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Microfiltration productivity and water quality in relation to pretreatment, temperature and flux

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ABSTRACT: Microfiltration was evaluated as a water treatment process using the 60 gpm (3.8 L/s) Memtec pilot plant in Manitowoc, WI, USA. The pilot plant operated for over six months. Productivity as measured by mass transfer coefficient (MTC) decline and water quality, as measured by turbidity, particles and coliform rejection were evaluated for microfiltration with no pretreatment, microfiltration with alum addition and microfiltration with PAC addition in the pilot plant study. The effects of temperature on microfilter fouling were evaluated by model development and data collection. Alum addition relative to PAC addition or conventional pretreatment increased the run-time from 10 days to 30 days at 50 gfd (85 L/hm^2) and 25 °C. Turbidity, particle and coliform rejection was independent of pretreatment. Run-time between chemical cleanings increased with decreasing flux and increasing temperature. Log rejection of turbidity and particles increased with increasing concentration. Infinite log rejection of coliforms was observed for a 1–2 log feed stream concentration.

INTRODUCTION

The Manitowoc Public utilities water department is located in Manitowoc, MI, and currently utilises a 10 MGD (0.44 m^3/s) conventional water treatment facility. The conventional water treatment plant consists of chemical addition followed by flocculation, sedimentation and filtration. Its water source is Lake Michigan.

Following an outbreak of *Cryptosporidium* in 1993, the EPA put forward the Enhanced Surface Water Treatment Rule (ESWTR). This rule requires an increased removal and inactivation of microbial contaminants from surface water. To obtain high quality drinking water, we studied a low-pressure membrane filtration alternative. Microfiltration (MF) and ultrafiltration (UF) are both technologies that are capable of providing water that meets both current and anticipated water quality regulations, and both offer several advantages in comparison to conventional treatment processes. In particular, they offer the ability, under most conditions, to remove particulate matter, including micro-organisms (*Giardia*, *Crypstoridium*) without further chemical addition.

This paper describes a microfiltration pilot plant operating from 24 April 1995 to 5 March 1996 at Manitowoc, Wisconsin. The objectives of the study were to determine if microfiltration could be used to produce drinking water effectively. Productivity and water quality data were used for evaluation.

LITERATURE

The application of microfiltration and ultrafiltration for the treatment of drinking water is a relatively recent concept. Their effectiveness in industrial, pharmaceutical and food processing applications has led to their use in drinking water treatment [1]. Depending on treatment requirements, they can replace conventional physical separation processes for drinking water production. The performance of MF and UF can be enhanced by the addition of PAC (Powdered Activated Carbon) to the influent.

Because of their cut-off threshold, microfiltration and ultrafiltration membranes constitute a near absolute barrier, which efficiently retains any particulate pollution; suspended matter and colloids and their degree of retention are apparently independent of source water quality. Although no processes provide absolute rejection pathogens, UF or MF membranes typically provide more than five log rejection as compared to more than two log rejection of conventional processes. Most full scale MF and UF plants that are currently being used for potable water treatment report permeate turbidities of less than 0.1 NTU [2]. The Surface Water Treatment Rule (SWTR) requires that filtration plants must achieve a filtered turbidity of $\leqslant 0.5$ NTU in 95% of the samples collected each month, with no samples having a turbidity of greater than 5 NTU. The California Department of Health Services has imposed a more stringent requirement ($\leqslant 0.2$ NTU) for the Saratoga Water Treatment Plant, which is the largest microfiltration system in the USA currently being used for potable water treatment (5 MGD/0.22 m^3/s). The quality of the microfiltered water at Saratoga has been exceptional from the first day of plant operation. Turbidity was consistently $\leqslant 0.2$ NTU, regardless of the raw water quality which has been as great as 250 NTU [3].

A potential advantage of ultrafiltration treatment is the effective removal of turbidity. Turbidities of greater than 0.1 NTU have been documented for typical drinking water sources. At the bench-scale, four ultrafiltration membranes were selected, and for each membrane the resulting turbidity was equal to 0.05 NTU [4]. Two source waters located in Northern California were used to test for removal of particulates. For the water from Mokelumme, turbidities ranged from 0.3 to 0.82 NTU. Following treatment with Aquasource ultrafiltration membranes, turbidity was reduced to an average of 0.03 NTU. For the Delta water source, turbidity ranged from 11.5 to 24.8 NTU and the permeate turbidity was 0.03 NTU [5]. For the Mokelumme water, approximately 3100 particles (1–120 μm) per millilitre were detected. The ultrafiltration membrane achieved a 2.6-log order reduction in particle count. As for the Delta water source which had a feed particle count of approximately 54 000, less than two particles per millilitre were detected in the permeate. Consequently, it is evident that feed water variation does not affect the quality of ultrafiltration permeate.

