Effects of pre-ozonation and selected advanced water treatment processes on Mount Seymour impoundment water

C. Bonneville* and D.W. Smith**

* EPCOR Water Services, 10065 Jasper Avenue, Edmonton T5J 3B1, Canada
** Department of Civil and Environmental Engineering, University of Alberta, 304 Environmental Engineering Building, Edmonton T6G 2M8, Canada

Abstract In May 1999, a project using a dissolved air flotation (DAF)/ozone/filtration pilot plant was started to study the effects of pre-ozonation on the flocculation of particles and removal of organic matter in an advanced treatment process. Results indicate that small doses of ozone pre-ozonation slightly improve the flocculation of particles and their subsequent removal in the DAF unit when used in conjunction with alum or PACl. However, it was found that high ozone doses impeded flocculation. More significant is ozone’s benefit for the removal of UV-absorbing organic matter. The study also found that DAF is very effective at removing turbidity causing particles and colour from the water, thereby improving filter performance.

Keywords Water treatment; preozonation; flocculation; coagulation; DAF

Introduction

Project background

The Mount Seymour water supply reservoir is one of three impoundments located in the Coast Mountains to the north of the city of Vancouver, on the west coast of Canada. This reservoir, which has a storage capacity of approximately 30 billion litres and covers 262 hectares, supplies 40% of the water for 1.7 million Greater Vancouver area residents. The water is generally of very good quality, with low turbidity and alkalinity.

A dissolved air flotation/ozone pilot plant was built at the base of the Seymour Falls Dam in the early 1990s to investigate a number of treatment alternatives for Seymour Impoundment water. At that time, the only treatment used for Vancouver’s drinking water supply was chlorination and pH control. Numerous studies have been conducted to research water treatment alternatives for Vancouver. The project was initiated to investigate the effects of ozone on the flocculation of particles and the removal of organic matter in an advanced treatment train, including DAF, coagulation and flocculation, and filtration. Phase 1 of the project was approved and commenced in May 1999.

Objectives

The primary objectives of the study were to obtain new information on the performance of various water treatment processes on Seymour Impoundment water. Specifically, the objectives of the study are as follows:
1. to evaluate the effects of different coagulants on the flocculation of turbidity causing particles;
2. to evaluate the effects of ozone on the flocculation of turbidity causing particles;
3. to evaluate the effects of ozone dose and coagulant type and dose on organic matter removal;
4. to evaluate the effects of flocculation and DAF operating conditions on clarification performance;
5. and to study the effect of DAF on filter performance.
Seymour description

The damming of the Seymour River in 1924 created the Seymour reservoir. The dam was upgraded to its current height of 30 metres in 1961. The water in the reservoir has generally low turbidity, however, because of an easily erodable floodplain and heavy winter precipitation, high turbidity events do occur. However, these events normally have a short duration because the silts and sands in the watershed settle quickly to the bottom of the impoundment. The water also has low alkalinity, hardness and pH. The average pH throughout the year stays near a value of 6.3 which is below the “Guidelines for Canadian Drinking Water Quality” and must therefore be adjusted with soda ash (Health Canada, 1996). Giardia lamblia and Cryptosporidium spp have also been detected in the water. Seymour raw water quality for a number of parameters is summarized in Table 1.

The Vancouver area has very dry summers and very wet, moderate winters. The Seymour watershed area receives an average of 5100 mm of precipitation a year, most of which occurs between October and March. The wet season begins in mid-October, as indicated in the raw water data by increases in suspended particles and organic matter.

The Seymour pilot plant is located in a two-story building equipped with a small laboratory. The sludge handling tanks, coagulation tanks and dosing equipment, ozone generation equipment, ozone columns, filter columns and laboratory are located on the main level. The DAF unit, static mixers, flocculators and access to the tops of the filter columns are located on the mezzanine level. Online turbidity meters, pH meters, and particle counters continuously measure raw and filter effluent water. All other analytical tests were performed in the laboratory. The process train used for the duration of the study is diagramed in Figure 1. Sample ports for laboratory analyses are labeled “sp”. The four sample ports used for analyses of water were located at the raw water feed, after chemical injection (before DAF), after DAF and in the filter effluent line. Raw water turbidity, particle counts and pH, and filter effluent turbidity, particle counts, headloss and flow were continuously logged and stored on the control computer in the laboratory. Filter operation was also controlled from this computer.

