

Evaluation of temperature impacts on drinking water treatment efficacy of magnetic ion exchange and enhanced coagulation

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ABSTRACT

Magnetic ion exchange (MIEX[®]) is an emerging technology for disinfection by-product (DBP) precursor removal in the drinking water industry. Although recent research has demonstrated that this technology is capable of achieving excellent natural organic matter (NOM) removal, there is paucity of published research showing the efficacy of ion exchange (IX) technology in cold water conditions. The overall objective of this research was to evaluate at bench-scale the potential impact of cold water operating conditions on enhanced coagulation with alum, MIEX[®] and a combination of MIEX[®] and low dose alum. All three treatments were evaluated at 1 and 20 °C with settled water quality compared in terms of turbidity, UV254, dissolved organic carbon (DOC), specific UV absorbance (SUVA), trihalomethane formation potential (THMFP) and haloacetic acid formation potential (HAAFP). The results of the study showed that all three technologies evaluated were significantly impacted by cold water operating conditions in terms of turbidity removal, and UV254 removal was significantly reduced in both the MIEX[®] and MIEX[®]-Alum processes. However, treatment of the surface water with the combined process resulted in the highest removal of DBP precursor material and lowest THMFP and HAAFP concentrations at both temperatures compared to the individual unit operations.

Key words | coagulation, disinfection by-products, ion exchange, natural organic matter

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INTRODUCTION

Natural organic matter (NOM) is present in all surface waters and is the result of the biological degradation of organic material (Sharp *et al.* 2006). NOM can be problematic in drinking water treatment due to aesthetic and operational issues, as well as providing precursor material for the formation of chlorinated disinfection by-products (DBPs) (Beckett & Ranville 2006; Cornelissen *et al.* 2008). Coagulation processes have been shown to be very effective in the removal of significant amounts of NOM from source waters prior to chlorine disinfection (Liu *et al.* 2011). However, coagulation can generate large volumes of concentrated solid waste residuals that can be problematic to water utilities from an operational and economic perspective (Cornwell 1999; Walsh *et al.* 2008). Coagulation

processes can also be impacted during the winter months, as alum in particular has been known to perform poorly for NOM and turbidity removal in cold-water conditions (i.e. <5 °C) (Morris & Knocke 1984; Knocke *et al.* 1986; Haarhoff & Cleasby 1988; Exall & Vanloon 2000; Braul *et al.* 2001).

Ion exchange (IX) technology is based on the reversible exchange of oppositely charged ions between a solid phase (e.g. IX resin) and target contaminants in the water phase. The use of anion exchange resins (AER) for the treatment of humic rich waters is well published (Brattebo *et al.* 1987; Symons *et al.* 1995) and generally involves the selective exchange of chloride ions (Cl⁻) with dissolved organic carbon (DOC) to occupy the active side of the resin.

The recent development of magnetic ion exchange resins (MIEX[®]) that can be used in continuous stirred tank reactor (CSTR) designs has been shown to achieve upwards of 90% NOM removal (Singer & Bilyk 2002; Fearing *et al.* 2004; Boyer & Singer 2005; Humbert *et al.* 2005; Jarvis *et al.* 2008; Drikas *et al.* 2011).

Collectively, these previous studies have shown the effectiveness of MIEX[®] at removing NOM and DBP precursor material. However, most of the studies to date have been conducted at room temperature, or for applications in warm climates. A study conducted by Humbert *et al.* (2005) evaluated the efficacy of MIEX[®] at water temperatures ranging from 6 to 36 °C and concluded that MIEX[®] had a more significant impact on organic removal at the warmer operating temperatures. There is a lack of information on the efficacy of MIEX[®] technology in cold water operating conditions, and therefore the performance of this technology in colder climates where surface water temperatures can approach 2 °C seasonally is unknown. The overall objective of this study was to evaluate enhanced coagulation with alum, MIEX[®] and a combined MIEX[®]-Alum process at warm (20 °C) and cold water (1 °C) operating conditions. Settled water quality was evaluated in terms of pH, turbidity, true color, DOC, UV254, specific UV absorbance (SUVA), trihalomethane formation potential (THMFP) and haloacetic acid formation potential (HAAFP).