The removal of *Giardia* by microfiltration and ultrafiltration has been well documented in the literature for several membranes [6,7]. In these studies, a removal of more than 4-logs was reported with both ultra and microfiltration membranes having provided absolute removal of protozoan cysts. In these cases the level of removal depends on the concentration of the organism in the feed water. A more recent bench-scale study reported that both polymeric microfiltration and ultrafiltration membranes reject more than seven logs of protozoan cysts with membranes free of defects. All membranes tested—with exception of one microfiltration with a defective membrane seal ring—were found to remove *Cryptosporidium* and *Giardia* to below the detection limit (1 cyst/L) [8]. These results were confirmed at pilot-plant scale, where removals ranged from 6 to 7-log order reduction. *Cryptosporidium* and *Giardia* concentrations were seen to be a function of the influent concentration. This result is consistent with other results that have shown that an intact 0.2 μm microfiltration filtration process provides a near absolute barrier to *Cryptosporidium* and *Giardia* [3].

THEORY

Basic flux in a membrane process can be described by Equation 1.

$$F_W = K_w \Delta P = \frac{Q_p}{A} \tag{1}$$

where: F_w: water flux (L^3/L^2t); K_w: solvent mass transfer coefficient (MTC) (L^2t/M); ΔP: transmembrane pressure (L); Q_p: permeate stream flow (L^3/t); A: membrane area (L^2).

Equation 2 is the Hagen–Poiseuille equation, which shows that flow through membrane pores is a function of viscosity, pore diameter, porosity, applied pressure and membrane thickness (Cheryan, 1986). Based on this equation, flux is inversely proportional to solvent viscosity. The viscosity of water decreases as temperature increases, which causes the flux to increase as temperature increases.

$$F_W = \frac{\Delta P}{R_W} = \frac{\epsilon r^2 \Delta P}{8\delta\mu} = \frac{1}{\mu}\frac{\epsilon r^2 \Delta P}{8\delta} \tag{2}$$

where: r: pore radius, δ: membrane thickness, ε: porosity, μ: solvent viscosity.

Because of the temperature effect upon flux, flux must be normalised or adjusted to a common temperature. The most common equation for normalising flux is shown in Eqn 3. This equation can be rearranged into a linear form, where θ can then determined by regression. The temperature correction factor (TCF) can be determined from either Eqns 4 or 5. Note that all factors other than temperature must be equal when this technique is applied. From Eqn 5, θ is calculated to be 1.03.

$$TCF = \frac{F_{T^\circ C}}{F_{25^\circ C}} = \theta^{(T-25)} \tag{3}$$

$$Log\frac{F_{T^\circ C}}{F_{25^\circ C}} = (T-25)Log\theta \tag{4}$$

$$Log\frac{\mu_{T^\circ C}}{\mu_{25^\circ C}} = (T-25)Log\theta \tag{5}$$

METHODS

Source of supply

Table 1 shows the range of Lake Michigan water quality for specific parameters measured during the course of the study.

Pilot plant description

Manitowoc Public Utilities operated a microfiltration unit developed by Memtec. The system consisted of a polypropylene hollow fibre membrane that has a nominal pore size of 0.2 μm. The membrane pilot unit contained six modules giving a total membrane area of 90 m^2. The unit was capable of treating a flow of up to 60 gpm (3.8 L/s). Each membrane module, which was 1 m high and 0.1 m in diameter, was the same size and construction as that proposed for the full-scale facility.

The pressurised raw water was pumped through the filter

Table 1 Lake Michigan water quality

Parameter (unit)	Range
pH	7.6–8.1
Total organic carbon (mg/L)	0.6–1.8
Turbidity (NTU)	1.0–100
Total coliform (no./100 mL)	0–140
Faecal coliform (no./100 mL)	0–10
E. coli (no./100 mL)	0–6

modules. The unit operated at a feed pressure of approximately 30 psi (2 bar) and a transmembrane pressure (TMP) of less than 10 psi (0.7 bar). The TMP is calculated by subtracting the filtrate pressure from the feed pressure. The feed water is pumped to the outside of the fibres and passes through the microporous hollow fibres (microfiltration). This flow regimen is described as 'inside-out'. The filtered water is collected from the inside or inner lumen and forms a filtrate water stream. The filtration cycle lasts 25–45 min and is followed by a 60–90 s air-water cleaning of the membranes, defined as 'backwashing'.

The backwash consists of passing air from the inside to the outside of the microfiltration. Particulates are dislodged from the outside of the microfiltration. Once the air is passing the outside of the microfiltration, particles are flushed from the element. Subsequently, the feed water was used to flush out the dislodged solids/particles from the feed water side of the membranes. However, this backwash procedure does not remove 100% of the particles that collect on the membrane fibres. Thus, the TMP across the membrane slowly increases. When the TMP exceeds 18–22 psi (1.2–1.5 bar) at the operating flow rate, chemical cleaning of the membranes is required. The chemicals used during cleaning include sodium hydroxide (2% solution), hydrogen peroxide (1.5% solution) and a small amount of surfactant. After proper chemical cleaning, the TMP returns to the initial TMP of 8–10 psi (0.5–0.7 bar).

Pilot plant monitoring

Table 2 presents a summary and frequency of the water quality and operational data that were monitored. Table 3 presents the intervals characterised by backwash frequency, dose of alum, and dose of powdered activated carbon (PAC). Moreover, each interval was initiated following a cleaning cycle or a change in operation and maintained until the initiation of the next run scenario.