Theoretical background

Ozone as a coagulant aid

Ozone, although most commonly used as an alternative to chlorine for microbial reduction, has numerous other applications in drinking water treatment. Along with microorganism reduction, oxidation of inorganic pollutants, oxidation of organic micropollutants and the oxidation of organic macropollutants, ozone, when added to water, has a significant effect on particle behavior (Reckhow, et al., 1986). Ozone cannot be used alone, and does not act as a coagulant in the true sense of the word. It must be used in combination with other coagulants such as alum or ferric chloride. Coagulants destabilize colloidal particles by

Table 1 Seymour raw water quality summary

<table>
<thead>
<tr>
<th>Parameter (Unit)</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity (NTU)</td>
<td>0.35 to 1.88</td>
<td>May</td>
<td>December</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>4.0 to 15.0</td>
<td>January</td>
<td>August</td>
</tr>
<tr>
<td>pH</td>
<td>6.3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>UV254 (cm⁻¹)</td>
<td>0.059 to 0.096</td>
<td>September</td>
<td>November</td>
</tr>
<tr>
<td>Colour (TCU)</td>
<td>11 to 16</td>
<td>May</td>
<td>December</td>
</tr>
<tr>
<td>DOC (mg/L)</td>
<td>1.3 to 2.3</td>
<td>September</td>
<td>January</td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>1.6 to 2.5</td>
<td>September</td>
<td>February</td>
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</tbody>
</table>
neutralizing their charge. By doing so, colloidal particles become more hydrophobic and attach to other particles forming an easier to remove, larger jelly-like particle called a floc.

Some benefits of ozone induced particle destabilization are comparable suspended particle removal at lower coagulant doses, increased filter run lengths, precipitation of natural organic matter (NOM), increased TOC/DOC removal and decreased sludge production, (Jekel, 1994). The mechanisms by which these processes are carried out are poorly understood. This lack of understanding may be responsible for a number of inconsistencies in the reported results among investigators. It appears that the mechanism or combination of mechanisms that occur in a given system is highly dependent on the nature of the DOC in the system and the composition of the raw water. The principle mechanisms that are thought to occur in the system are as follow (Reckhow, et al., 1986).

1. Increased concentration of oxygenated functional groups. These groups, most notably the carboxylic acids (–COOH), are theorized to form complexes with aluminum oxide surfaces that will then bond to organic matter and precipitate out.

2. The increase in carboxylic acid groups may lead to an increase in calcium complexation and therefore the direct precipitation of organic matter.

3. Ozone may affect the absorbency of organic matter by reducing the stabilizing effects of NOM on inorganic particles.

4. Oxidation of organo-metallic complexes and release of metal ions such as Fe$^{3+}$, Fe$^{2+}$, and Al$^{3+}$.

5. Lysis and destruction of algae cell walls, thereby releasing various biopolymers, which will become more easily coagulatable, filterable or flotable.

It is important to note that other mechanisms may be occurring in the system. In addition, more than one mechanism may be occurring at one time and it is not known which ones are dominant. Even more importantly, the same mechanisms are not responsible for the removal of organic matter and the reduction of particles, (Jekel, 1994). It is clear that tests must be done on the raw water to determine if ozone induced particle destabilization may be beneficial.
DAF

Conventional water treatment plants (coagulation, flocculation, sedimentation and filtration) use a multi-barrier philosophy for treating natural water for distribution to and consumption by the public. Dissolved air flotation (DAF) has been used as an alternative to sedimentation since the early 1900s to treat waters with low turbidity and low-density particles that do not settle out in a reasonable amount of time. DAF is a clarification process where air that is saturated in water under pressure is released from a nozzle that is placed at the bottom of the flotation tank. When the air-water mixture is released into the water, the pressure drop from the saturator to the nozzle outlet (350 to 480 kPa) causes the air to come out of solution and form small bubbles. These small bubbles (40 to 50 µm) then float to the water surface, attaching to flocculated particles along the way. The sludge accumulates at the top of the flotation tank and is mechanically skimmed from the tank to a waste outlet. The size, shape, volume and distribution of air bubbles are factors that effect the efficiency with which particles are removed (Shawwa and Smith, 1998). These parameters are controlled by the magnitude of the pressure change from the saturator to the flotation tank, the injection flow rate, the water temperature, the air temperature and the design of the injection nozzles. Smaller air bubbles are produced with larger pressure changes. Each one of these parameters must be evaluated for the DAF process to be optimized.

DAF has some additional advantages that should be noted. The most significant of these is the smaller amount of time required for flocculation. Because there is a greater chance of bubble-particle collisions in DAF cells than particle collisions in sedimentation tanks, flocculation times can be reduced from 20 or 30 minutes, to as little as 5 minutes (Edzwald, 1995). Decreased flocculation times will result in smaller flocculation tanks, saving floor space and money, and increasing water production. Because loading rates can be higher with DAF, filter loading rates can also be higher without sacrificing effluent quality. This allows for longer filter runs and an increase in plant capacity. DAF is also effective at removing algae, which can clog filters.