MATERIALS AND METHODS

Source water

Lake water from a municipality located in New Brunswick, Canada was used for this study. The raw water used in the experiments is representative of other surface waters in Atlantic Canada, with low turbidity (<2 NTU) and alkalinity (<10 mg/L as CaCO₃), and moderate NOM content (DOC = 3–5 mg/L). Water samples were taken quarterly during the period of May 2010 to May 2011 and were stored at 4 °C. The raw water samples were characterized at various times throughout the study, and are summarized in Table 1. DOC concentrations ranged from 3.7 to 4.0 mg/L, which were nearly identical to the total organic carbon

Table 1 | Raw water characteristics

Analyte	Number of samples	Average	Standard deviation
pH	6	6.3	0.01
Turbidity (NTU)	6	1.5	0.05
True Color (TCU)	6	20	2
UV 254 (cm ⁻¹)	6	0.150	0.010
TOC (mg/L)	6	4.1	0.2
DOC (mg/L)	6	4.1	0.2
SUVA (mg/L·m)	6	3.6	0.5
THMFP (µg/L)	3	349.9	74.6
HAAFP (µg/L)	3	153.8	9.80

(TOC) concentrations, demonstrating that the organics in the source water are mostly in the dissolved form.

Bench-scale experiments

Bench-scale experiments were conducted using a standard jar test apparatus (Phipps and Bird, Fisher Scientific) to evaluate: (1) enhanced coagulation with alum; (2) MIEX[®]; and (3) a combination of MIEX[®] followed by coagulation with a low dose of alum. Each treatment process was evaluated at warm (20 °C) and cold (1 °C) water temperature conditions in replicates ($N = 5$).

For the coagulation experiments, alum dosages ranging from 10 to 60 mg/L were evaluated. A pH of 6.2 was maintained during the coagulation experiments at both cold and warm water conditions through the addition of soda ash (0.1 N Na₂CO₃) and was selected for this study based on typical coagulation pH targets practiced by surface water treatment plants in Atlantic Canada using aluminum based coagulants for the treatment of highly colored water. The jars were rapidly mixed for 1 minute at 300 rpm followed by two-stage flocculation of 10 minutes at 40 rpm then 10 minutes at 20 rpm. The jars were then allowed to settle for 1 hour before settled water samples were taken for analysis.

A sample of fresh MIEX[®] resin was supplied by Orica Watercare Inc. (Dry Ridge, KY) and, prior to the start of the experiments, was regenerated with a brine solution (10% NaCl) reported in other studies (Slunjski *et al.* 2000; Humbert *et al.* 2005). MIEX[®] resin is applied in water treatment with an operating parameter known as a Bed Volume

(BV) defined as:

$$BV = \frac{V_{\text{water}}}{V_{\text{resin}}} \quad (1)$$

where V_{water} = the volume of water treated; V_{resin} = the volume of resin applied.

For the 1 L jar test experiments, 5 mL resin/L raw water (200 BV) MIEX[®] dose was applied and mixed for 15 minutes at 150 rpm followed by a 4 minute settling period, based on procedures presented in other studies (Singer & Bilyk 2002; Johnson & Singer 2004; Boyer & Singer 2005). For higher BV treatments, the same resin was used with an additional 1 L of raw water increments, simulating the multi-bed loading procedure which has been shown in other studies to model continuous full-scale MIEX[®] treatment at bench-scale outlined in other studies (Slunjski *et al.* 2000; Semmens *et al.* 2000; Kitis *et al.* 2007; Mergen *et al.* 2008).

For both the enhanced coagulation and MIEX[®] experiments, optimum dose and BV treatment level were determined based on UV254 measurements of the settled water during the warm water (20 °C) experiments. The optimum alum dose and MIEX[®] BV were then evaluated in the cold water (1 °C) experiments to examine the impact of variable operating temperatures on treatment performance. For the combined MIEX[®]-Alum treatment, the water was treated with MIEX[®] at the optimum BV followed by the addition of a low dose of alum (5 mg/L) using the same methodology for the enhanced coagulation trials. No pH adjustment was required in the MIEX[®] and combined MIEX[®]-Alum treatments due to the pH of the MIEX[®] treated water (6.3 ± 0.1) and low dose of alum evaluated. For the cold water trials, the raw water samples were refrigerated at 1 °C overnight prior to testing, during which the test jars were tightly insulated with crushed ice to maintain the cold water temperature. For the warm water temperature trials, a second refrigerator was set at 20 °C and the raw water samples were left to temperature adjust overnight prior to testing.

