbance decreased from 48.3% to 39.6% and from 81.7% to 72.5% after 30 min of the contact time, respectively. The sulfate anion in raw water showed higher removal percent by MAERs due to their high selectivity for sulfate, which was also found in a previous study (Boyer and Singer, 2006). When the sulfate content became higher in raw water it could also limit the DOM removal by MAER because of the competition phenomenon (Humbert et al., 2005; Boyer and Singer, 2008).

3 Conclusions

It was found that MAERs could remove DOM effectively and showed fast dynamics for removal from surface water. Among ion exchange resins, strong-base anion exchange resins with higher water content and enhanced exchange

Fig. 6 Effect of temperature on the kinetics of removal of DOC and UV_{254} by NDMP for raw water. Resin dose: 10 mL/L.

capacity appeared to be the most effective ones for DOM removal. The best removal of DOC and UV absorbance were about 48.9% and 82.4% by NDMP-1, respectively, with a resin dose of 10 mL/L after 30 min of contact time.

The MAERs also showed excellent ability for the removal of anions. Fluoride, nitrate and sulfate concentrations were reduced by about 63.1%, 81.4% and 92.2% with NDMP-1, respectively. The concentration changes of chloride confirmed the speculation that the most important mechanism in ion exchange processes for DOM removal is the exchange of DOM ions and chloride ions on resins.

The treatment conditions had some impact on DOM removal by NDMP-1. It was concluded that the DOM removal in raw water by NDMP was more effective than that in clarified water. This could be explained by the higher SUVA value of the raw water, that would benefit the removal of DOM by NDMP. The influence of temperature on the removal of DOC between 6 and 26°C was minor compared to that at 36°C. The pH value had a small effect on the kinetics of the removal of DOM by NDMP. Increasing the sulfate concentration in the raw water by approximately 40 mg/L resulted in a decrease in the removal of DOC and UV-absorbing substances by 8.7% and 9.2% after 30 min of contact time, respectively.

Acknowledgments

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