RESULTS AND DISCUSSION

This section contains a quantitative discussion of the data, based on data analysis, statistical regression and modelling. The data is separated into sections describing microfiltration productivity and water quality, which are the primary areas of the data analysis section. Productivity was analysed using the flux model presented in the theory section, while water quality was analysed by numerical integration of the applicable data for the microfiltration pilot study. Finally, water quality relationships for productivity were investigated using statistical hypothesis testing.

Productivity

Membrane productivity can be determined by the drop in flux at constant pressure over period of operation, or by the mass transfer coefficient (K_w or MTC). The MTC is determined by the quotient of flux and the pressure gradient through the membrane. The resulting normalisation of the MTC with respect to pressure is consequently the best way of evaluating membrane productivity over the period of operation. Productivity in this section is analysed by determining MTC slope decline by regression, which was then used to predict a cleaning frequency.

Temperature effects on MTC and flux

A temperature correction factor (TCF) had to be developed for the mass transfer coefficient instead of flux, because the pressure varied throughout the investigation. This equation

Table 2 Water quality and operating parameters monitoring schedule membrane processes pilot study, Manitowoc

Parameter	Sampling location	Frequency	
Water quality monitoring			
Inorganic			
Turbidity	Feed, filtrate	Continuous	
Particle counts	Feed, filtrate	Continuous	
pH	Feed, filtrate	Daily	
Bacteriological			
Total coliform	Feed, filtrate, backwash	Daily	
Faecal coliform	Feed, filtrate, backwash	Daily	
E. coli	Feed, filtrate, backwash	Daily	
Plant operations monitoring			
Temperature	Feed	Daily	
Flow		Feed, filtrate	Continuous
Pressure	Feed, Filtrate	Continuous	
Backwash			
Duration	–	Continuous	
Frequency	–	Continuous	
Chemical dosage	Feed	As needed	

Table 3 Interval identification

Test interval	Operation (days)	Backwash frequency (min)	Alum dose (mg/L as $Al_2(SO_4)_3$)	PAC dose (mg/L)
1	1–25	25	—	–
2	26–40	25	—	–
3	41–50	25	—	–
4	51–67	35	—	–
5	68–72	35	—	–
6	73–81	45	—	–
7	82–86	35	—	–
8	87–90	35	—	–
9	91–99	35	—	–
10	100–109	25	—	–
11	110–114	25	—	–
12	115–121	20	—	–
13	122–143	20	8–10	–
14	144–158	25	18–20	–
15	159–161	25	—	10
16	162–170	25	—	25
17	171–185	25	—	–
18	186–193	25	—	–

could be developed theoretically; however, this development assumed that temperature only affects the water and does not affect the membrane. Another method of developing the TCF is to develop a statistical relationship between MTC and temperature using only data following cleaning. This technique accounts for temperature effects on both the water and membrane; however, it assumes that the membrane is cleaned effectively.

In order to solve the TCF for the MTC, based on the operational data, the same equation form as shown in Eqn 4 is used.

$$TCF = \frac{F_{T^\circ C}}{F_{25^\circ C}} = \theta^{(T-25)} \qquad (4)$$

where T is in degree Celsius. In previous section, $\theta = 1.03$ was shown in both Dupont equation and theoretical Hagen–Poiseuille equation. Taking the logarithm of both sides of the equation gives:

$$LogTCF = Log\frac{MTC_{T^\circ C}}{MTC_{25^\circ C}} = (T-25)Log\theta \qquad (6)$$

Figure 1 is a plot of Log MTC of the actual operational data vs. $T - 25$. Logθ is the slope of this curve and was determined by linear regression. The θ was determined to be $10^{0.0187}$, or 1.044, which is close to the theoretical $\theta = 1.03$, but does indicate that temperature affects the membrane as well as water.

$$TCF = \frac{MTC_{T^\circ C}}{MTC_{25^\circ C}} = 1.044^{(T-25)} \qquad (7)$$

A TCF can be determined for flux using the actual flux and temperature data. The equation is as follows:

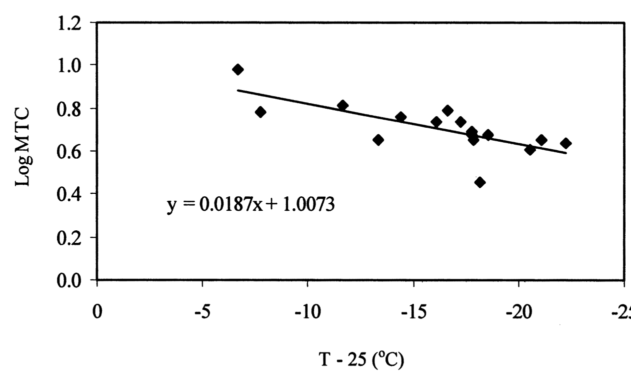

Fig. 1 MTC vs. temperature for operational data.

$$TCF = \frac{F_{T^\circ C}}{F_{25^\circ C}} = \theta^{(T-25)} \qquad (8)$$

The θ can be determined only if the initial TMP is constant for each test at different temperature.