Throughout all experiments, temperature and pH were monitored. Settled water samples were analyzed for pH, turbidity, true color, DOC and UV254. A composite sample of 6 L of treated water was generated for each process at the determined optimum dose at 1 and 20 °C to perform DBP formation potential testing (THMFP, HAAFP).

Analytical methods

pH measurements were taken with an Orion model 210A pH meter and turbidity was measured with a HACH 2100 AN Turbidimeter (Hach Company, Loveland, CO). True color and UV254 were measured on 0.45 μm filtrate samples using a HACH DR/4000 spectrophotometer (Hach Company, Loveland, CO) according to methodology as described in *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA & WEF 1998). Water samples for DOC analysis were filtered through a 0.45 μm pore size filter (GE PES Membrane, GE Water Systems, Inc.) that had been pre-rinsed with 500 mL of milli-Q water. Samples were collected headspace free in 40 mL pre-cleaned glass vials and analyzed using a TOC-V CHP analyzer (Shimadzu Corporation, Kyoto, Japan) using Standard Methods 5310 B.

DBP formation potential tests were conducted on the raw and treated water samples using the Uniform Formation Conditions (UFC) test proposed by Summers *et al.* (1996). The UFC test defines incubation conditions of 24 ± 1 h time, 20.0 ± 1.0 °C temperature, 8.0 ± 0.2 pH and a 1.0 ± 0.4 mg/L free chlorine residual after 24 hours. Free chlorine residuals were measured using a HACH DR5000 spectrophotometer (Hach Company, Loveland, CO). THM and HAA samples were collected and analyzed as outlined in McCormick *et al.* (2010). The THMs measured were collectively referred to as total trihalomethanes (TTHMs), including chloroform, bromoform, dichlorobromomethane, and dibromochloromethane. Collectively referred to as HAA9, the individual HAAs measured were chloroacetic acid, bromoacetic acid, dichloroacetic acid, trichloroacetic acid, bromochloroacetic acid, dibromoacetic acid, dibromodichloroacetic acid, chlorodibromoacetic acid, and tribromoacetic acid.

Statistical methods

Paired *t*-testing ($\alpha = 5\%$) was performed using Minitab to determine the significance of temperature on treatment efficacy at cold and warm water conditions, and to evaluate the difference between treatment technologies at equivalent operating temperatures. Standard error was calculated and is portrayed on each figure via error bars from five replicates.

RESULTS AND DISCUSSION

Determination of optimum coagulant dose and MIEX[®] bed volume

Jar tests were run at alum dosages from 10 to 60 mg/L at 20 °C to determine the optimum coagulant dosage to achieve maximum reduction in DBP precursor material as quantified with UV254 measurements (Figure 1). From a diminishing returns perspective, the most favorable alum dosage was determined to be 40 mg/L, which achieved a 74% reduction in UV254 measurements from raw water levels. Beyond the 40 mg/L alum dosage, minimal improvements in UV254 removals were observed in the settled water samples. A similar trend was seen for DOC removal with varying alum dosages (Figure 1). The dosage of 40 mg/L alum resulted in the lowest DOC concentration, with a 35% reduction in DOC concentrations from raw water levels. Beyond 40 mg/L, DOC concentrations reached a plateau; therefore further addition of alum did not significantly reduce the concentration of dissolved organics.

Fair to good DOC removal with NOM influencing coagulation processes is generally accepted for source waters with SUVA values between 2 and 4 mg/L·m (Edzwald & Van Benschoten 1990; Edzwald 1993). The results of the enhanced coagulation experiments with alum showed moderate DOC removal ranging from 24 to 35%. The calculated SUVA value of the source water was 3.3 mg/L·m (Table 1), indicating a mixture of aquatic humics, hydrophobic/hydrophilic NOM and molecular weights. NOM fractionation was not conducted in this study, and it is possible that the organics in the source

water used in this study are comprised of a higher fraction of hydrophilic and low molecular weight NOM compounds which are more difficult to remove with coagulation processes. However, further study would be required to verify this theory.