Experimental design

There are two methods that can be used to carry out experiments to test a number of parameters. Factorial designs are becoming more popular as they are a very efficient way to design and analyze complex data sets. Not only can factorial designs handle with precision variables that act additively, but they can also detect and estimate interactions among variables that do not act additively. One-variable-at-time analyses are easy to plan and perform, but they ignore interactions among experimental variables. They estimate the effect of a response variable by changing one parameter and keeping all others fixed. Parameters and the levels that they are tested at must be chosen carefully to make the design worthwhile. In addition, the control parameters must remain constant in a factorial design for the results to be meaningful. In the case of the Seymour pilot plant study, raw water conditions must be constant during a complete factorial design for the results to be meaningful.

Variables from a number of treatment units were chosen to determine their effects on DAF performance and finished water quality. The following is a list of the factors for each unit process used in the study.

Ozonation:  
- Ozone dose – varied from 0.0 to 2.0 mg/L
- Contact time – constant at 6 minutes

Coagulation:  
- Coagulants – alum, ferric chloride (FeCl₃) and polyaluminum chloride (PACl)
- Coagulant dose – dependant on raw water quality
- Rapid mixing – constant at approximately 2240 s⁻¹
Flocculation: Stages – 2 or 3  
Detention time – 8 to 15 minutes  
Velocity gradient – 27 to 122 s⁻¹  

DAF:  
Loading rate – 5 to 12 m/hr  
Saturator pressure – constant at 480 +/- 80 kPa  
Recycle ratio – varied between 6 and 20%  

Filtration:  
Loading rate – constant at 360, 310, 372 L/hr for filter 4, 5 and 10, respectively  
Media configuration – 300 mm of 0.7 mm sand overlain by 2400 mm of 1.4 mm anthracite  

Each run was performed in generally the same manner, irrespective of the parameters being tested. Normally, filters were backwashed before the start of each run. All experimental run information and equipment settings were recorded on run data sheets. Runs were normally run for a long time if filter performance was being investigated (> 12 hours or until particle breakthrough), or for a shorter period of time if flocculation or DAF performance were being tested. A minimum of six plant volumes of water were run through the plant before measurements were taken to ensure that the unit processes had stabilized and that water affected by previous runs had gone through. This normally took approximately 1.5 hours.

Grab samples were taken from four points in the process train as indicated by sample points s, r, c, d and f on Figure 1. Each sample was analyzed for turbidity, particle counts, temperature, pH, colour and UV-absorbance at a wavelength of 254 nm. All analytical tests were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Particle counts were determined by a bench scale potable water sensor based on a laser light blocking principle (SM 2560C).

Results and discussion

Four objectives were established at the beginning of the pilot plant study. The first one of these was to evaluate the effects of different coagulants on the flocculation of particles. Alum, PACl and FeCl₃ were the coagulants chosen for this study. Alum and PACl were each tested at two different times of the year with different temperatures and raw water qualities. Ferric chloride was only tested in December, where the water was cold and the turbidity was decreasing to levels below 0.40 NTU. Coagulant performance was based on particle and organic matter removal in the DAF unit since there was no analytical methods, such as zeta potential, to evaluate particle destabilization. Both alum and PACl worked well at reducing particle counts, turbidity and colour in the DAF unit when their doses were optimized. It can been seen from Figure 2 that with small changes in coagulant dose, there is a vast difference in particle removal percentages.

Turbidity removal of up to 80 percent could be achieved with alum and PACl. Results also indicated that DAF was better at removing particles when the raw water quality deteriorated. The most significant difference between the way alum and PACl functioned was their effects on the pH of the water. Very little alkalinity was required with PACl, therefore very little soda ash was required to be added to maintain the pH at optimum levels for coagulation. Alum required much more soda ash to maintain its pH at optimum levels. Ferric chloride was not as effective a coagulant as alum or PACl. Most runs with FeCl₃ resulted in turbidity removal rates of less than 70 percent. Particle removal with FeCl₃ was also poor. Like alum, ferric chloride required the addition of much more soda ash than PACl required. In addition, it adds a lot of colour to the water. The colour after coagulant addition increased every time to over 80 apparent colour units (ACU), as compared to very little change with alum or PACl. The DAF unit could remove 50 to 60 percent of that, but the rest had to be removed by the filters.
The second objective of the study was to evaluate the effects of ozone on the flocculation of particles. Results were mixed, however, it appears that the effectiveness of ozone as a coagulant aid was highly dependent on the nature of the raw water. When the raw water turbidity and organic matter content were low at the beginning of the study (turbidity = 0.25 NTU), ozone doses, even as little as 0.25 mg/L, had a negative impact on the removal of particles and turbidity in the DAF unit. In this case, an ozone dose of 0.25 mg/L resulted in a drop in turbidity removal of 15 percent. A dose of 0.50 mg/L caused a drop in turbidity removal of 35 percent compared to when no ozone was used. Results were very different when the turbidity and organic matter content began to rise. When the raw water turbidity was 0.40 NTU, an ozone dose of 0.25 mg/L resulted in an increase of turbidity and particle reduction of approximately 10 percent (refer to Figure 3).