MTC decline

The purpose of determining MTC decline is to analyse microfiltration productivity and predict the frequency of the cleaning for the microfiltration. This frequency can be predicted if a maximum allowable TMP is set and the decline of the MTC is known.

Overall operating conditions for temperature, flux, transmembrane pressure, mass transfer coefficient vs. time of operation are shown for the entire study in Figs 2 and 3. This data was divided into 18 intervals, which are shown on the time axis. These intervals were typically cleaning intervals as identified previously, and other time intervals where an operating variable was changed. These 18 intervals were intended to provide a period where all variables were constant, except for the time of operation. If flux, pressure, temperature or any other operational variable was changed at a given point in time of operation, a new interval was identified. Consequently the data analysis section will have more intervals than were defined in the data discussion presented earlier.

There were five general divisions of operation:

1 *Start Up*. Start up or beginning means that this time was allocated towards familiarisation with the equipment. Consequently this time was not used for analysis or productivity. No data was used for analysis until 40 days had elapsed.
2 *No alum or PAC*. This period is typified by no addition of any filter or treatment aid during production. As the only additions prior to microfiltration were alum and PAC, this period is described as 'no alum or PAC' and was in effect from day 41 until day 121.
3 *Alum*. This period is typified by the addition of alum and was in effect from day 122 to day 158.
4 *PAC*. This period is typified by the addition of PAC and was in effect from day 159 to day 170.
5 *Final*. This period was used for varying water quality, and for integrity testing that did not effect productivity, and was not used for analysis of productivity. This period was in effect from day 171 till the end of the study.

As noted previously, temperature significantly affected TMP, flux and MTC.

Assuming there is no change in the membrane surface, increasing temperature would increase flux, decrease TMP and increase MTC. Conversely, a decreasing temperature would have the reverse effect. These trends are apparent in the operational data which is shown in Figs 2 and 3, and are observed for Intervals 12 and 13.

Temperature may also affect cleaning efficiency and the membrane surface. The data shows that the TMP was generally above 10 psi (0.7 bar) during periods where the temperature was below 7 °C and was typically 10 psi (0.7 bar) or lower at higher temperatures.

The membrane porosity may vary with temperature as well as the viscosity of water. The benefit of alum addition from day 122 to day 158 is seen in Figs 2 and 3. TMP decreases and MTC increases from days 122 to 144 (interval 13) when the alum was

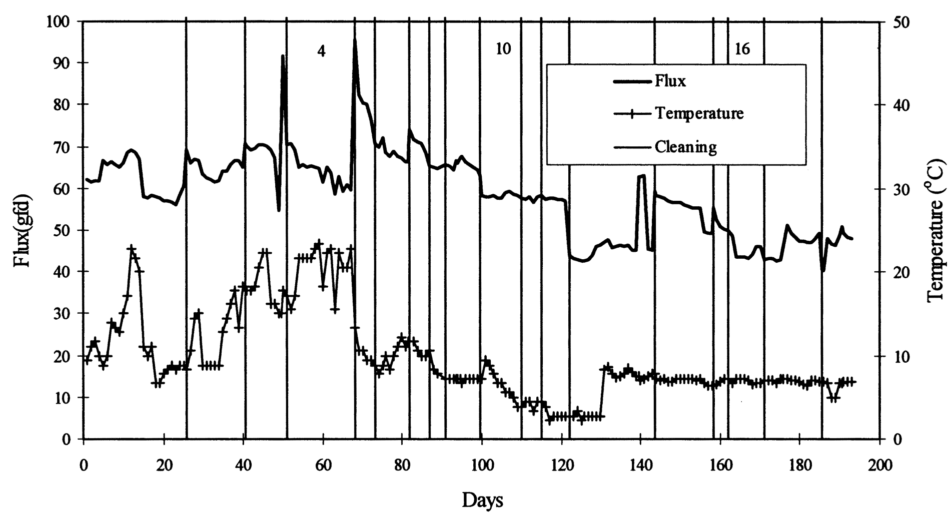

Fig. 2 Temperature, flux, and cleaning interval vs. operating time.

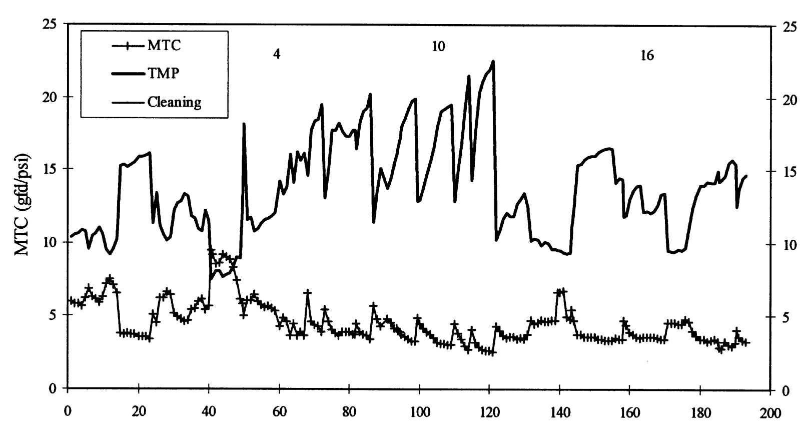

Fig. 3 Transmembrane pressure, mass transfer coefficient and cleaning interval vs. operating time.