Settled water DOC and UV254 measurements versus the MIEX[®] BV treatment rate at 20 °C are shown in Figure 2. The 600 BV treatment rate was chosen as optimum, with DOC and UV254 reduced by 51 and 79%, respectively, from the raw water levels. At the higher treatment rates of 800 and 1000 BV corresponding to increased water to resin contact time, UV254 and DOC removal were shown to be impeded. From 200 to 600 BV, UV254 measurements were found to be relatively constant, but 600 BV was chosen as the optimum treatment rate due to the fact that it represented the longest water to resin contact time, above which the test results indicated that the resin had reached full capacity on the exchange sites to achieve further removal of UV254. As expected, settled water DOC concentrations followed a similar pattern to the UV254 measurements. The 600 BV treatment rate resulted in the lowest DOC concentration of approximately 2.0 ± 0.1 mg/L, increasing to approximately 2.5 ± 0.4 and 3.7 ± 0.05 mg/L at the 800 and 1000 BV rates, respectively.

Impact of operating temperature on treatment performance

Settled water turbidity

Figure 3 presents settled water turbidity at 1 and 20 °C for all three treatments investigated in this study. Due to the low

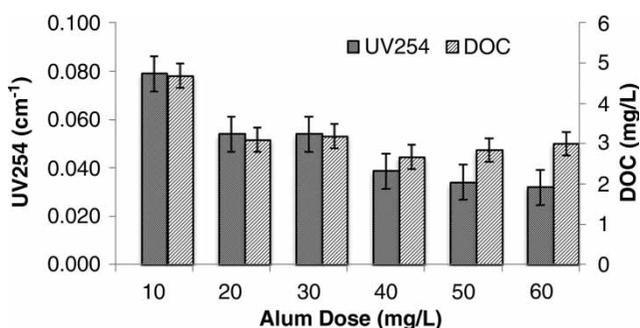


Figure 1 | Settled water DOC and UV254 for optimum alum dose determination (20 °C operating temperature).

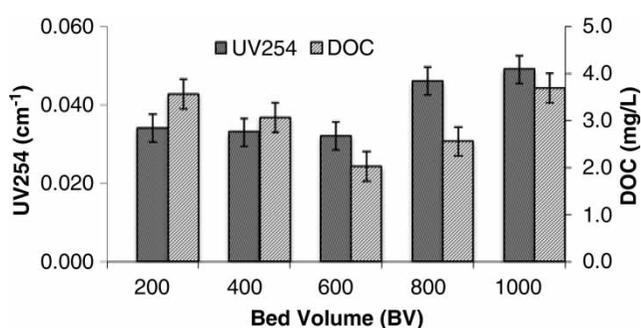


Figure 2 | Settled water DOC and UV254 for optimum bed volume treatment determination (20 °C operating temperature).

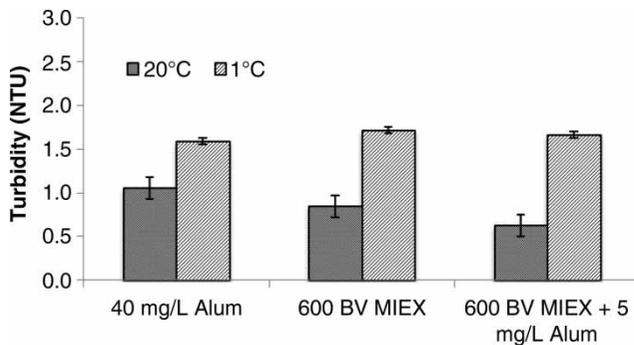


Figure 3 | Settled water turbidity at 1 and 20 °C operating temperatures.

turbidity (<5 NTU) of the source water used in this study, the settled water turbidity (i.e. residual turbidity) results of the bench-scale testing can be viewed as representing the removal efficiency of floc formed in coagulation with alum or the combined process (MIEX[®]-Alum), or that of the ion exchange resin in the MIEX[®] experiments. Settled water turbidity measurements can provide an indication of floc or resin carryover that may impact downstream filtration operations, and in this study were evaluated to determine potential differences under warm and cold water operating conditions. It has been shown in other studies that turbidity removal in coagulation-sedimentation processes using inorganic coagulants can be hindered by cold water temperatures (Morris & Knocke 1984; Exall & Vanloon 2000; Braul *et al.* 2001).