Ozone had similar results with PACl. Figure 4 shows particle and organic matter removal with ozone and PACl, when the raw water turbidity was much higher, at 1.10 NTU. Increasing the ozone dose from 0.25 to 0.75 mg/L caused only a slight reduction in particle removal. Its effect on colour removal was more significant and was due to an unknown factor. It may also be important to note that in Figures 2, 3, and 4, removal of larger particles in...
the DAF unit was better than for smaller particles. Results also indicated that ozone had a much larger negative effect on ferric chloride coagulation, than with alum or PACI.

Although there appears to be no advantage for particle removal in the DAF unit with ozone in terms of percent reduction, the particle size distribution (PSD) diagram (refer to Figure 5) shows that ozone decreased particle loading to the DAF unit. PSDs (SM 2560A) present normalized particle data, based on number, volume or surface area concentration. They are a convenient way for presenting particle data. Particle sizes used for the entire study were based on *Cryptosporidium* spp, *Giardia lamblia*, and floc particle size ranges. When a coagulant was added to the water, the number of particles in that water increases, effectively increasing the particle loading to the DAF unit. When ozone was used with the coagulant, the increase in particles due to coagulant addition was not as great, thereby decreasing particle loading to the DAF unit. Therefore, even if particle removal in the DAF unit was the same with and without ozone, the run with ozone was more likely to produce fewer particles in the DAF effluent in terms of absolute number of particles. This will result in a lower particle loading rate to the filters.

![Figure 4 Effects of ozone dose (with PACI) on removal of particles and organic matter](image)

![Figure 5 Particle distribution diagram](image)
The third objective of the study was to evaluate organic matter removal based on colour and UV-absorbance. Colour was primarily removed in the DAF unit by flotation of colour-causing particles (metallic ions, humus, peat, plankton) to the surface of the DAF unit. Colour removal was normally 60 percent, when coagulant dose was optimized. Ozone generally had the same effect on colour removal as it did with particle and turbidity removal. Ferric chloride was generally less effective at removal colour than PACl or alum, however there is much more colour to be removed when ferric chloride is used as the coagulant.

UV-absorbing organic matter (lignin, tannin, humic substances), measured at a wavelength of 254 nm was removed via adsorption onto coagulant precipitates before the DAF unit. The DAF unit did not contribute to the removal of this type of organic matter. It was then clear that the same material that caused colour in the water did not cause increased UV-absorbance levels. When there was high removal of particles in the DAF unit, there was high organic matter removal by adsorption. However, even if particle removal was not good, organic matter removal prior to the DAF was still good. This indicates that the critical amount of coagulant required for the removal of particles in the DAF is more than that required for the removal of UV-absorbing organic matter. Pre-DAF UV$_{254}$ removals are shown on Figures 3 and 4.

Figure 3 and 4 also show that ozone had a more positive effect on the removal of organic matter that it did for particle and turbidity removal. Ozone normally enhanced particle removal by 10 percent. Even when ozone had negative effects on particle and turbidity removal in the DAF unit, the removal of organic matter stayed the same or improved.

The DAF unit appears to be very robust with respect to flocculator and DAF operating conditions. Varying the flocculator velocity gradient and detention time had little effect on flocculation performance, so long as they were kept within reasonable values (40 s$^{-1}$ < G < 100 s$^{-1}$; 5 min < t$_d$ < 15 min). Similarly, DAF recycle flow, saturator pressure and loading rate had little effect on its performance, (6% < Q$_R$ < 20%; 380 kPa < P$_{sat}$ < 540 kPa; 6 m/hr < dL/dt < 10 m/hr).

The results from this study strongly indicate the importance of some sort of pretreatment before filtration. They show that DAF is very effective at removing particles, turbidity and colour from the water. When particle removal in the DAF unit was greater than 50%, 100% of filter runs produced effluent turbidity of less than 0.1 NTU. When particle was less than 50%, only 13% of filter runs produced effluent with turbidity less than 0.1 NTU. Fewer particles in the turbidity effluent mean a smaller risk of contamination by microbial pathogens, resulting in a safer drinking water supply for the public.

References