Table 4 Average MTC decline

Condition	Temperature (°C)	Flux (gfd (L/hm^2))	β_1 (gfd/psi-d (L/hm^{2}bar-d))
No alum-PAC	11.7	67 (114)	−0.31 (−7.64)
Alum	5.6	50 (85)	−0.11 (−2.71)
PAC	6.7	48 (81)	−0.16 (−3.94)

added, although temperature decreased relative to the previous interval, no. 10. The alum was essentially cleaning the microfilter. In interval 14 (days 144–158) flux was increased while alum was still being added and TMP naturally increased. However, the MTC decline was less than in intervals 3–12. As a consequence, alum appears to be beneficial for reduction membrane fouling. However, no work was done to determine if aluminium solids accrued in the membrane. Such accrual could damage a membrane and should be considered when evaluating alum addition.

The purpose of this study was to predict the frequency of cleaning. As shown earlier, this frequency can be predicted if the decline in MTC is known. Since a constant performance is required, more pressure has to be applied to the microfiltration during its operation to maintain a constant flux, because of fouling of the microfiltration process over time. Typically, the microfiltration TMP can vary over several cycles, from as little as 3 psi (0.2 bar) to as much as 22 psi (1.5 bar). Initially, the microfiltration cycle TMP may only vary from 3 to 4 psi (0.2–0.3 bar) and just prior to cleaning the microfiltration cycle TMP may vary from 18 to 22 psi (1.2–1.5 bar). These values, given by Memtec, are in the maximum range of TMPs. In this study the typical TMP varied initially from approximately 10 psi (0.7 bar) to nearly 18 psi (1.2 bar) prior to cleaning. Consequently, at a constant temperature, the cleaning frequency could be predicted to be the time required for the TMP to go from 10 to 18 psi (0.7 to 1.2 bar). If the MTC decline is known, then the cleaning frequency could be calculated by dividing the MTC decline into the difference between the MTC at 10 psi (0.7 bar) and the MTC at 18 psi (1.2 bar). If the flux is constant, the only change during operation is the TMP at the beginning and end of an operating cycle. However, temperature changes can also effect MTC change. In fact, a temperature increase at day 131 is observed to decrease the TMP over the period of operation from day 131 to 143. Therefore temperature effects must be considered when the cleaning frequency is determined. This is typically carried out by normalising flux for temperature changes.

The method of predicting MTC decline for a given operating condition over time of operation was determined empirically using a linear regression. The independent variable is time and the dependent variable is MTC. This equation assumes a zero order relationship between MTC and time. The equation is:

$$\mathrm{MTC} = \beta_0 + \beta_1 \mathrm{Time} \qquad (9)$$

The slope β_1 is the decline of MTC during the time of operation. These β_1s were analysed by regression to determine the effect of temperature and flux on productivity. As expected, β_1 increased as flux increased and temperature decreased; however, the relationships were not statistically significant. The effects of temperature and flux on run-time were assessed by averaging β_1 by pretreatment and using the temperature correction factor developed shown in eqn 7.

The intervals were averaged by treatment condition as in no alum-PAC, alum and PAC operation in order to assess the effect of pretreatment. The MTC average decline was determined for no alum-PAC, alum and PAC and is shown in Table 4. The benefit of alum addition is clearly seen. Despite having the lowest average temperature, the condition for alum addition is seen to have the lowest MTC decline. Previously, it had been shown that the highest rates of productivity decline were observed at the lowest temperatures. However, the β_1 for alum is lower than all the other β_1s, even though the alum operating temperature is the lowest of all treatments. Consequently, this data suggests that alum addition on a continuous basis would benefit productivity at all temperatures.

The effects of flux and temperature on productivity or run-time were estimated using the average productivity declines with the derived relationship for the effect of temperature on MTC shown in eqn 7. These estimates are shown in Fig. 4. The run times were determined by assuming an initial and final TMP of 10 and 18 psi (0.7 and 1.2 bar) for a flux of 70 gfd (120 L/hm^2) at 25 °C. By this assumption, the MTC would decrease from 7 gfd/psi (173 L/hm^{2}bar) initially, to 3.9 gfd/psi (96 L/hm^{2}bar) before cleaning. The ΔMTC would be 3.1 gfd/psi (76 L/hm^{2}bar) and the run time could be estimated by dividing the average MTC decline, 0.11 gfd/psi-d (2.7 L/hm^{2}bar-d) for alum and 0.31 gfd/psi-d (7.6 L/hm^{2}bar-d) for no-alum/PAC, into the ΔMTC. This was an average MTC decline for all conditions. This example would give a run-time of 28 days for a flux of 70 gfd (120 L/hm^2).