Paired *t*-testing at the 95% confidence interval was conducted for all three treatments to determine if there was a significant impact on residual turbidity in the settled water samples under cold water temperature conditions. For the enhanced coagulation experiments conducted at a dosage of 40 mg/L alum, paired *t*-testing showed that operating at the colder water temperature had a significant impact ($p < 0.05$) on residual turbidity after settling. Residual turbidity was 33% higher in the cold water trial compared to the warm water experiments. Similar results have been reported in previous studies. Morris & Knocke (1984) found that residual turbidity measured at 1 and 20 °C after coagulation with alum was a direct function of solution temperature. A similar study that evaluated turbidity removal at 2 and 22 °C with alum dosages ranging from 20 to 100 mg/L demonstrated that the operating temperature had a significant impact on turbidity removal efficacy (Knocke *et al.* 1986).

It has been reported in other studies that MIEX[®] treatment results in elevated turbidity in the treated water due to resin carryover (i.e. suspended resin beads) (Cook *et al.* 2001; Singer & Bilyk 2002; Humbert *et al.* 2005; Kitis *et al.* 2007). However, water sampling protocols for turbidity measurements in those studies were not reported. In this study, the first 50 mL of water sample collected after MIEX[®] treatment was discarded in order to remove any resin particles that may have collected in the jar test apparatus sample port during mixing. This methodology follows those used by Boyer & Singer (2005) in bench-scale MIEX[®] studies. Paired *t*-testing of the MIEX[®] treated settled water samples showed that residual turbidity in the samples generated under cold operating conditions was significantly higher ($p < 0.05$) than levels generated under warm water operating conditions.

The combined treatment (600 BV MIEX[®] followed by a 5 mg/L dosage of alum) was also shown to be impacted by cold water conditions in terms of turbidity removal (Figure 3). Paired *t*-testing demonstrated a highly significant difference ($p < 0.05$) in mean turbidity values between the 1 and 20 °C operating temperatures. Specifically, the combined MIEX[®]-Alum treatment resulted in settled water turbidity levels that were 62% higher at the 1 °C operating temperature compared to 20 °C. Although settling of the coagulated floc in the alum experiments, the resin in the MIEX[®] experiments and the combined MIEX[®]-Alum process was demonstrated to be impacted by the colder operating conditions, it is important to note that the residual turbidity levels for all treatments were below 2.0 NTU.

Removal of NOM and DBP precursors

The removal of dissolved organic material with alum coagulation was not found to be impacted under colder operating conditions (Figure 4). Paired *t*-test results showed that there was not a significant difference ($p > 0.05$) in DOC removal between the two operating temperatures evaluated for alum coagulation at 40 mg/L. It has been previously noted that DOC removal is not as sensitive as turbidity, or may not be impacted at all by cold water conditions (Knocke *et al.* 1986; Randtke 1988; Hanson & Cleasby 1990; Braul *et al.* 2001).

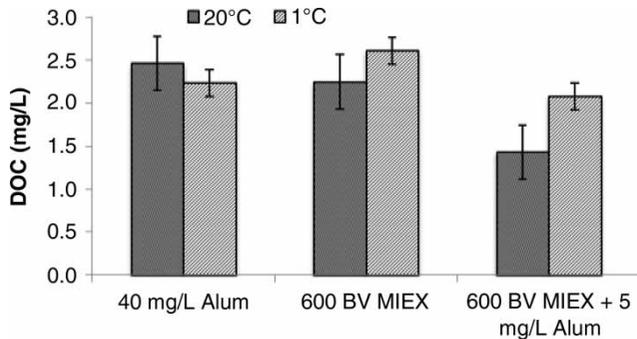


Figure 4 | Settled water DOC concentrations at 1 and 20 °C operating temperatures.

In a bench-scale study, [Humbert *et al.* \(2005\)](#) found that DOC removal with MIEX[®] was not impeded at cold water conditions (6 °C) compared to warm water conditions (36 °C). In that study, with a resin dose of 8 mL/L and a contact time of 15 minutes, minimal difference between settled water DOC concentrations at both temperatures was observed. Similar results were found in this study, and paired *t*-testing showed no significant difference ($p > 0.05$) between MIEX[®] treatment at 1 °C compared to 20 °C in terms of DOC removal. [Semmens *et al.* \(2000\)](#) evaluated the NOM removal capability of MIEX[®] at temperatures ranging from 5.5 to 24.2 °C using a 6 mL/L resin dose and found a 12% decrease in TOC removal at the cold temperature condition. [Semmens *et al.* \(2000\)](#) attributed this change in performance to a combination of cold temperature and changes in NOM chemistry.