The run times shown in Fig. 4 show that alum addition is very beneficial for increasing run time. While this approach does show run time, it does not consider any phase change of the foulant by temperature. The operational data showed clearly that a marked fouling occurred when the temperature dropped to approximately 7 °C. The increased fouling was not due to a change in the viscosity of water as that is minimal. This could have been the result of a change in the membrane due to temperature, but was most likely due to a change in the foulant due to temperature. It is possible that the fouling material began to change form, to a more gelatinous material, at about

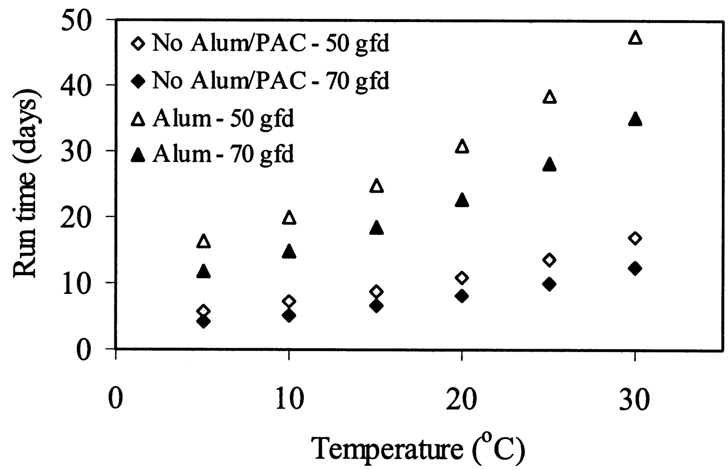

Fig. 4 Run time vs. Temperature for varying flux for No alum-PAC, and for Alum.

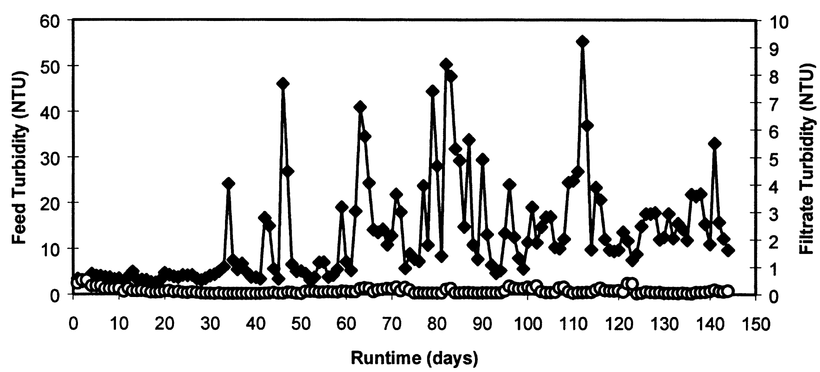

Fig. 5 Plot of average feed and filtrate turbidity vs. cumulative run-time with associated turbidity data collection.

7 °C. It is also possible that the water quality changed during this study and that the fouling material was available when the temperature dropped to 7 °C. In whatever case, the addition of alum and a higher feed water temperature was clearly beneficial to the operation ofmicrofiltration by observation and analysis at Manitowoc.

Water quality

Water quality assessment is based on quantitative calculations and observations. During the course of operation, the microfiltration system was operated under various conditions allowing for assessment of the impact of these varying conditions on microfiltration performance in terms of filtrate water quality.

Turbidity summary

Extensive turbidity data was available for all but three intervals and is shown in Fig. 5. The detection limit of the turbidimeter was 0.01 NTU. Visual inspection of this data indicates that there is no relationship between filtered turbidity and raw water turbidity.

Of the some 200 days of operation, turbidity data was collected for 145 days. This is reflected in the graphical presentations of the turbidity data in this section. This data is presented as though there was no downtime and the contiguous data is partitioned only by operational interval. Turbidity data was generated continuously, except when the in-line turbidimeter was off-line, in unison with flux and TMP. Both feed and filtrate streams were measured for turbidity. Each of the interval data sets was then compiled. In order to quantify the removal of turbidity for each interval, cumulative turbidity loaded to the microfiltration and passed to the filtrate were used. Given relatively uniform conditions for both influent flow and turbidity data over an interval of time, the products of the average flow, average turbidity concentration, and total length of time for the interval ($Q \times C \times t$ = Cumulative turbidity) yields an approximate value of turbidity entering and passing through the microfiltration for a given amount of time. Intervals of approximation were typically for an entire day. However, in instances where significant deviations occurred for either flow or concentration, the intervals were reduced accordingly. With an approximate cumulative value for feed and filtrate turbidity for a given interval, per cent rejection for the entire interval was estimated, and hence log-order removal. The results from the integration technique, in terms of a percentage rejection of turbidity and respective log-order reduction are provided in the Table 5 by test interval.

As can be seen in Table 5, turbidity was greatly reduced by microfiltration, and the microfiltration performed reliably from run to run. The turbidity log-removal vs. run-time by test interval is presented in Fig. 6. However this data shows that

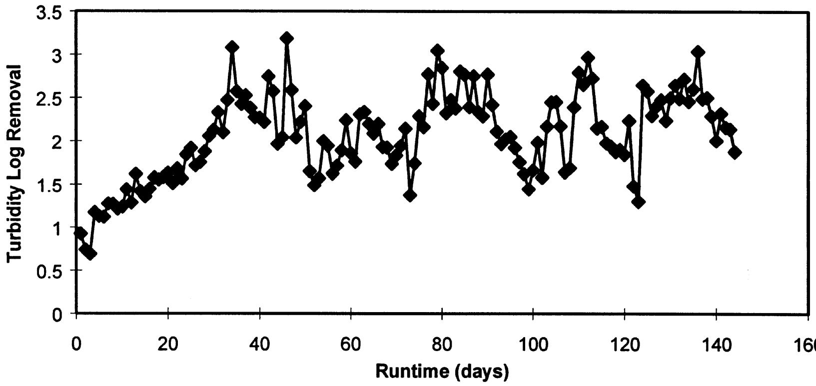

Fig. 6 Plot of turbidity log removal vs. cumulative run-time with associated turbidity data collection.

Table 5 Turbidity removal efficiency by interval

Interval	Rejection (%)	Log removal
1	–	–
2	91.6	1.08
3	97.1	1.54
4	99.4	2.26
5	99.5	2.29
6	–	–
7	–	–
8	99.7	2.48
9	99.8	2.64
10	98.3	1.77
11	99.3	2.16
12	98.7	1.88
13[a]	99.6	2.45
14[a]	98.6	1.86
15[p]	99.8	2.71
16[p]	99.0	2.00
17	99.4	2.23
18	99.4	2.25

a = alum addition, p = PAC addition.

the log removal of turbidity varied from 1.08 to 2.71. Regression analysis established a weak relation between feed water turbidity and filtered water turbidity. Therefore, log-order removal was affected by both the raw water turbidity, and by turbidity coming from the membrane itself. In fact, the highest filtered water turbidity were measured when the lowest feed water turbidity occurred. The addition of alum or PAC did not result in higher log-order removal of turbidity, as shown in Table 5.

Particle count summary

Particle count data was generated during the major part of the operational intervals. Both feed stream and filtrate particles were measured. The detection limit of the particle counter was 0.5 μm. The data reflects values for particles of two different sizes. Unfortunately, these data sets are not overlapping. Initially, particulates were measured for the feed and filtrate streams of size range 2–100 μm. Shortly after the study began, it was realised that gas bubbles remaining in the system from the pneumatic cleaning cycles were interfering with particle count information compiled in the 2–100 μm range. The system was modified to include a relief tube that allowed many of the air bubbles to escape to the atmosphere, and data was collected only for the 2–5 μm size range. The reduced size range was consistent with the size range of protozoan cysts and provided a more pertinent data set.

During the first half of the study, particle count data was collected for 6 h every day at half-hour intervals, as shown in Fig. 7. The remaining particle count data sets were collected every 3–5 min. Like the turbidity data, particle count data is presented as though there was no downtime, and once again the contiguous data is partitioned by operational interval. There were only 115 actual days where one particle count or more was recorded, which defines the time axis in Fig. 7. The data in Fig. 7 indicates that the filtered water particle count is not related to raw water particle count.

Average particulate values were determined for each day that turbidity was monitored. The feed and filtrate cumulative particle count values were determined by numerical integration and used to determine particulate removal efficiency. Percentage removal and log-order reduction in particle counts were reported by time interval. Table 6 displays microfiltration performance over 18 referenced intervals.

It can be seen that the particles were efficiently rejected by the microfilter in all test periods, as indicated by the removal efficiency and log order removal calculations. Average log reduction data vs. run-time is provided graphically in Fig. 8, which has a time axis of 88 days. Time here is determined on a 24-h basis, and consequently the 115 days' run-time were reduced to 88 24-h days. The pilot project ran for 16 h of every day. When no samples were collected, an average for the last reading and the first reading of the next day were used. The log-order removal for feed and raw water particle counts varied from 1.32 to 4.25. The addition of alum or PAC did not have an effect on the log order removal of particles from the raw water.

Table 6 Estimated particle count removal efficiency by scenario

Interval	Particle size range (μm)	Rejection (%)	Log removal
1	–	–	–
2	2–100	95.24	1.32
3	–	–	–
4	2–100	99.70	2.51
5	2–5 & 2–100	99.90	3.01
6	2–5	99.97	3.47
7	2–5	99.97	3.58
8	2–5	99.98	3.73
9	2–5	99.98	3.65
10	2–5	99.94	3.23
11	2–5	99.90	2.99
12	2–5	99.99	3.78
13[a]	2–5	99.96	3.38
14[a]	2–5	99.98	3.84
15[p]	–	–	–
16[p]	2–5	99.99	4.26
17	2–5	99.99	4.12
18	2–5	99.98	3.69

a = alum addition, p = PAC addition.

The particle count in the raw water was taken prior to the addition of alum or PAC.