In contrast to the results of the alum and MIEX[®] treatments alone, DOC removal with the combined MIEX[®]-Alum process was found to be impacted at cold operating temperatures. Paired *t*-testing results showed that there was a significant impact ($p < 0.05$) of operating temperature on the DOC removal capabilities of the combined process, with DOC removal reduced by approximately 31% at 1 °C versus 20 °C. Several studies have investigated the use of combined MIEX[®]-Alum treatment and its ability to significantly reduce DOC concentrations as well as coagulant demand ([Singer & Bilyk 2002](#); [Boyer & Singer 2005](#); [Kitis *et al.* 2007](#); [Drikas *et al.* 2011](#)). However, none of these previous studies evaluated potential impacts of cold water operating conditions. The results of this study demonstrate that although DOC removal with a combined MIEX[®]-coagulation process can be significantly hindered

at cold operating conditions, the overall DOC removal achieved is still higher compared to alum coagulation or MIEX[®] treatments as single unit operations.

Figure 5 presents the settled water UV254 measurements for each treatment evaluated at 1 and 20 °C. The results of the enhanced coagulation with alum experiments showed there was no significant difference ($p > 0.05$) between the settled water UV254 measurements obtained during the cold and warm operating temperatures. Similar results were reported by [Braul *et al.* \(2001\)](#) who found that temperature did not affect UV254 absorbance reduction at 1.5 °C compared to 20 °C.

The MIEX[®] treatment was found to perform significantly better ($p < 0.05$) in terms of UV254 removal at the warmer operating temperature than under cold water conditions, as the treatment efficacy was reduced by 45% at 1 °C. [Semmens *et al.* \(2000\)](#) evaluated the changes in settled water UV254 from 5.5 to 24.2 °C using a 6 mL/L MIEX[®] dose and a 45 minute contact time, observing nearly identical UV254 measurements at both temperatures. [Humbert *et al.* \(2005\)](#) evaluated UV254 absorbance at an 8 mL/L MIEX resin dosage with operating temperatures ranging from 6 to 36 °C, and found minor effects of temperature on UV254 removal. In that study, a slight temperature impact on UV254 removal for the first 10 minutes of contact time was observed, which diminished as contact time increased to 30 minutes. The significant impact of temperature on UV254 removal observed in this study may be linked to the lower temperatures investigated (i.e. 1 °C vs 6 °C), the lower MIEX[®] dosage evaluated (5 mL/L vs 6–8 mL/L) and/or the lower resin contact time (15 min vs 30–45 min) compared to the other studies.

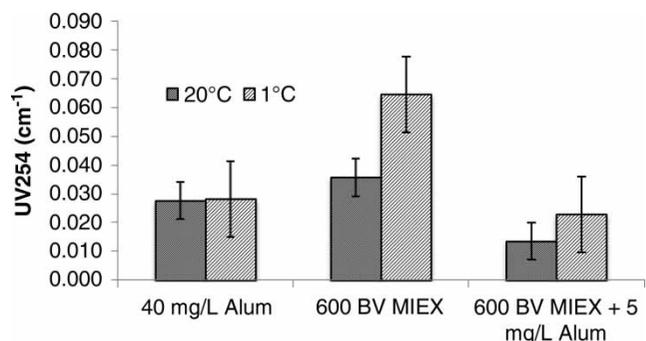


Figure 5 | Settled water UV254 at 1 and 20 °C operating temperatures.

The combined MIEX®-Alum treatment process also showed a significant difference ($p < 0.05$) in UV254 removal with operating temperature, with UV254 removal reduced by 40% at 1 °C compared to 20 °C. However, operation of the combined MIEX®-Alum process in cold water conditions still resulted in an 85% reduction in UV254 from raw water levels.

Disinfection by-product formation potential

Figure 6 presents the mean THM formation potential results for each treatment at both 1 and 20 °C. Paired t -test results showed that operating temperature did not significantly ($p > 0.05$) impact THMFP of the alum treated water. As UV254 removal with enhanced coagulation was not found to be impacted at cold water operating temperatures, these results were expected. In drinking water treatment, it has been shown that UV254 is a good surrogate parameter for predicting THMFP in source or treated water (Edzwald *et al.* 1985). THM formation with the MIEX® treatment was found to be significantly ($p < 0.05$) impacted by cold water operating temperatures, with a 43% increase in THMFP concentrations at 1 °C compared to water generated at 20 °C. These results agree with the reduced UV254 removal observed with MIEX® treatment in cold water conditions (Figure 5). The combined MIEX®-Alum treatment did not show any significant impacts of cold water temperatures on THMFP ($p > 0.05$), as expected based on settled water UV254 values.

For the HAAFP results shown in Figure 7, paired t -testing results showed that there was no significant impact ($p > 0.05$) of operating temperature on HAAFP with

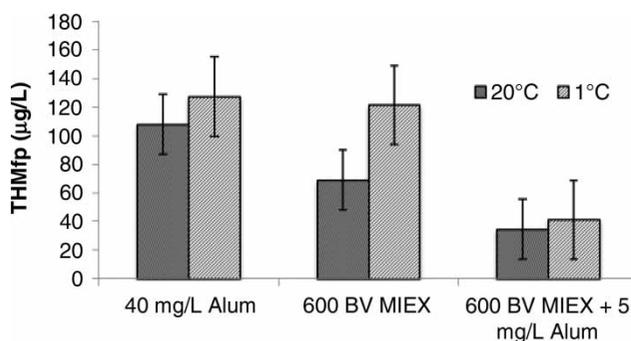


Figure 6 | Trihalomethane formation potential at 1 and 20 °C operating temperatures.

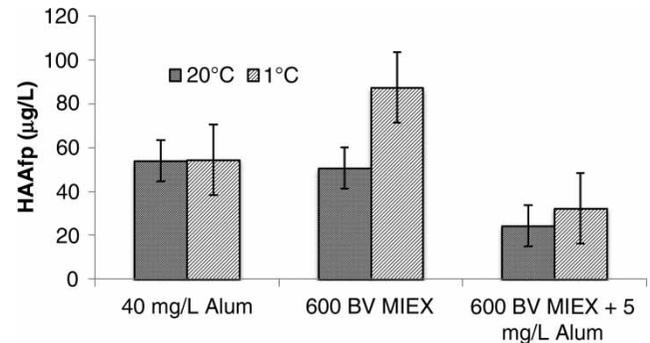


Figure 7 | Haloacetic acid formation potential at 1 and 20 °C operating temperatures.

enhanced coagulation with alum and the combined MIEX®-Alum processes, as their means were nearly identical. This was in agreement with the THMFP and UV254 removal results found with both of these processes which were not found to be impacted by cold water conditions. The MIEX® treatment showed HAAFP concentrations were significantly higher ($p < 0.05$) in the cold temperature trials compared to warm water conditions. These results are also consistent with the THMFP and UV254 removal results for the MIEX® treatment as a single unit operation.

Specific UV absorbance (SUVA), a concept developed by Edzwald (1993) and calculated as the ratio of UV254 to DOC, has been correlated with DBP formation, as it serves as a good indicator of the humic and aromatic content of the water linked to greater DBPFP (Liang & Singer 2003; Weishaar *et al.* 2003; Kitis *et al.* 2004, 2007; Ates *et al.* 2007). Figure 8 presents SUVA values for each treatment evaluated in this study at both 1 and 20 °C operating conditions. Paired t -testing showed that temperature did not have a significant ($p > 0.05$) impact on SUVA reduction with the enhanced coagulation and combined MIEX®-Alum

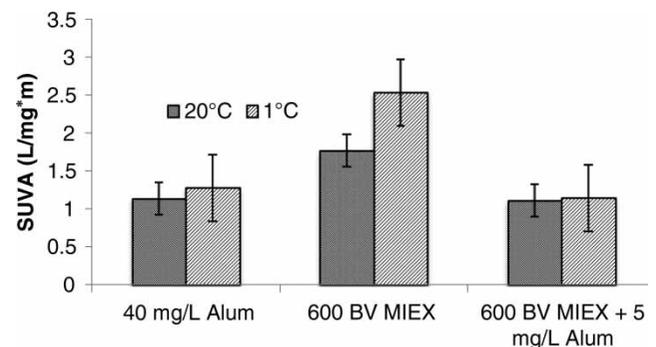


Figure 8 | Specific UV absorbance at 254 nm at 1 and 20 °C operating temperatures.

treatments. MIEX[®] treatment as a single unit operation showed a significantly higher ($p < 0.05$) SUVA value at 1 °C compared to at 20 °C. These results with SUVA analysis present the same correlation with the THMFP and HAAFP results, reinforcing the idea of SUVA serving as an indicator for THMFP.