Coliform summary

Coliform bacteria are commonly used as indictor organisms for measurement of pathogenic contamination. Data for total coliform, faecal coliform and *Escherichia* coliform (*E. coli*) were collected during the 210 days of operation. The feed stream concentrations ranged between 0 and 140 counts/100 mL for total coliform, 0–10 counts/100 mL for faecal coliform and 0–6 counts/100 mL for *E. coli*. There was no coliform in filtered water samples. These results indicate that the log removal is greater than 2, 1 and 1 for total coliform, faecal coliforms, and *E. coli*, respectively. In this investigation, the microfiltration membrane could be described as having achieved an absolute removal of total coliform, faecal coliform and *E. coli*. However, absolute removal by any processes is unrealistic but this process does outperform the existing treatment process.

Water quality summary

The relationship between particle, turbidity and coliform rejection is not readily apparent. Absolute rejection of coliform was observed, whereas absolute rejection of turbidity and particles was never observed. The log rejection of particles and turbidity increased as the concentration of particles and turbidity

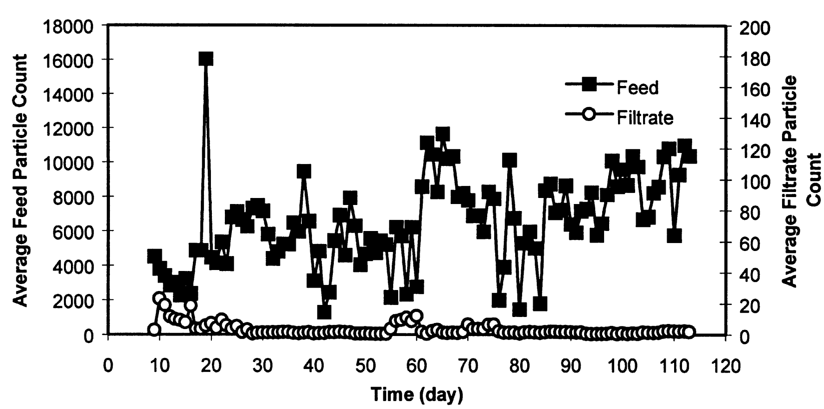

Fig. 7 Plot of particle count for raw feed and filtrate vs. consecutive day of particle count data collection.

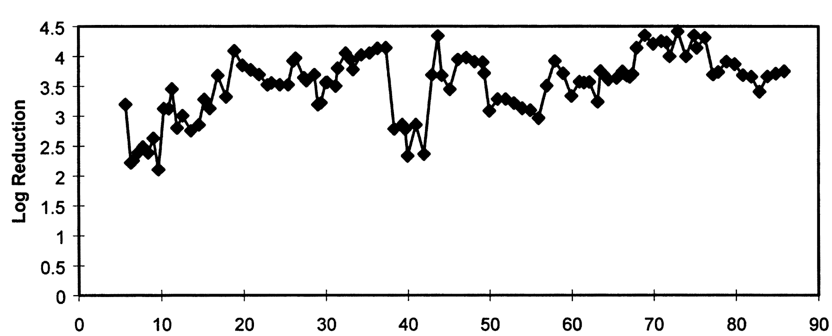

Fig. 8 Plot of average particle count log removal vs. cumulative run-time of particle count data collection.

increased in the feed stream. The rejection of coliform was absolute, constant and greater than only 1–2 logs for the limits of this study. Assessing the rejection capability of the microfiltration membrane for coliforms would require challenging the membrane with higher coliform concentrations and/or collecting larger sample sizes. Turbidity is used by regulators as a indicator of bacterial integrity, but cannot easily be used for quantifying bacterial rejection because it is not a direct measure of concentration. Particles are a better measure of bacterial rejection because particles are a direct measure of concentration. The relationship between bacterial rejection and particle or turbidity rejection cannot be defined by this data as no bacteria were observed in the permeate. It can be stated that an infinite bacterial rejection given a 1–2 log challenge corresponded to a 3–4 log rejection of particles and a 2–3 log rejection of turbidity. It is very probable that bacteria can be detected in the permeate given larger challenges and/or sample sizes. Additional work is required to quantify microbial rejection by membranes and conventional water treatment processes so that process capabilities can be correctly assessed.

CONCLUSIONS

The microfilter was operated over a six-month period under variable temperature, flux and pretreatment conditions. It produced a high and consistent filtered water quality with an average permeate turbidity and particle count in the 2–5 μm range of 0.11 NTU and 2/100 mL.

Alum pretreatment enabled the period of operation between cleanings to be increased by 2.5–3-fold. However, no work was done to determine if aluminium solids accrued in the membrane. Such accrual could damage membranes and should be taken into consideration when evaluating alum addition.

The period between cleanings using alum would be no more than once every 20–30 days. This is a significant improvement over PAC or conventional microfiltration.

The time of operation between cleanings increased with temperature and decreased with flux.

No total, faecal and *Escherichia* coliforms were found in the microfiltration filtrate. The number of coliforms were less than 200/100 mL in the feed water. This represents an infinite removal given a 1–2 log challenge, but does not represent infinite removal for higher challenges. Spikes of coliforms in the feed water or the collection of larger permeate samples could better assess the microfiltration log rejection.

The log rejection of particles and turbidity was 3.7 and 2.4 and increased as the particles and turbidity in the feed stream increased. This rejection of particle and turbidity corresponded to a absolute rejection of coliform, given a 1–2 log coliform challenge.

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