Process treatment efficacy at equivalent temperatures

Statistical analysis using paired *t*-testing was used to compare the treatment efficacy of the three treatment technologies at equivalent operating temperatures. With warm water operating conditions (20 °C), no significant difference ($p > 0.05$) was found between the enhanced coagulation and MIEX[®] treatments in terms of all of the water quality parameters measured in this study. Under reduced operating temperature (1 °C), significantly higher ($p < 0.05$) DOC and UV254 measurements were observed in the MIEX[®] versus coagulated settled water. However, overall reductions in UV254 (0.065 cm⁻¹) and SUVA (2.5 mg/L·m) from raw water levels (0.150 cm⁻¹ and 3.6 mg/L·m, respectively) with the MIEX[®] treatment resulted in DBP formation potential concentrations that were not found to be significantly different ($p > 0.05$) from those formed after coagulation treatment in cold water.

Overall, the combined MIEX[®]-Alum treatment provided equal or greater removal of DBP precursors compared to the treatments as single unit operations at both operating temperatures. DBP formation potential concentrations, however, were not found to be statistically significantly different ($p > 0.05$) between the three technologies at 20 °C. At both operating temperatures, the combined process resulted in the lowest mean THMFP and HAAFP concentrations in the settled water, well below the maximum acceptable concentrations (MAC) outlined in the Canadian drinking water quality guidelines (TTHM MAC < 100 µg/L and HAA MAC < 80 µg/L) (Health Canada 2009), compared to the technologies operated as single unit operations.

CONCLUSIONS

The objective of this study was to investigate the treatment efficacy of three NOM removal technologies: enhanced

coagulation with alum, MIEX[®] and a combined process of MIEX[®] followed by a low dose of alum (MIEX[®]-Alum), at warm and cold operating temperatures (20 vs 1 °C). The results of this study showed the following:

- Cold water operating conditions resulted in significantly higher settled water turbidity for all three of the processes evaluated in this study. However, the residual turbidity measurements were all lower than 2.0 NTU.
- NOM removal as quantified by settled water DOC concentrations was not found to be significantly impeded by cold water conditions for the enhanced coagulation and MIEX[®] treatments. DOC removal in the MIEX[®]-Alum process was found to be significantly reduced under colder operating conditions; however, this combined process was found to result in greater DOC reductions compared to the individual treatments as single unit operations at both operating temperatures.
- DBP precursor removal as quantified by settled water UV254 measurements was not found to be significantly impacted by cold water conditions for the enhanced coagulation treatment. In contrast, results of the study found that the colder operating temperature significantly reduced UV254 removal in both the MIEX[®] and MIEX[®]-Alum processes. However, the combined process resulted in the greatest reduction in UV254 compared to the technologies operated as single unit operations.
- Disinfection by-product formation potential as quantified by THM and HAA concentrations measured under uniform formation conditions was not significantly impacted by water temperature changes in the enhanced coagulation and combined MIEX[®]-Alum experiments. The combined process was found to provide the lowest THM and HAA formation potential concentrations at both operating temperatures.
- MIEX[®] treatment was found to be impacted by the lower 1 °C operating temperature in terms of DBP precursor removal which corresponded to THMFP and HAAFP concentrations greater than current DBP guidelines. These results indicate that operating at a lower bed volume rate may be warranted in cold water conditions, although further study would be required to determine if the colder water conditions would concurrently result in reduced DBP formation rates.

ACKNOWLEDGEMENTS

The authors acknowledge funding provided by the Natural Science and Engineering Research Council of Canada (NSERC) for this study. The authors gratefully acknowledge the assistance from the supporting water utility and Orica Watercare for the provision of the MIEX® samples used in this study.

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First received 5 July 2012; accepted in revised form 18 October 2012